

CONVERGING TECHNOLOGIES FOR IMPROVING HUMAN PERFORMANCE

June 2002

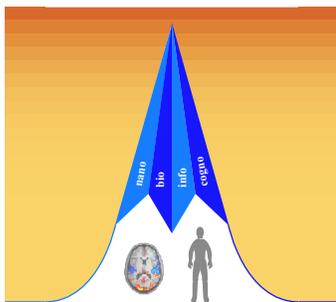


National Science Foundation Department of Commerce

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.

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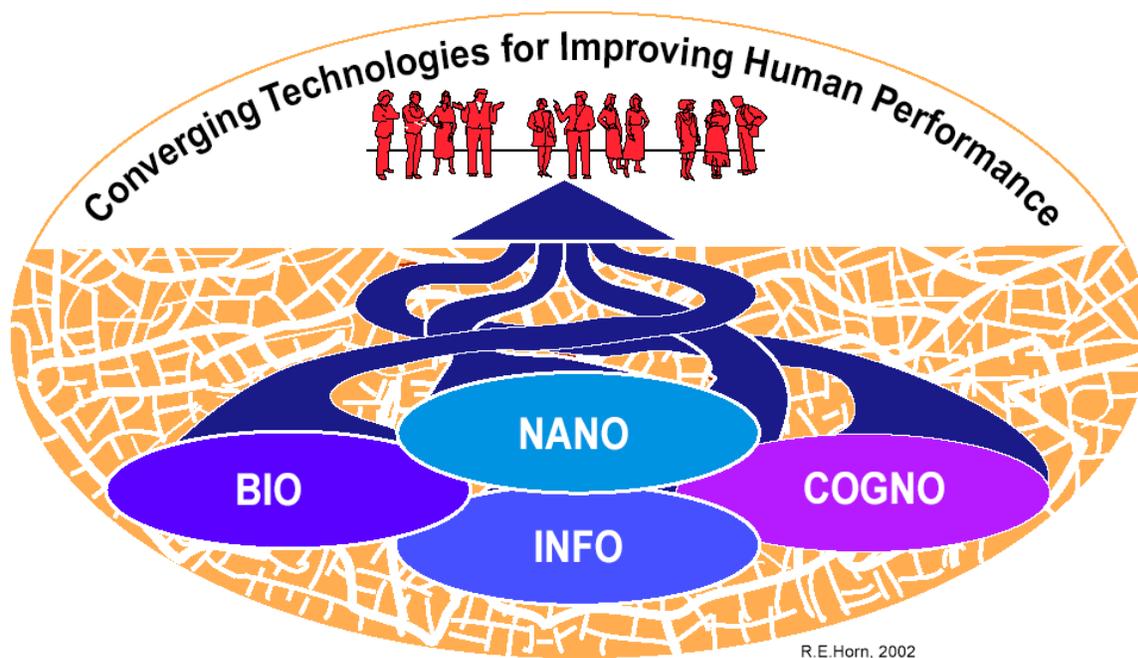
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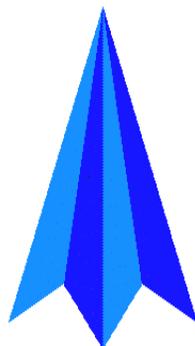
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*Changing the societal “fabric” towards a new structure
(upper figure by R.E. Horn)*

The integration and synergy of the four technologies (nano-bio-info-cogno) originate from the nanoscale, where the building blocks of matter are established. This picture symbolizes the confluence of technologies that now offers the promise of improving human lives in many ways, and the realignment of traditional disciplinary boundaries that will be needed to realize this potential. New and more direct pathways towards human goals are envisioned in working habits, in economic activity, and in the humanities.



NBIC “arrow”

This picture suggests advancement of converging technologies.

EXECUTIVE SUMMARY

M.C. Roco and W.S. Bainbridge

In the early decades of the twenty-first century, concentrated efforts can unify science based on the unity of nature, thereby advancing the combination of nanotechnology, biotechnology, information technology, and new technologies based in cognitive science. With proper attention to ethical issues and societal needs, converging technologies could achieve 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*. The building blocks of matter that are fundamental to all sciences originate at the nanoscale. 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, human society, and scientific research as *closely coupled complex, hierarchical systems*. At this moment in the evolution of technical achievement, *improvement of human performance through integration of technologies* becomes possible.

Examples of payoffs may 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, sustainable and “intelligent” environments including neuro-ergonomics, 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.

The workshop participants envision important breakthroughs in NBIC-related areas in the next 10-20 years. Fundamental research requires about the same interval to yield significant applications. Now is the time to anticipate the research issues and plan an R&D approach that would yield optimal results.

This report addresses key issues: What are the implications of unifying sciences and converging technologies? How will scientific knowledge and current technologies evolve and what emerging developments are envisioned? 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 addressed within twenty years' time. Moving forward simultaneously along many of these paths could achieve an age of innovation and prosperity that would be a turning point in the evolution of human society. The

right of each individual to use new knowledge and technologies in order to achieve personal goals, as well as the right to privacy and choice, are at the core of the envisioned developments.

This report is based on exploratory research already initiated in representative research organizations and on the opinions of leading scientists and engineers using research data.

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. The aim is to offer individuals and groups an increased range of attractive choices while preserving fundamental values such as privacy, safety, and moral responsibility. 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. The sciences have reached a watershed at which they must unify if they are to continue to advance rapidly. 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 and research needs to improve human performance, as well as the overall potential for revolutionary changes in the economy and society. 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 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 are: 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 and regenerative biosystems as replacements for human organs or for monitoring of physiological well-being; nanoscale machines 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. Other areas of focus are in enhancing group creativity and productivity, cognitive engineering and developments related to networked society. A key priority will be revolutionary new products and services based on the integration of the four technologies from the nanoscale.
- *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 people 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 institutions 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 sets goals for societal transformation and educational. 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, 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. Ethical, legal, moral economic, environmental, workforce development, and other societal implications must be addressed from the beginning, involving leading NBIC scientists and engineers, social scientists and a broad coalition of professional and civic organizations. Research on societal implications must be funded, and the risk of potential undesirable secondary effect must be monitored by a government organization in order to anticipate and take corrective actions. Tools should be developed to anticipate scenarios for future technology development and applications.
- 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 capabilities.

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*. This would be a suitable framework for a long-term, coherent strategy in research and education. Science and 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 essential to the future of humanity.

OVERVIEW

CONVERGING TECHNOLOGIES FOR IMPROVING HUMAN PERFORMANCE: Nanotechnology, Biotechnology, Information Technology, and Cognitive Science (NBIC)

M.C. Roco and W.S. Bainbridge

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 for reaching human goals. In the early decades of the twenty-first century, concentrated effort can bring together nanotechnology, biotechnology, information technology, and new 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? How will scientific knowledge and current technologies evolve and what emerging developments are envisioned? 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 Converging 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.

This report is based on exploratory research already initiated in representative research organizations and on the opinions of leading scientists and engineers using research data. Contributors to this report have considered possibilities for progress based on full awareness of ethical as well as scientific principles.

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," which symbolizes this convergence. 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.

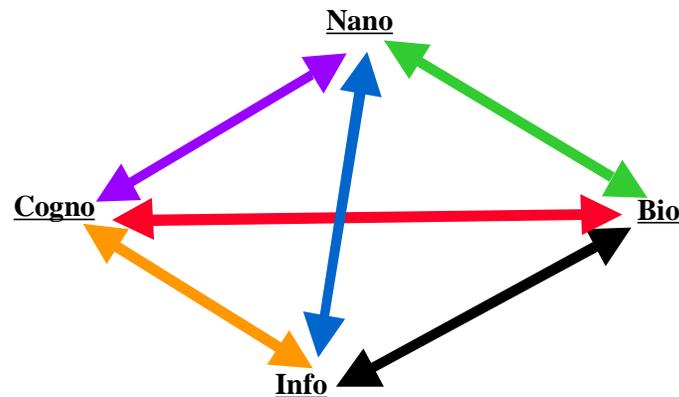


Figure 1. NBIC tetrahedron.

2. Timely and Broad Opportunity

The sciences have reached a watershed at which they must combine in order to advance most rapidly. 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 can yield results over the next two decades 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 on technology integration from that scale*. Science can now understand the ways in which atoms combine to form complex molecules, and how 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 materials 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 harder to surmount.
- c) Developments in systems approaches, mathematics, and computation in conjunction with work in NBIC areas allow us for the first time to understand the natural world and cognition in terms of *complex, hierarchical systems*. Applied both to particular research problems and to the overall organization of the research enterprise, this complex systems approach provides holistic awareness of opportunities for integration, in order to obtain maximum synergy along the 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 means 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.

The history of science across the vast sweep of human history undermines any 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, although at a much slower rate than that experienced by Europe and North America over the past five centuries. For modern civilization, the most relevant and instructive precursor remains the classical civilizations 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 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 with the 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 on an accelerating path 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. A creative individual, schooled in multiple arts, might be a painter one day, an engineer the next, and a writer the day after that. However, as the centuries passed, the holism of the Renaissance gave way to specialization and intellectual fragmentation. Today, with the scientific work of recent decades showing us at a deeper level the fundamental unity of natural organization, 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. 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 discovery 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 present quality of

life (United Nations Development Program 2001) will be accelerated by NBIC, and new possibilities for human performance will be unleashed.

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 significantly our level of understanding, 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 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, their potential contribution is vast. Following are twenty ways the workshop determined that convergent technologies could benefit humanity in a timeframe of 10 to 20 years. Each of these scenarios are presented in detail in the body of the report:

- Fast, broadband interfaces directly between the human brain and machines will transform work in factories, control automobiles, ensure military superiority, 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, chemical pollutants, potential hazards, and information of interest about local businesses, natural resources, and the like.
- Robots and software agents will be far more useful for human beings, because they will operate on principles compatible with 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 multinational partnerships.
- The human body will be more durable, healthy, energetic, easier to repair, and resistant to many kinds of stress, biological threats, and aging processes.
- Machines and structures of all kinds, from homes to aircraft, will be constructed of 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 will eradicate altogether some handicaps that have plagued the lives of millions of people.

- National security will be greatly strengthened by lightweight, information-rich war fighting 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; widespread consensus about ethical, legal, and moral issues will be built in the process.
- The vast promise of outer space will finally be realized by means of efficient launch vehicles, robotic construction of extraterrestrial bases, and profitable exploitation of the resources of the Moon, Mars, or near-Earth approaching asteroids.
- 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.
- Average persons, as well as policymakers, will have a vastly improved awareness of the cognitive, social, and biological forces operating their lives, 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 realtime 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 a turning point for human productivity and quality of life. 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, distributed and interconnected “brain” based in new core pathways of society. This will be an enhancement to the productivity and independence of individuals, giving them greater opportunities to achieve personal goals.



Figure 2. Vision of the world as a distributed, interconnected “brain” with various architectural levels, which can empower individuals with access to collective knowledge while safeguarding privacy.

Table 1 shows a simplified framework for classifying improving human performance areas as they relate to an individual (see also 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 ingestible 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

Science and engineering as well as societal activities are expected to change, regardless of whether there are policies to guide or promote such changes. To influence and accelerate changes in the most beneficial directions, it is not enough to wait patiently while scientists and engineers do their traditional work. Rather, the full advantages of NBIC developments may be achieved by making special efforts 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:

- e) We should prepare key organizations and social 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.
- f) Activities must be enhanced that accelerate convergence of technologies for improving human performance, including focused research, development, and design; increasing synergy from the nanoscale; developing interfaces among sciences and technologies; and taking a holistic approach to monitor the resultant societal evolution. The aim is to offer individuals and groups an increased range of attractive choices while preserving fundamental values such as privacy, safety, and moral responsibility. A research and development program for exploring the long-term potential is needed.
- g) Education and training at all levels should use converging technologies as well as 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 a scientific community that will achieve the convergence of technologies that can greatly improve human capabilities.
- h) Experimentation with innovative ideas is needed 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.
- i) Concentrated multidisciplinary research thrusts could achieve crucially important results. Among the most promising of such proposed endeavors are the Human Genome Project 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.
- j) Flourishing communities of NBIC scientists and engineers will need a variety of multiuser, multiuse research and information facilities. Among these will be data infrastructure archives, that employ 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.

- k) 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 structures at the nanoscale, and the hierarchical logic of intelligence.
- l) 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 face. Examples are the moral and ethical issues involved in applying new brain-related scientific findings (*Brain Work* 2002). Should we make our own ethical decisions or “are there things we’d rather not know” (Kennedy 2002)? To live in harmony with nature, we must understand natural processes and be prepared to protect or harness them as required for 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.
- m) It is necessary to accelerate developments in medical technology and healthcare in order to obtain maximum benefit from 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 detection and correction of abnormal individual health indications, and 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-technology 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 variety of currently low-technology areas.

The U.S. 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-technology fields into high-technology fields, thereby increasing the fraction of the U.S. economy that is both growing and world-preeminent.

This beneficial transformation will not take place without fundamental research in fields where such research has tended to be rare or 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 that 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 on a marriage of biology and nanotechnology.

Another example is in the area of information science, where progress 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 nonorganic 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.

Thus, in order to attain the maximum benefit from scientific progress, the goal can be 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 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. It will therefore 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 the future to take on entirely new tasks from those they have traditionally handled. The traditional tool kit 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 manufacturing, 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 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 from 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 NBIC 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 NBIC areas (nanotechnology, biotechnology, information technology, 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 fascinating questions, the answers to which would enable significant 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 both 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 fields had discovered autonomous truths that should not be reduced to the laws of other sciences. But such a discipline-centric outlook is self-defeating, because as this report makes clear, through recognizing their connections with each other, all the sciences can progress more effectively. 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, the 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. We envision that 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.

6. Major Themes

A planning 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 policymakers 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 2001 workshop on Convergent Technologies to Improve Human Performance submitted more than fifty written contributions, each of which is like a single piece in a jigsaw puzzle. Together, they depict the future unification of nanotechnology, biotechnology, information technology, and cognitive science, with the amazing benefits they promise. Roughly half of these written contributions, which we call *statements*, describe the current situation and suggest strategies for building upon it. The other half describe *visions* of what could be accomplished in ten or twenty years. During the workshop, participants examined the vast potential of NBIC 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 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 continued progress in NBIC technologies is an essential component for government agencies 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 machines programmed with human-like characteristics, and the ways that convergent technologies could enhance our understanding and effective use of human mental abilities. The group 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 proposed 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 of workshop participants 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 via neuromorphic engineering. Six technological capabilities for improvement of human health and physical performance received high priority: bio-nano machines for development of treatments, including those resulting from bioinformatics, genomics and proteomics; nanotechnology-based implants as replacements for human organs (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 connections to the human neural system; multi-modality platforms for vision- 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 of workshop participants 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 to communities and the nation as a whole has been identified, and a specific vision has been proposed of how these could be achieved through a focused research effort to develop a system this group called The Communicator. This NBIC technology would remove barriers to communication caused by 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. Converging technologies will lead to revolutionary new industries, products and services based on the synergism and integration of biology, information and cognitive sciences from the nanoscale.
- 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 caused by sleep deprivation; and applications of brain-machine interfaces. These highly varied goals could be achieved through specific convergences of NBIC technologies.
- f) **Unifying Science and Education.** The final group examined the opportunities for unifying science and the current limitations of scientific education, which is poorly designed to meet the coming challenges. The group documented the need for radical transformation in science education from elementary school through postgraduate 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 (Figure 3; see Tolles 2002, in this volume). New curricula, new concepts to provide intellectual coherence, and new types of educational institutions will be necessary.

Thus, based on the contributions of individual participants and the work of the six subgroups, the workshop identified the major areas where improved human performance is needed, and identified both short-term and longer-term opportunities to apply convergent technologies to these needs. Table 2 summarizes the key visionary projects discussed in this report. 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 policymakers. In addition, the workshop recognized specific needs to develop meaningful partnerships and coherent interdisciplinary activities.

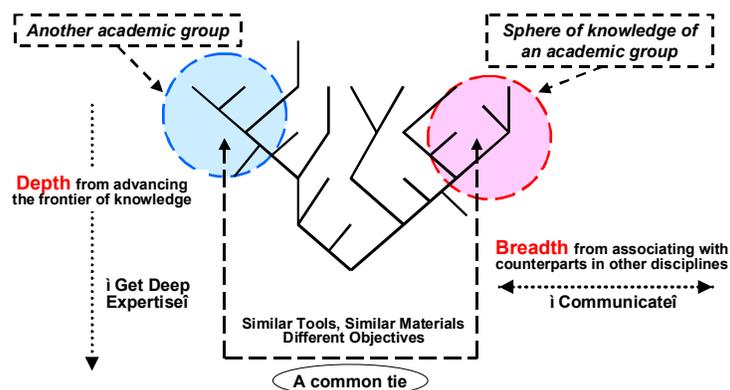


Figure 3. Combining depth with breath in NBIC education and research of various groups.

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
	Sustainable and “intelligent” environments
	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 and creativity
	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 networked society
	Breadth, depth, “trading zones,” and reshaping education at all levels
	Changing the human culture

7. Future Prospects

Nanotechnology, biotechnology, and information technology are moving closer together, following an accelerated path of unparalleled breakthroughs. Their focus on human dimensions is still emerging but promises to dominate the next decades. Despite efforts of workshop organizers, given the breadth of the topic, it was impossible to recruit leading experts in all the areas where the convergence of NBIC technologies are 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, the section below presents the following *admittedly speculative* additional ideas on how technological convergence may transform human abilities two decades and more in the future. Many of the ideas that follow emerged during the workshop, and others were suggested in discussions with participants afterward.

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 an efficient length scale for manufacturing (NSTC 2002) because rearranging 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 (National Research Council 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 and permit very rapid reconfiguration of manufacturing processes and product lines (National Research Council 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. National Research Council 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 multiple sensory modalities for visually and hearing impaired persons, 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; another is a method of optimizing oxygenization of blood when metabolism is compromised in a critical medical situation. Others would be realtime 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 may be accomplished in the next two decades that would allow for better understanding of its functions. An artificial brain (Cauler and Penz 2002) 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 with 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 (Bonadio 2002; Heller 2002; Connolly 2002).

Communication and Education

New communication paradigms (brain-to-brain, brain-machine-brain, group) could be realized in 10-20 years. Neuromorphic engineering may allow the transmission of 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 could 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 be able to 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 multimedia information displays are seamlessly integrated into the physical world. Strategies for hierarchical, architectural, global analysis, and design of complex systems will help 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 understanding and remediating 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 will 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 nano-, bio-, and information 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 can compensate for cognitive or emotional deficiencies.

Aeronautics and Space Flight

NBIC synergies could greatly expand capabilities for piloted adaptive aircraft, unmanned aircraft, and human space flight. Nanostructured materials and advanced electronics have the promise of reducing the weight of spacecraft by three quarters 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 costs and efficient subsystems can be solved, then human society can effectively exploit Earth orbital space, the Moon, asteroids, 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 will be endowed with intelligence and communication capabilities reflecting human behavior.

Food and Farming

Farmers have long appreciated the advantages of science and technology; 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 (National Research Council 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 has 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 contains.

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 help stabilize the supply of resources. Value will stem from 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 nonrenewable energy supplies. Sensing the environment and biosystems of the world will become essential in global environmental monitoring and remediation. New sources for a

distributed energy system are envisioned, as well as new solutions such as highly efficient photosynthetic proteins, membranes, and devices.

Interactive and “intelligent” environments for human activities are envisioned, responding to advancements in areas such as neuro-ergonomics and the needs of persons with disabilities.

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 have developed sufficiently, adaptive materials need not be especially expensive, especially when their increased performance and energy efficiency are factored in. For example, nanotechnology materials and IT-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 respond to particular design features.

Self-Presentation and Fashion

Government-supported academic researchers frequently ignore many economically important industries, in part because those industries traditionally 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 multibillion 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 cosmetics that change 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 are 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 adjusts to changing temperatures and weather conditions. Perhaps the colors and apparent textures of this “smart clothing” would adjust also 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 twenty-first century. Processes both of decentralization and integration would render society ever more complex, resulting in a new, dynamic social architecture. There would be entirely new patterns in manufacturing, the economy, education, and military conflict.

People may 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 acceptance of brain implants, the role of robots in human society, and the ambiguity of death in an era of increasing

experimentation with cloning. 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 intended 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 and the innate human appreciation for beauty.

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

Generations	Several Key Advancements (human kind, tools and technology, communication)
-m	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
½	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?

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. It could be structured to enhance individuals' creativity and independence. 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 enabled through NBIC convergence could 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 the Industrial Revolution.

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 that it is capable of 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 systems perspective and improving human performance, research and education must have deep scientific roots and superior communication among the fields of human endeavor.

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

- Development of NBIC tools for investigation and transformational engineering at four levels: nano/microscopic, individual, group, and society
- Integration of fundamental concepts of NBIC across all scales, beginning with the nanoscale
- Investigation of converging technologies that is systems- and holistic-based
- 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. Expected to be a major challenge in approaching complex systems is the hierarchical architecture in which various components are integrated and used. Consideration of the human implications of converging technologies will include examination of potential unexpected consequences of NBIC developments, including ethical and legal aspects.

Recommendations to Individuals and Organizations

This report has educational and transformational goals. Building on the suggestions developed in the five topical groups and the ideas in the more than fifty individual contributions, workshop participants 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 now is broad, enduring, and of general interest. The report contributors addressed the roles that individuals, academe, the private sector, the U.S. Government, professional societies, and other organizations should play in this converging technology priority area:

- g) **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.
- h) **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 the human dimensions of science and technology. Investigations of converging technologies should 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.
- i) **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.
- j) **Government.** A national research and development priority area should be established that focuses on converging technologies that enhance 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 developments; and consider ethical, legal, and policy issues. Governments must provide support for education and training of future NBIC workers and to prepare society for the major systemic changes envisioned for a generation from now. Policymakers must envision development scenarios to creatively stimulate the convergence. Ethical, legal, moral, economic, environmental, workforce development, and other societal implications must be addressed from the beginning, involving leading NBIC scientists and engineers, social scientists and a broad coalition of professional and civic organizations. Research on societal implications must be funded, and the risk of potential undesirable secondary effect must be monitored by a government organization in order to anticipate and take corrective actions. Tools should be developed to anticipate scenarios for future technology development and applications. The transforming measures outlined in section 4 above suggest the dimensions of the Federal Government role.
- k) **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.

- l) **Other Organizations.** Nongovernmental 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 particular 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 social equality, 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 contributors to 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 application, and the role of government is important because no other participant can cover the breadth and level of required collective effort. Without special efforts for coordination and integration, the path of science 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 essential to the future of humanity.

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GENERAL STATEMENTS AND VISIONARY PROJECTS

The following six sets of contributions (chapters A to F) present key statements and visions from academe, private sector and government illustrating what technological convergence could achieve in the next ten to twenty years. In each set, statements are grouped at the beginning that consider the current situation in the particular area and project how we could build on it to achieve rapid progress. The later contributions in the set present visions of what might be achieved toward the end of the two-decade period. In the first of these six sets, government leaders and representatives of the private sector provide the motivation for this effort to understand the promise of converging technologies. The second and third sets of contributions identify significant ways in which the mental and physical abilities of individual humans could be improved. The third and fourth sets examine prospects on the group and societal level, one considering ways in which the internal performance of the society could benefit and the other focusing on the defense of the society against external threats to its security. The sixth and final set of essays considers the transformation of science and engineering themselves, largely through advances in education.

A. MOTIVATION AND OUTLOOK

THEME A SUMMARY

Panel: P. Bond, J. Canton, M. Dastoor, N. Gingrich, M. Hirschbein, C.H. Huettner, P. Kuekes, J. Watson, M.C. Roco, S. Venneri, R.S. Williams

In a sense, this section of the report gives the authors their assignment, which is to identify the technological benefits of convergence that could be of greatest value to human performance and to consider how to achieve them. Five of the statements were contributed by representatives of government agencies: The Office of Science and Technology Policy, The Department of Commerce, The National Aeronautics and Space Administration, the National Institutes of Health, and the National Science Foundation. The remaining three were contributed from private sector organizations: The American Enterprise Institute, Hewlett Packard, and the Institute for Global Futures. But these eight papers are far more than mission statements because they also provide an essential outlook on the current technological situation and the tremendous potential of convergence.

- i) It is essential to identify new technologies that have great potential to improve human performance, especially those that are unlikely to be developed as the natural consequence of the day-to-day activities of single governmental, industrial, or educational institutions. Revolutionary technological change tends to occur outside conventional organizations, whether through social movements that promulgate new goals, through conceptual innovations that overturn old paradigms of how a goal can be achieved, or through cross-fertilization of methods and visions across the boundaries between established fields (Bainbridge 1976). Formal mechanisms to promote major breakthroughs can be extremely effective, notably the development of partnerships between government agencies to energize communication and on occasion to launch multiagency scientific initiatives.

- ii) Government has an important role in setting long-term priorities and in making sure a national environment exists in which beneficial innovations will be developed. There must be a free and rational debate about the ethical and social aspects of potential uses of technology, and government must provide an arena for these debates that is most conducive to results that benefit humans. At the same time, government must ensure economic conditions that facilitate the rapid invention and deployment of beneficial technologies, thereby encouraging entrepreneurs and venture capitalists to promote innovation. Of course, government cannot accomplish all this alone. In particular, scientists and engineers must learn how to communicate vividly but correctly the scientific facts and engineering options that must be understood by policymakers and the general public, if the right decisions are to be made.
- iii) While American science and technology benefit the entire world, it is vital to recognize that technological superiority is the fundamental basis of the economic prosperity and national security of the United States. We are in an Age of Transitions, when we must move forward if we are not to fall behind, and we must be ready to chart a course forward through constantly shifting seas and winds. Organizations of all kinds, including government itself, must become agile, reinventing themselves frequently while having the wisdom to know which values are fundamental and must be preserved. The division of labor among institutions and sciences will change, often in unexpected ways. For many years, scholars, social scientists, and consultants have been developing knowledge about how to manage change (Boulding 1964; Drucker 1969; Deming 1982; Womack and Jones 1996), but vigorous, fundamental research will be needed throughout the coming decades on the interaction between organizations, technology, and human benefit.
- iv) Government agencies need progress in NBIC in order to accomplish their designated missions. For example, both spacecraft and military aircraft must combine high performance with low weight, so both NASA and the Department of Defense require advances in materials from nanotechnology and in computing from information technology. Furthermore, in medicine and healthcare, for example, national need will require that scientists and engineers tackle relatively pedestrian problems, whose solutions will benefit people but not push forward the frontiers of science. But practical challenges often drive the discovery of new knowledge and the imagination of new ideas. At the same time, government agencies can gain enhanced missions from NBIC breakthroughs. One very attractive possibility would be a multiagency initiative to improve human performance.
- v) Science must offer society new visions of what it is possible to achieve. The society depends upon scientists for authoritative knowledge and professional judgment to maintain and gradually improve the well-being of citizens, but scientists must also become visionaries who can imagine possibilities beyond anything currently experienced in the world. In science, the intrinsic human need for intellectual advancement finds its most powerful expression. At times, scientists should take great intellectual risks, exploring unusual and even unreasonable ideas, because the scientific method for testing theories empirically can ultimately distinguish the good ideas from the bad ones. Across all of the sciences, individual scientists and teams should be supported in their quest for knowledge. Then interdisciplinary efforts can harvest discoveries across the boundaries of many fields, and engineers will harness them to accomplish technological progress.

The following eight statements develop these and other ideas more fully, thereby providing the motivation for the many chapters that follow. They also provide a perspective on the future by identifying a number of megatrends that appear to be dominant at this point in human history and by suggesting ways that scientists and policymakers should respond to these trends. Their advice will help Americans make history, rather than being subjects of it, strengthening our ability to shape our future. The statements include a message from the White House Office of Science and Technology Policy (OSTP) concerning the importance of this activity to the nation, a message from the

Department of Commerce on its potential impact on the economy and U.S. competitiveness, a vision for converging technologies in the future, examples of activities already underway at NASA and NIH, industry and business perspectives on the need for a visionary effort, and an overview of the trend toward convergence of the megatrends in science and engineering.

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NATIONAL STRATEGY TOWARDS CONVERGING SCIENCE AND TECHNOLOGY

Charles H. Huettner, OSTP, White House

Good morning. I want to express to you on behalf of Dr. John Marburger, who is the President's science advisor and the Director of the Office of Science and Technology Policy (OSTP), his regrets for not being able to be with you, particularly because this workshop is a very important first step towards the future in which different sciences come together.

The role of the OSTP is to identify cross-cutting, high-risk technologies that don't reside in a particular department or agency and to sponsor them, thus helping them move across government agencies. Nanotechnology is a clear example of the kinds of technologies that have great potential and yet need government-wide review and focus.

Obviously, nanotechnology is just one of a number of emerging technologies. We are living in a very exciting time. Just think of what has happened with information technology over the last 10 years. It has allowed us to have the Internet, a global economy, and all of the things that we know about and have been living through. In just this past year, the field of biology has experienced tremendous advances with the human genome project. New this year in the budget is the national nanotechnology initiative, and similar kinds of progress and accomplishment are anticipated there.

Could these technologies and others merge to become something more important than any one individually? The answer to that question obviously is that they must. Convergence means more than simply coordination of projects and groups talking to one another along the way. It is imperative to integrate what is happening, rise above it, and get a bigger picture than what is apparent in each individual section.

There is an institute at Harvard called the Junior Fellows, formed many, many years ago by a forward thinker at Harvard and endowed with a beautiful building with a wonderful wine cellar. Senior Fellows, who were the Nobel Laureates of the university, and Junior Fellows, who were a select group of people picked from different disciplines, came together there for dinner from time to time. Sitting together at one Junior Fellows dinner I attended several years ago were musicians, astrophysicists, and astronomers discussing how certain musical chords sound good and others don't, and how those sorts of harmonics actually could help to explain the solar system, the evolution of galaxies, and so forth. Essentially, this is what the two-day NBIC workshop is doing, bringing together thinkers from different disciplines to find common ground and stimulate new thinking. When professionals as diverse as musicians and astrophysicists can discover mutually resonant concepts, think about what we can do with the kinds of technologies that we have today. That is why this NBIC workshop is so important.

You are the national technology leaders, or you are connected with them. You are the beginnings of an important group coming together. Nuclear and aerospace technology, psychology, computer science, chemistry, venture capital, medicine, bioengineering, social sciences — you're all here, and you represent not only the government, but also industry and academia. I thought it was tremendously creative, the way that the working sessions were broken down around people's needs because, in the end, that's why science is here. Science is here to serve people. So, it is very important for the breakout groups to look at human cognition and communications and human physical performance by focusing on how to solve human needs.

Take this opportunity to begin the cross-fertilization and understanding of each other's disciplines. The language of each technology is different. The key ideas that define them are different. The hopes and visions are different. The needs to accomplish those are different. But the network that we can form and the learning that we can have as a result of today's efforts can somehow bridge those gaps and begin the understanding.

I applaud you for being here today. I challenge you to learn and think beyond your discipline to help to establish the inner technology visions, connections, and mechanisms that will solve the human problems of our world. This is the beginning of the future, and we at OSTP are both anxious to help and anxious to learn from you.

CONVERGING TECHNOLOGIES AND COMPETITIVENESS

The Honorable Phillip J. Bond, Undersecretary for Technology, Department of Commerce

Good morning, and thank you all. It is a pleasure to be here as a co-host, and I want to give you all greetings on behalf of Secretary of Commerce Don Evans, whom I am thrilled and privileged to serve with in the Bush administration. Thank you, Mike Roco and Joe Bordogna for bringing us all together. Charlie Huettner, please give my best wishes to Jack Marburger. Dr. Marburger and I were confirmation cousins, going through our Senate hearings and then floor consideration together.

It is a rare thing to see people inside the Washington Beltway coming together to actually think long-term in a town that is usually driven by the daily headlines. I believe it was George Will who observed that most people inside the Beltway survive on the intellectual capital they accumulated before they came inside the Beltway. I certainly hope that's not true in my case. I do want to encourage you and join you. Let us lift our eyes, look at the future, and really seize the opportunity for some of the policy implications.

I stand before you today not as a scientist, but as an advocate. My background as the head of Hewlett-Packard's office here in Washington, before that with an IT association, and then on the Hill, and

before that with Dick Cheney at the Pentagon, implies that I am supposed to know something about moving the gears of government toward positive policy outcomes. With that in mind, I now have the privilege of overseeing the National Institute of Standards and Technology (NIST), the Office of Technology Policy, and the National Technical Information Service that I am sure many of you periodically go to for information, as well as the National Medal of Technology.

I am sure that many of you saw the news this morning that one of our past National Medal of Technology winners has unveiled what was previously code-named Ginger, which I now understand is the Segway Human Transporter — Dean Kamen's new project. So, next time we can all ride our two-wheelers to the meeting. At any rate, I want to pledge to you to really try to provide the kind of support needed over the long term on the policy front.

Historical perspective is useful for a meeting such as this, and for me this is best gained in very personal terms. My grandparents, Ralph and Helen Baird, just passed away. He died earlier this year at 101 and she two years ago at 99. They taught me about the importance of science and technology to the human condition. Before they passed on, they sat down and made a videotape reviewing the things they had seen in their life.

In that arena, what was particularly relevant is the fact that Ralph had been a science teacher. Both of my grandparents saw men learn to fly and to mass-produce horseless carriages. They told great stories about living in Kansas and getting on the community phone, ringing their neighbors and saying, "Quick, run down to the road. One's coming. Run down to see one of these gizmos rolling by." They saw the generation and massive transmission of electricity, the harnessing of the power of the atom, the space-travel to our moon, the looking back in time to the origins of our universe, the development of instantaneous global communications, and most recently, the deciphering of the human genome and cloning of very complex organisms. Each of these is extraordinary in its technical complexity but also profound in terms of its economic and social significance.

This is one of the challenges we have for you in the discussions. To borrow from Churchill, as everybody seems to do, this is "the end of the beginning." As we head into the 21st Century, we are going to have not only accelerating change, but accelerating moral and ethical challenges. Again here, I take a very personal view of this. My daughters Jackie and Jesse are 10 and 7. So when I look at the future and think about the ethical possibilities and possibilities of robo-sapiens, as *Wired* magazine talks about, I think in terms of what my daughters will face and how we as a society can reap the harvest of technology and remove the chaff of unethical uses of that technology. We have a real balancing act moving forward. The future of all of us — and my daughters' futures — are on the line.

Other speakers have mentioned the exciting fields that you're going to be looking at today and how they converge. I will leave most of the description of that to others, including the always provocative and mesmerizing Newt Gingrich and my friend Stan Williams from HP, and to your breakout discussions. However, as a political appointee, let me do what I do best, and that is to observe the obvious.

Obviously, powerful technologies are developing. Each is powerful individually, but the real power is synergy and integration, all done at the nanoscale. There's plenty of room at the bottom. Intel recently announced it expects to produce a terahertz chip about six or seven years out — 25 times the number of transistors as the top-of-the-line Pentium 4. Within the next few years we're going to be looking at computers that are really personal brokers or information assistants. These devices will be so small that we'll wear them and integrate them. They will serve as information brokers. Again, when I think about my daughters, if current trends hold, one of those information brokers will be looking at science and horses and the other will be looking at hairstyles — but to each their own. Seriously, that day is coming fast, based on breakthroughs in producing computer chips with extremely small components.

If we do policy right, with each breakthrough will come technology transfer, commercialization, economic growth, and opportunity that will pay for the next round of research.

In all of this, at least as a policy person, I try to separate hype from hope. But the more I thought about that, the more I determined that in this political town, maybe the separation isn't all that important, because hype and hope end up fueling the social passion that forms our politics. It gets budgets passed. It makes things possible for all of you. Without some passion in the public square, we will not achieve many of our goals. Those goals are mind-boggling — what we used to think of as miraculous — the deaf to hear, the blind to see, every child to be fed. And that's just for starters.

Always, each advance in technology carries a two-edged sword. As a policy person I need your help. One hundred years ago, the automobile was not immediately embraced; it was rejected as a controversial new innovation. Eventually it was accepted, then we had a love affair with it, and now it's perhaps a platonic relationship. Our journey with these other technologies is going to have similar bumps in the road. And so, as you set out today, I think you should include these three important considerations in your mission:

- to achieve the human potential of everybody
- to avoid offending the human condition
- to develop a strategy that will accelerate benefits

Earlier, we talked about the network effect of bringing you all together, and these new technologies are going to enhance group performance in dramatic ways, too. We really must look at some of the ethical challenges that are right around the corner or even upon us today. Our strategy must establish priorities that foster scientific and technical collaboration, and ensure that our nation develops the necessary disciplines and workforce. We need a balanced but dynamic approach that protects intellectual property, provides for open markets, allows commercialization, and recognizes that American leadership is very much at stake.

Look all around the globe at the work that's going on at the nanoscale. American leadership is at stake, but we need a global framework for moving forward. The federal government, of course, has an important role: ensuring a business environment that enables these technologies to flourish, to work on that global aspect through the institutions of government, to continue to provide federal support for R&D. I am proud that President Bush recommended a record investment in R&D. I know there are concerns about the balance of the research portfolio. We need your help on that. President Bush specifically requested a record increase in the nano budget, over \$604 million, almost double what it was two years ago.

The federal government has a clear fiscal role to play but also should use the bully pulpit to inspire young kids like one daughter of mine who does love science right now, so that they will go ahead and pursue careers like yours to reach the breakthroughs, so we will have more people like 39-year-old Eric Cornell at NIST, one of our recent winners of a Nobel Prize for Physics.

I think we can achieve our highest aspirations by working together as we are today — and we've got some of the best minds gathered around this table. But my message is distilled to this: If we set the right policies and we find the right balance, we can reap the rewards and avoid the really atrocious unethical possibilities. At every step — whether it's funding, advocacy, policy formation, public education, or commercialization — we're going to need you scientists and engineers to be intimately involved. I look forward to being a part of this promising effort. Thank you.

VISION FOR THE CONVERGING TECHNOLOGIES

Newt Gingrich

My theme is to argue that you want to be unreasonable in your planning.

I was struck with this at the session Mike Roco invited me to about six months ago, where somebody made a very impassioned plea against promising too much too quickly and not exaggerating. In 1945, Vannevar Bush wrote what was a quite unreasonable article for his day, about the future of computational power. Einstein's letter to Franklin Delano Roosevelt in September of 1939 was an extremely unreasonable letter. Edward Teller told me recently that he got in a big argument with Niels Bohr about whether or not it was possible to create an atomic bomb. Bohr asserted emphatically, it would take all of the electrical production capacity of an entire country. Teller said they didn't meet again until 1944 when they were at Los Alamos and Bohr yelled down the corridor "You see, I was right." By Danish standards, the Manhattan Project was using all the power of an entire country.

Vannevar Bush's classic article is a profound, general statement of what ultimately became the ARPANET, Internet, and today's personal computation system. At the time it was written, it was clearly not doable. And so, I want to start with the notion that at the vision level, those who understand the potential have a real obligation to reach beyond any innate modesty or conservatism and to paint fairly boldly the plausible achievement.

Now, in this case you're talking about converging technology for improving human performance. Perhaps you should actually put up on a wall somewhere all of the achievable things in each zone, in the next 20 years, each of the stovepipes if you will. And then back up and see how you can move these against each other. What does the combination make true?

Think about the nanoscale in terms of a whole range of implications for doing all sorts of things, because if you can in fact get self-assembly and intelligent organization at that level, you really change all sorts of capabilities in ways that do in fact boggle the imagination, because they are that remarkable. If you bring that together with the biological revolution, the next 20 years of computation, and what we should be learning about human cognition, the capability can be quite stunning. For example, there's no reason to believe we can't ultimately design a new American way of learning and a new American way of thinking about things.

You see some of that in athletics, comparing all the various things we now do for athletes compared to 40 years ago. There is a remarkable difference, from nutrition to training to understanding of how to optimize the human body, that just wasn't physically possible 40 years ago. We didn't have the knowledge or the experience. I would encourage you first of all to put up the possibilities, multiply them against each other, and then describe what that would mean for humans, because it really is quite astounding.

I was an army brat in an era when we lived in France. In order to call back to the United States you went to a local post office to call the Paris operator to ask how many hours it would be before there would be an opening on the Atlantic cable. When my daughter was an *au pair*, I picked up my phone at home to call her cell phone in a place just south of Paris. Imagine a person who, having gotten cash out of an ATM, drives to a self-serve gas station, pays with a credit card, drives to work on the expressway listening to a CD while talking on a digital cell phone, and then says, "Well, what does science do for me?"

This brings me to my second point about being unreasonable. *When you lay out the potential positive improvements for the nation, for the individual, for the society, you then have to communicate that in relatively vivid language.*

People like Isaac Asimov, Arthur C. Clarke, and Carl Sagan did an amazing amount to convince humans that science and technology were important. Vannevar Bush understood it at the beginning of the Second World War. But if those who know refuse to explain in understandable language, then they should quit griping about the ignorance of those who don't know. Science can't have it both ways. You can't say, "This is the most important secular venture of mankind; it takes an enormous amount of energy to master it, and by the way, I won't tell you about it in a language you can understand." Scientists have an obligation as citizens to go out and explain what they need and what their work will mean.

I am 58 and I am already thinking about Alzheimer's disease and cancer. The fact that George Harrison has died and was my age makes mortality much more vivid. So, I have a vested interest in accelerating the rate of discovery and the application of that discovery. The largest single voting block is baby boomers, and they would all understand that argument. They may not understand plasma physics or the highest level of the human genome project. But they can surely understand the alternative between having Alzheimer's and not having it.

If you don't want Alzheimer's, you had better invest a lot more, not just in the National Institutes of Health (NIH) but also at the National Science Foundation (NSF) and a variety of other places, because the underlying core intellectual disciplines that make NIH possible all occur outside NIH. And most of the technology that NIH uses occurs outside of NIH. The argument has to be made by someone. If the scientific community refuses to make it, then you shouldn't be shocked that it's not made.

Let me suggest at a practical level what I think your assignments are once you've established a general vision. If you bring the four NBIC elements together into a converging pattern, you want to identify the missing gaps. What are the pieces that are missing? They may be enabling technologies, enabling networking, or joint projects.

Here again, I cite the great work done at the (Defense) Advanced Research Projects Agency ([D]ARPA). Scientists there consciously figured out the pieces that were missing to make computation easy to use and then began funding a series of centers of excellence that literally invented the modern world. You would not have gotten modern computing without ARPA, at least for another 30 years. Part of what they did that was so powerful was start with a general vision, figure out the pieces that were blocking the vision, and get them funded.

The predecessor to the Internet, ARPANET, wouldn't have occurred without two things: one was ARPA itself which had the funding, and the second was a vision that we should not be decapitated by a nuclear strike. People tend to forget that the capacity to surf on the Web in order to buy things is a direct function of our fear of nuclear war.

It helps to have the *vision* of very large breakthrough systems and some pretty long-term source of consistent funding. I've argued for the last three years that if we are going to talk about global warming, we ought to have several billion dollars set aside for the kind of climatology capabilities that will be comparable to the international geophysical year, and it would really give us the knowledge to move things a long way beyond our current relative guesses. If you look at the difference between the public policy implications of the Kyoto agreement, in the \$40 trillion range, and the amount of money you could plausibly invest if you had an opportunity-based atmospheric and climatological research program, the differences are just stunning. For far less than one percent of the cost we would in theory pay to meet Kyoto, you would have a database and a knowledge base on climatology that would be stunning.

That's outside current budgeting, because current budgeting is an incremental-increase pork barrel; it is not an intellectual exercise. I would argue that's a profound mistake. So, it's very important for you to figure out what are the large projects as a consequence of which we would be in a different league of capabilities. I would suggest, too, that both the international geophysical year and its stunning impact on the basic understanding of geology may be the most decisive change in paradigms in 20th century, at least in terms that everybody agreed it was right. I would also suggest to you the example of ARPANET, which ultimately enabled people to invent the World Wide Web. For today's purpose, take the NBIC convergence and work back to identify the large-scale projects that must be underway in order to create parallel kinds of capabilities.

I want to make further points about being unreasonable. Scientists really have an obligation to communicate in vivid, simple language the possibilities so that the President, the Vice-President and the various people who make budget decisions are forced to reject that future if they settle for lower budgets. It's really important that people understand what's at stake. It is my experience that consistently, politicians underestimate the potential of the future.

If we in fact had the right level of investment in aeronautics, we would not currently be competing with Airbus. We would be in two different worlds. Considering all the opportunities to dramatically change things out of nanoscale technology combined with large-scale computing, there's no doubt in my mind if we were willing to make a capital investment, we would create a next-generation aviation industry that would be stunningly different. It would be, literally, beyond competition by anything else on the planet. Our military advantage in Afghanistan compared with the 1979 Soviet capabilities isn't courage, knowledge of military history, or dramatically better organizational skills, but a direct function of science and technology. We need to say that, again and again.

I'll close with two thoughts. First, my minimum goal is to triple the NSF budget and then have comparable scalable increases. One of the major mistakes I made as Speaker of the House is that I committed to doubling NIH without including other parts of science. In retrospect, it was an enormous mistake. We should have proportionally carried the other scientific systems, many of which are smaller, to a substantial increase. I'm probably going to do penance for the next decade by arguing that we catch up. Second, in the media there is some talk that the Administration may offer cuts in science spending in order to get through this current budget. Let me just say this publicly as often as I can. That would be madness.

If we want this economy to grow, we have to be the leading scientific country in the world. If we want to be physically safe for the next 30 years, we have to be the leading scientific country in the world. If we want to be healthy as we age, we have to be the leading scientific country in the world. It would be literally madness to offer anything except an increase in science funding. And if anybody here is in the Administration, feel free to carry that back. I will say this publicly anywhere I can, and I will debate anyone in the Administration on this.

Congress finds billions for pork and much less for knowledge. That has to be said over and over. It's not that we don't have the money. You watch the pork spending between now and the time Congress leaves. They'll find plenty of appropriations money, if there is enough political pressure. Scientists and engineers have to learn to be at least as aggressive as corn farmers. A society that can make a profound case for ethanol can finance virtually anything, and I think we have to learn that this is reality.

Now, a lot of scientists feel above strongly advocating government funding for their work. Fine, then you won't get funded. Or you'll get funded because somebody else was a citizen. However, I don't accept the notion that scientists are above civic status, and that scientists don't have a citizen's duty to tell the truth as they understand it and argue passionately for the things they believe in.

I have this level of passion because I believe what you're doing is so profoundly real. It's real in the sense that there are people alive today that would have died of illnesses over the last week if it weren't for the last half-century of science. There are capabilities today that could allow us to create a fuel cell system in Afghanistan, as opposed to figuring out how to build a large central electric distribution system for a mountainous country with small villages. With satellite technology, we could literally create a cell phone capability for most of the country instantaneously as opposed to going back to copper.

I just visited in Romania ten days ago and saw a project that goes online December 2002 to provide 156 K mobile capability, and the Romanians think they'll be at the third generation of cellular phones at a 1.2 million capability by January of 2003. In effect, I think Romania may be the first country in the world that has a 100% footprint for the 1.2 meg cellphone business.

We ought to talk, not about re-creating 1973 Afghanistan, but about how to create a new, better, modern Afghanistan where the children have access to all kinds of information, knowledge, and capabilities. My guess is it will not be a function of money. You watch the amount of money we and the world community throw away in the next 6 years in Afghanistan, and the relatively modest progress it buys. Take the same number of dollars, and put them into a real connectivity, a real access to the best medicine, a real access to logical organization, and you will have a dramatically healthier country in a way that would improve the lives of virtually every Afghan.

Real progress requires making the connection between science and human needs. Vannevar Bush's great effort in the Second World War was to take knowledge and match it up with the military requirements in a way that gave us radical advantages; the submarine war is a particularly good example. The key was bringing science into the public arena at the state of possibility. Most of the technological advances that were delivered in 1944 did not exist in 1940. They were invented in real-time in places like MIT and brought to bear in some cases within a week or two of being invented.

I think we need that sense of urgency, and we need the sense of scale, because that's what Americans do well. We do very big things well, and we do things that are very urgent well. If they are not big enough and we bureaucratize them, we can often extend the length of time and money it takes by orders of magnitude. Thus, to be unreasonable in our planning can actually be quite realistic. We have entered a period I call The Age of Transitions, when science can achieve vast, positive improvements for the individual and the society, if we communicate the vision effectively.

The Age of Transitions: Converging Technologies

Overview

1. We are already experiencing the dramatic changes brought on by computers, communications, and the Internet. The combination of science and technology with entrepreneurs and venture capitalists has created a momentum of change which is extraordinary. Yet these changes will be overshadowed in the next twenty years by the emergence of an even bigger set of changes based on a combination of biology, information, and nanoscience (the science of objects at a billionth of a meter, from one to four hundred atoms in size). This new and as yet unappreciated wave of change will combine with the already remarkable pattern of change brought on by computers, communication, and the Internet to create a continuing series of new breakthroughs, resulting in new goods and services. We will be constantly in transition as each new idea is succeeded by an even better one. This will be an Age of Transitions, and it will last for at least a half-century.
- vi) In the Age of Transitions, the ways we acquire goods and services are rapidly evolving in the private sector and in our personal lives. Government and bureaucracy are changing at a dramatically slower rate, and the gaps between the potential goods and services, productivity,

efficiencies, and conveniences being created and the traditional behaviors of government and bureaucracies are getting wider.

- vii) The language of politics and government is increasingly isolated from the language of everyday life. Political elites increasingly speak a language that is a separate dialect from the words people use to describe their daily lives and their daily concerns. The result in part is that the American people increasingly tune out politics.
- viii) Eventually a political movement will develop a program of change for government that will provide greater goods and services at lower and lower costs. When that movement can explain its new solutions in the language of everyday life, it will gain a decisive majority as people opt for better lives through better solutions by bringing government into conformity with the entrepreneurial systems they are experiencing in the private sector.
- ix) Understanding the Age of Transitions is a very complex process and requires thought and planning. It involves applying principles to create better solutions for delivery of government goods and services and developing and communicating a program in the language of everyday life, so that people hear it and believe it despite the clutter and distractions of the traditional language of politics and government.

Introduction

We are living through two tremendous patterns of scientific-technological change: an overlapping of a computer-communications revolution and a nanotechnology-biology-information revolution. Each alone would be powerful; combined, the two patterns guarantee that we will be in constant transition as one breakthrough or innovation follows another.

Those who study, understand, and invest in these patterns will live dramatically better than those who ignore them. Nations that focus their systems of learning, healthcare, economic growth, and national security on these changes will have healthier, more knowledgeable people in more productive jobs creating greater wealth and prosperity and living in greater safety through more modern, more powerful intelligence and defense capabilities.

Those countries that ignore these patterns of change will fall further behind and find themselves weaker, poorer, and more vulnerable than their wiser, more change-oriented neighbors.

The United States will have to continue to invest in new science and to adapt its systems of health, learning, and national security to these patterns of change if we want to continue to lead the world in prosperity, quality of life, and military-intelligence capabilities.

At a minimum, we need to double the federal research budget at all levels, reform science and math learning decisively, and modernize our systems of health, learning, and government administration.

Periods of transition are periods of dramatic cost crashes. We should be able to use the new patterns of change to produce greater health and greater learning at lower cost. Government administration can be more effective at lower cost. Our national security will experience similar crashes in cost.

This combination of better outcomes at lower cost will not be produced by liberal or conservative ideology. It will be produced by the systematic study of the new patterns and the use of new innovations and new technologies.

Simply Be a More Powerful Industrial Era

Computing is a key element in this revolution. The numbers are stunning. According to Professor James Meindl, the chairman of the Georgia Tech Microelectronics Department, the first computer built with a transistor was Tradic in 1955, and it had only 800 transistors. The Pentium II chip has 7,500,000 transistors. In the next year or so, an experimental chip will be built with one billion transistors. Within fifteen to twenty years, there will be a chip with one trillion transistors. However that scale of change is graphed, it is enormous, and its implications are huge. It is estimated that we are only one-fifth of the way into developing the computer revolution.

Yet focusing only on computer power understates the scale of change. Communications capabilities are going to continue to expand dramatically, and that may have as big an impact as computing power. Today, most homes get Internet access at 28,000 to 56,000 bits per second. Within a few years, a combination of new technologies for compressing information (allowing you to get more done in a given capacity) with bigger capacity (fiber optic and cable) and entirely new approaches (such as satellite direct broadcast for the Internet) may move household access up to at least six million bits per second and some believe we may reach the 110 million bits needed for uncompressed motion pictures. Combined with the development of high definition television and virtual systems, an amazing range of opportunities will open up. This may be expanded even further by the continuing development of the cell phone into a universal utility with voice, Internet, credit card, and television applications all in one portable hand-held phone.

The S-curve of Technological Change

The communications-computer revolution and the earlier Industrial Revolution are both examples of the concept of an “S”-curve. The S-curve depicts the evolution of technological change. Science and technology begin to accelerate slowly, and then as knowledge and experience accumulates, they grow much more rapidly. Finally, once the field has matured, the rate of change levels off. The resulting pattern looks like an S. An overall S-curve is made up of thousands of smaller breakthroughs that create many small S-curves of technological growth.

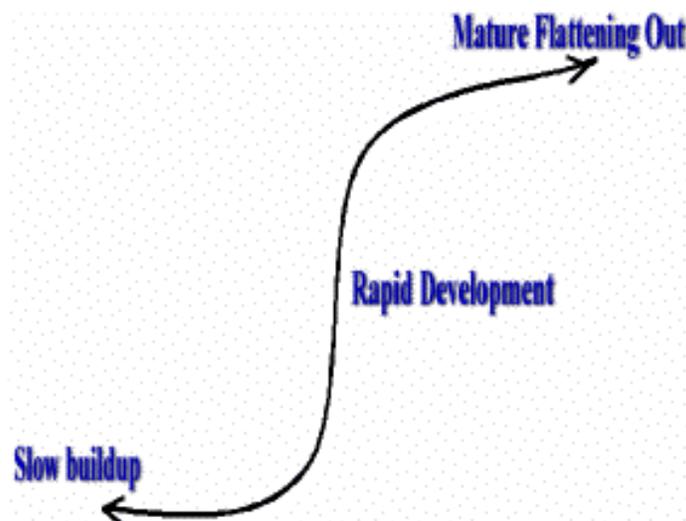


Figure A.1. The S-curve of technological change.

The Two S-Curves of the Age of Transitions

We are starting to live through two patterns of change. The first is the enormous computer and communications revolution described above. The second, only now beginning to rise, is the combination of the nanotechnology-biology-information revolution. These two S curves will overlap. It is the overlapping period that we are just beginning to enter, and it is that period that I believe will be an Age of Transitions.

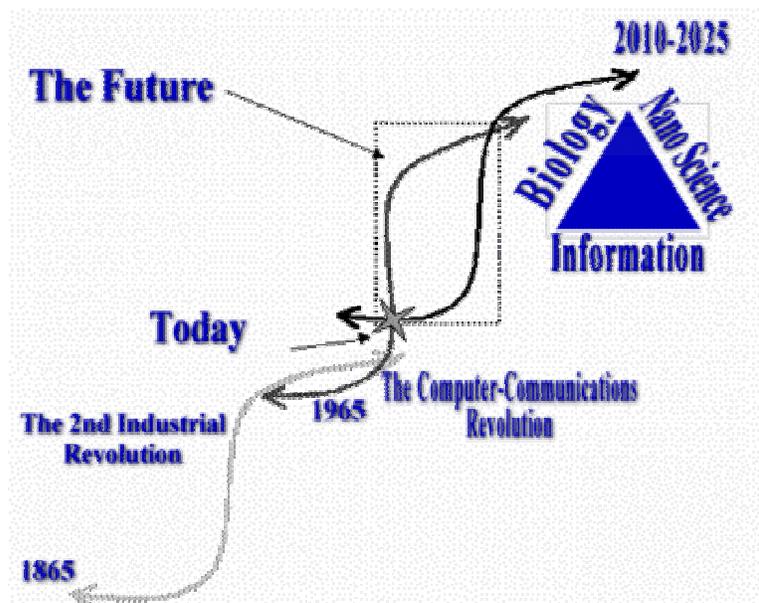


Figure A.2. The Age of Transitions.

The Nano World, Biology, and Information as the Next Wave of Change

Focusing on computers and communications is only the first step toward understanding the Age of Transitions. While we are still in the early stages of the computer-communications pattern of change, we are already beginning to see a new, even more powerful pattern of change that will be built on a synergistic interaction between three different areas: the nano world, biology, and information.

The nano world may be the most powerful new area of understanding. “Nano” is the space measuring between one atom and about 400 atoms. It is the space in which quantum behavior begins to replace the Newtonian physics you and I are used to. The word “nano” means one-billionth and is usually used in reference to a nanosecond (one billionth of a second) or a nanometer (one billionth of a meter). In this world of atoms and molecules, new tools and new techniques are enabling scientists to create entirely new approaches to manufacturing and healthcare. Nanotechnology “grows” materials by adding the right atoms and molecules. Ubiquitous nanotechnology use is probably twenty years away, but it may be at least as powerful as space or computing in its implications for new tools and new capabilities.

The nano world also includes a series of materials technology breakthroughs that will continue to change how we build things, how much they weigh, and how much stress and punishment they can take. For example, it may be possible to grow carbon storage tubes so small that hydrogen could be safely stored without refrigeration, thus enabling the creation of a hydrogen fuel cell technology, with dramatic implications for the economy and the environment. These new materials may make possible a one-hour flight from New York to Tokyo, an ultra-lightweight car, and a host of other possibilities.

Imagine a carbon tube 100 times as strong as steel and only one-sixth as heavy. It has already been grown in the NASA Ames Laboratory. This approach to manufacturing will save energy, conserve our raw materials, eliminate waste products, and produce a dramatically healthier environment. The implications for the advancement of environmentalism and the irrelevancy of oil prices alone are impressive.

The nano world makes possible the ability to grow molecular “helpers” (not really “tools” because they may be organic and be grown rather than built). We may be able to develop anti-cancer molecules that penetrate cells without damaging them and hunt cancer at its earliest development. Imagine drinking with your normal orange juice 3,000,000 molecular rotor rooters to clean out your arteries without an operation.

The nano world opens up our understanding of biology, and biology teaches us about the nano world because virtually all biological activities take place at a molecular level. Thus, our growing capabilities in nano tools will dramatically expand our understanding of biology. Our growing knowledge about molecular biology will expand our understanding of the nano world.

Beyond the implications of biology for the nano world, in the next decade, the Human Genome Project will teach us more about humans than our total knowledge to this point. The development of new technologies (largely a function of physics and mathematics) will increase our understanding of the human brain in ways previously unimaginable. From Alzheimer’s to Parkinson’s to schizophrenia, there will be virtually no aspect of our understanding of the human brain and nervous system that cannot be transformed in the next two decades.

We are on the verge of creating intelligent synthetic environments that will revolutionize how medical institutions both educate and plan. It will be possible to practice a complicated, dangerous operation many times in a synthetic world with feel, smell, appearance, and sound, that are all precisely the same as the real operation. The flight and combat simulators of today are incredibly better than the sand tables and paper targets of forty years ago. An intelligent, synthetic environment will be an even bigger breakthrough from our current capabilities. It will be possible to design a building or an organization in the synthetic world before deciding whether to actually build it. The opportunities for education will be unending.

Finally, the information revolution (computers and communications) will give us vastly better capabilities to deal with the nano world and with biology.

It is the synergistic effect of these three systems (the nano world, biology, information) that will lead to an explosion of new knowledge and new capabilities and create intersecting S-curves. We will simultaneously experience the computer/communications revolution and the nano/biology/information revolution. These two curves will create an Age of Transitions.

This rest of this paper attempts to outline the scale of change being brought about by the Age of Transitions, the principles that underlie those changes, and how to apply those principles in a strategic process that could lead to a governing majority.

Politics and Government in the Age of Transitions

In the foreseeable future, we will be inundated with new inventions, new discoveries, new startups, and new entrepreneurs. These will create new goods and services. The e-customer will become the e-patient and the e-voter. As expectations change, the process of politics and government will change. People’s lives will be more complex and inevitably overwhelming. Keeping up with the changes that affect them and their loved ones exhausts most people. They focus most of their time and energy on the tasks of everyday life. In the future, when they achieve success in their daily tasks, people will

turn to the new goods and services, the new job and investment opportunities, and the new ideas inherent in the entrepreneurial creativity of the Age of Transitions. No individual and no country will fully understand all of the changes as they occur or be able to adapt to them flawlessly during this time. On the other hand, there will be a large premium placed on individuals, companies, and countries that are able to learn and adjust more rapidly.

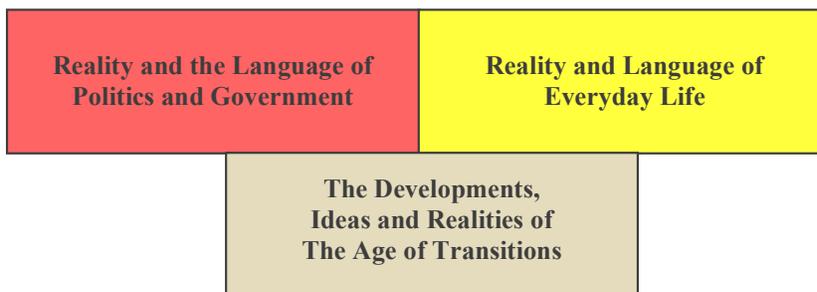


Figure A.3. Zones of social reality in the Age of Transitions.

The political party or movement that can combine these three zones into one national dialogue will have an enormous advantage, both in offering better goods and services, and in attracting the support of most Americans.

The new products and services created by the Age of Transitions are creating vast opportunities for improving everyday life. The government has an opportunity to use these new principles to develop far more effective and appropriate government services. Politicians have the chance to explain these opportunities in a language most citizens can understand and to offer a better future, with greater quality of life, by absorbing the Age of Transitions into government and politics.

The average citizen needs to have political leadership that understands the scale of change we are undergoing, that has the ability to offer some effective guidance about how to reorganize daily life, and that simultaneously has the ability to reorganize the government that affects so much of our daily life. Inevitably, the Age of Transitions will overwhelm and exhaust people. Only after they have dealt with their own lives do they turn to the world of politics and government.

When we look at politics, we are discouraged and in some cases repulsed by the conflict-oriented political environment; the nitpicking, cynical nature of the commentaries; and the micromanaged, overly detailed style of political-insider coverage. The more Americans focus on the common sense and the cooperative effort required for their own lives, and the more they focus on the excitement and the wealth-creating and opportunity-creating nature of the entrepreneurial world, the more they reject politics and government as an area of useful interest.

Not only do politics and government seem more destructive and conflict oriented, but the language of politics seems increasingly archaic and the ideas increasingly trivial or irrelevant. People who live their lives with the speed, accuracy, and convenience of automatic teller machines (ATMs) giving them cash at any time in any city, cell phones that work easily virtually everywhere, the ease of shopping on the Web and staying in touch through email, will find the bureaucratic, interest-group-focused, and arcane nature of political dialogue and government policy to be painfully outmoded. Politicians' efforts to popularize the obsolete are seen as increasingly irrelevant and are therefore ignored.

This phenomenon helps explain the January 2000 poll in which 81% of Americans said that they had not read about the presidential campaign in the last 24 hours, 89% said that they had not thought about a presidential candidate in the same period, and 74% said that they did not have a candidate for president (up 10% from the previous November).

The average voter's sense of distance from politics is felt even more strongly by the entrepreneurial and scientific groups that are inventing the future. They find the difference between their intensely concentrated, creative, and positive focus of energy and the negative, bickering nature of politics especially alienating, so they focus on their own creativity and generally stay aloof from politics unless a specific interest is threatened or a specific issue arouses their interest.

Projects that focus on voter participation miss the nature of a deliberate avoidance by voters of politics. In some ways, this is a reversion to an American norm prior to the Great Depression and World War II. For most of American history, people focused their energies on their own lives and their immediate communities. The national government (and often even the state government) seemed distant and irrelevant. This was the world of very limited government desired by Jefferson and described by Tocqueville in *Democracy in America*. With the exception of the Civil War, this was the operating model from 1776 until 1930. Then the Depression led to the rise of Big Government, the Second World War led to even bigger government, and the Cold War sustained a focus on Washington. When there was a real danger of nuclear war and the continuing crisis threatened the survival of freedom, it was natural for the president to be the central figure in America and for attention to focus on Washington. With the collapse of the Soviet Union, there has been a gradual shift of power and attention from Washington and back to the state and local communities. There has been a steady decline in popular attention paid to national politics.

When Republicans designed a positive campaign of big ideas in the 1994 Contract With America, some nine million additional voters turned out (the largest off-year, one-party increase in history). When Jesse Ventura offered a real alternative (at least in style) in 1998, younger voters turned out in record numbers. The voter as a customer tells the political-governmental system something profound by his or her indifference. The political leadership is simply failing to produce a large enough set of solutions in a lay language worth the time, attention, and focus of increasingly busy American citizens.

After a year of traveling around 23 states in America and spending time with entrepreneurs, scientists, and venture capitalists, I am increasingly convinced that the American voters are right.

Let us imagine a world of 1870 in which the private sector had completed the transcontinental railroad and the telegraph but the political-governmental elites had decided that they would operate by the rules of the Pony Express and the stagecoach. In private life and business life, you could telegraph from Washington to San Francisco in a minute and ship a cargo by rail in seven days. However, in political-governmental life, you had to send written messages by pony express that took two weeks and cargo by stagecoach that took two months. The growing gap between the two capabilities would have driven you to despair about politics and government as being destructive, anachronistic systems.

Similarly, imagine that in 1900 a Washington Conference on Transportation Improvement had been created, but the political-governmental elite had ruled that the only topic would be the future of the horseshoe and busied themselves with a brass versus iron horseshoe debate. Henry Ford's efforts to create a mass-produced automobile would have been ruled impractical and irrelevant. The Wright brothers' effort to create an airplane would have been derided as an absurd fantasy. After all, neither clearly stood on either the brass or the iron side of the debate. Yet which would do more to change transportation over the next two decades: the political-governmental power structure of Washington or the unknown visionaries experimenting without government grants and without recognition by the elites?

Consider just one example of the extraordinary and growing gap between the opportunities of the Age of Transitions and the reactionary nature of current government systems. The next time you use your ATM card, consider that you are sending a code over the Internet to approve taking cash out of your checking account. It can be done on a 24 hours a day, seven days a week anywhere in the country.

Compare that speed, efficiency, security, and accuracy with the paper-dominated, fraud- and waste-ridden Healthcare Financing Administration (HCFA) with its 133,000 pages of regulations (more pages than the tax code). As a symbol of a hopelessly archaic model of bureaucracy there are few better examples than HCFA.

This growing gap between the realities and language of private life and the Age of Transitions, on the one hand, and the increasingly obsolete language and timid proposals of the political governmental system, on the other hand, convinces more and more voters to ignore politics and focus on their own lives and on surviving the transitions.

This is precisely the pattern described by Norman Nie and colleagues in *The Changing American Voter* (1979). They described a pool of latent voters who in the 1920s found nothing in the political dialogue to interest them. These citizens simply stayed out of the process as long as it stayed out of their lives. The Depression did not mobilize them. They sat out the 1932 election. Only when the New Deal policies of Franklin Delano Roosevelt penetrated their lives did they become involved. In 1936, Alf Landon, the Republican nominee, actually received a million more votes than Herbert Hoover had gotten in 1932. However, FDR received seven million more votes than he had gotten in his first election. It was this massive increase in participation that made the polls inaccurate and created the Democratic majority, which in many ways survived until the 1994 election. The Republican victory of 1994 drew nine million additional voters over its 1990 results by using bold promises in a positive campaign to engage people who had been turned off by politics.

There is a similar opportunity waiting for the first political party and political leader to make sense out of the possibilities being created by the Age of Transitions and develop both a language and a set of bold proposals that make sense to average Americans in the context of their own lives and experiences.

This paper should be seen as the beginning of a process rather than as a set of answers. Political-governmental leaders need to integrate the changes of the Age of Transitions with the opportunities these changes create to improve people's lives, develop the changes in government necessary to accelerate those improvements, and explain the Age of Transitions era — and the policies it requires — in the language of everyday life, so that people will understand why it is worth their while to be involved in politics and subsequently improve their own lives. Getting this done will take a lot of people experimenting and attempting to meet the challenge for a number of years. That is how the Jeffersonians, the Jacksonians, the early Republicans, the Progressives, the New Dealers, and the Reagan conservatives succeeded. Each, over time, created a new understanding of America at an historic moment. We aren't any smarter, and we won't get it done any faster; however, the time to start is now, and the way to start is to clearly understand the scale of the opportunity and the principles that make it work.

Characteristics of an Age of Transitions

Thirty-six years after Boulding's first explanation of the coming change, and thirty-one years after Drucker explained how to think about discontinuity, some key characteristics have emerged. This section outlines 18 characteristics and gives examples of how political and governmental leaders can help develop the appropriate policies for the Age of Transitions. It should first be noted that there is an overarching general rule: assume there are more changes coming.

It is clear that more scientists, engineers, and entrepreneurs are active today than in all of previous human history. Venture capitalists are developing powerful models for investing in and growing startup companies. In the process, they are acquiring more and more capital as the markets shift away from the smokestack industries and toward new models. It is also clear that there is a growing world market in which more entrepreneurs of more nationalities are competing for more customers than ever in human history.

All this growing momentum of change simply means that no understanding, no reform, no principle will be guaranteed to last for very long. Just as we get good at one thing or come to understand one principle, it will be challenged by an emerging new idea or achievement from a direction we haven't even considered.

Within that humbling sense that the change is so large that we will never really know in our lifetime the full analysis of this process, here are 18 powerful characteristics for developing government policy and politics in the Age of Transitions:

2. **Costs will crash.** A major pattern will be a continuing, and in many cases steep, decline in cost. An ATM is dramatically cheaper than a bank teller. A direct-dial phone call is much less expensive than an operator-assisted call. My brother used Priceline.com and received four airline tickets for his family for the price of one regular ticket. We have not even begun to realize how much costs will decline, even in the fields of health and healthcare, education and learning, defense procurement, and government administration. We also have not yet learned to think in terms of purchasing power instead of salary. Yet the pattern is likely to be a huge change in both purchasing power and behavior for both citizens and government. Those who are aggressive and alert will find remarkable savings by moving to the optimum cost crashes faster than anyone else. As a result, they will dramatically expand their purchasing power.
- x) **Systems will be customer-centered and personalized.** Customers of Amazon.com and other systems already can look up precisely the books or movies that interest them, and after a while, the company is able to project their interests and alert them to similar products in their inventory. Consumers can consider personal Social Security Plus accounts who already have personal Roth IRAs and 401Ks. Individuals can consider purchasing personal learning and personal health systems just as they purchase electronic airline tickets on the Internet. Anything that is not personalized and responsive to changing individual needs will rapidly be replaced by something that is.
- xi) **24-7 will be the world of the future.** Customer access 24 hours a day, 7 days a week, will become the standard of the future. ATMs symbolize this emerging customer convenience standard, providing cash to card-holders any day, round the clock. Yet today's schools combine an agricultural-era nine- or ten-month school year (including the summer off for harvesting) with an industrial era 50-minute class, with a "foreman" at the front of the room facing a class of "workers" in a factory-style school day, in a Monday-to-Friday work week. Learning in the future will be embedded in the computer and on the Internet and will be available with a great deal of customization for each learner and on demand. Similarly, government offices will have to shift to meeting its customers' needs at their convenience rather than demanding that the customers make themselves available at the bureaucrat's convenience. These are big changes, and they are unavoidable given the emerging technologies and the e-customer culture that is evolving.
- xii) **Convenience will be a high value.** As customers get used to one-click shopping (note the shopping cart approach on Amazon), they will demand similar convenience from government. People will increasingly order products and services to be delivered to their homes at their convenience. They will initially pay a premium for this convenience, but over time they will conclude that it is a basic requirement of any business that they deal with, and costs will go down.

After a while, e-customers will begin to carry these attitudes into their relationship with bureaucracy, and as e-voters they will favor politicians who work to make their lives easier (i.e., more convenient).

- xiii) **Convergence of technologies will increase convenience, expand capabilities, and lower costs.** The various computation and communication technologies will rapidly converge with cell phones, computers, land-lines, mobile systems, satellite capabilities, and cable, all converging into a unified system of capabilities that will dramatically expand both capabilities and convenience.
- xiv) **Processes will be expert system-empowered.** When you look up an airline reservation on the Internet, you are dealing with an expert system. In virtually all Internet shopping you are actually interacting with such a system. The great increase in capability for dealing with individual sales and individual tastes is a function of the growing capacity of expert systems. These capabilities will revolutionize health, learning, and government once they are used as frequently as they currently are in the commercial world. If it can be codified and standardized, it should be done by an expert system rather than a person: that is a simple rule to apply to every government activity.
- xv) **Middlemen will disappear.** This is one of the most powerful rules of the Age of Transitions. In the commercial world, where competition and profit margins force change, it is clear that customers are served more and more from very flat hierarchies, with very few people in the middle. In the protected guilds (medicine, teaching, law, and any group that can use its political power to slow change) and in government structures, there are still very large numbers of middlemen. This will be one of the most profitable areas for political-governmental leaders to explore. In the Age of Transitions, the customer should be foremost, and every unnecessary layer should be eliminated to create a more agile, more rapidly changing, more customer-centered, and less expensive system.
- xvi) **Changes can come from anywhere.** The record of the last thirty years has been of a growing shift toward new ideas coming from new places. Anyone can have a good idea, and the key is to focus on the power of the idea rather than the pedigree of the inventor. This directly challenges some of the peer review assumptions of the scientific community, much of the screening for consultants used by government, much of the credentialing done by education and medicine, and much of the contractor certification done by government. This principle requires us to look very widely for the newest idea, the newest product, and the newest service, and it requires testing by trial and error more than by credentialing or traditional assumptions.
- xvii) **Resources will shift from opportunity to opportunity.** One of the most powerful engines driving the American economy has been the rise of an entrepreneurial venture capitalism that moves investments to new opportunities and grows those opportunities better than any other economy in the world. There is as yet no comparable government capacity to shift resources to new start-ups and to empower governmental entrepreneurs. There are countless efforts to reform and modernize bureaucracies, but that is exactly the wrong strategy. Venture capitalists very seldom put new money into old corporate bureaucracies. Even many established corporations are learning to create their own startups because they have to house new ideas and new people in new structures if they are really to get the big breakthroughs. We need a doctrine for a venture capitalist-entrepreneurial model of government that includes learning, health, and defense.
- xviii) **The rapid introduction of better, less expensive products will lead to continual replacement.** Goods and services will take on a temporary nature as their replacements literally push them out of the door. The process of new, more capable, and less expensive goods and services, and in some cases, revolutionary replacements that change everything (as Xerox did to

the mimeograph, and as the fax machine, e-mail, and PC have done) will lead to a sense of conditional existence and temporary leasing that will change our sense of ownership.

- xix) **The focus will be on success.** Entrepreneurs and venture capitalists have a surprisingly high tolerance for intelligent failure. They praise those who take risks, even if they fail, over those who avoid risks, even if they avoid failure. To innovate and change at the rate the Age of Transitions requires, government and politicians have to shift their attitudes dramatically. (It would help if the political news media joined them in this.) Today it is far more dangerous for a bureaucrat to take a risk than it is to do nothing. Today the system rewards people (with retirement and noncontroversy) for serving their time in government. There are virtually no rewards for taking the risks and sometimes failing, sometimes succeeding. Yet in all the areas of science, technology, and entrepreneurship, the great breakthroughs often involve a series of failures. (Consider Edison's thousands of failed experiments in inventing the electric light and how they would have appeared in a congressional hearing or a news media expose.) Setting a tone that supports trying and rewards success while tolerating intelligent failure would do a great deal to set the stage for a modernized government.
- xx) **Venture capitalists and entrepreneurs will focus on opportunities.** This is similar to focusing on success but refers to the zone in which energy and resources are invested. It is the nature of politics and government to focus on problems (schools that fail, hospitals that are too expensive, people that live in poverty) when the real breakthroughs come from focusing on opportunities (new models of learning that work, new approaches to health and healthcare that lower the cost of hospitals, ways to get people to work so that they are no longer in poverty). Venture capitalists are very good at shifting their attention away from problem zones toward opportunity zones. Politicians and the political news media tend to do the opposite. Yet the great opportunities for change and progress are in the opportunities rather than the problems.
- xxi) **Real breakthroughs will create new products and new expectations.** Before Disney World existed, it would have been hard to imagine how many millions would travel to Orlando. Before the Super Bowl became a cultural event, it was hard to imagine how much of the country would stop for an entire evening. Before faxes, we did not need them, and before e-mail, no one knew how helpful it would be. One of the key differences between the public and private sector is this speed of accepting new products and creating new expectations. The public sector tends to insist on using the new to prop up the old. For two generations we have tried to get the computer into the classroom with minimal results. That's because it is backward. The key is to get the classroom into the computer and the computer to the child's home, so that learning becomes personal and 24/7. Doctors still resist the information technologies that will revolutionize health and healthcare and that will lower administrative costs and decrease unnecessary deaths and illnesses dramatically. In the private sector, competition and the customer force change. In government and government-protected guilds, the innovations are distorted to prop up the old, and the public (that is the customer) suffers from more expensive and less effective goods and services.
- xxii) **Speed matters: new things will need to get done quickly.** There is a phrase in the Internet industry, "launch and learn," which captures the entrepreneurial sense of getting things done quickly and learning while doing so. One Silicon Valley entrepreneur noted he had moved back from the East because he could get things done in the same number of days in California as the number of months it would have taken where he had been. Moving quickly produces more mistakes, but it also produces a real learning that only occurs by trying things out. The sheer volume of activity and the speed of correcting mistakes as fast as they are discovered allows a "launch and learn" system to grow dramatically faster than a "study and launch" system. This explains one of the major differences between the venture capitalist-entrepreneurial world and the world of traditional corporate bureaucracies. Since governments tend to study and study without

ever launching anything truly new, it is clear how the gap widens between the public and private sectors in an Age of Transitions. Today it takes longer for a presidential appointee to be cleared by the White House and approved by the Senate than it takes to launch a startup company in Silicon Valley.

- xxiii) **Start small but dream big.** Venture capital and entrepreneurship are about baby businesses rather than small businesses. Venture capitalists know that in a period of dramatic change, it is the occasional home run rather than a large number of singles that really make the difference. The result is that venture capitalists examine every investment with a focus on its upside. If it does not have a big enough growth potential, it is not worth the time and energy to make the investment. Government tends to make large, risk-averse investments in relatively small, controllable changes. This is almost the exact opposite of the venture capital-entrepreneurial model. The question to ask is, “If this succeeds, how big will the difference be, and if the difference isn’t very substantial, we need to keep looking for a more powerful proposal.”
- xxiv) **Business-to-business is the first big profit opportunity.** While most of the attention in the Internet market is paid to sales to the final customer, the fact is that that market is still relatively small and relatively unprofitable. However, there is no question that Internet-based systems such as Siebel and Intelisys are creating business-to-business opportunities that will dramatically lower the cost of doing business. Every government, at every level, should be rationalizing its purchasing system and moving on to the net to eliminate all paper purchasing. The savings in this area alone could be in the 20% to 30% range for most governments. The opportunities for a paperless system in health and healthcare could lead to a crash in costs rather than a worry about rising costs.
- xxv) **Applying quality and lean thinking can save enormous amounts.** Whether it is the earlier model of quality espoused by Edwards Deming, or the more recent concept of lean thinking advocated by James Womack and Daniel Jones, it is clear that there is an existing model for systematically thinking through production and value to create more profitable, less expensive approaches. The companies that have really followed this model have had remarkable success in producing better products at lower expense, yet it is almost never used by people who want to rethink government.
- xxvi) **Partnering will be essential.** No company or government can possibly understand all of the changes in an Age of Transitions. Furthermore, new ideas will emerge with great speed. It is more profitable to partner than to try to build in-house expertise. It allows everyone to focus on what they do best while working as a team on a common goal. This system is prohibited throughout most of government, and yet it is the dominant organizing system of the current era of startups. As government bureaucracies fall further and further behind the most dynamic of the startups (in part because civil service salaries cannot compete with stock options for the best talent), it will become more and more important to develop new mechanisms for government-private partnering.

These initial principles give a flavor of how big the change will be and of the kind of questions a political-governmental leader should ask in designing a program for the Age of Transitions. These principles and questions can be refined, expanded, and improved, but they at least let leaders start the process of identifying how different the emerging system will be from the bureaucratic-industrial system that is at the heart of contemporary government.

The Principles of Political-Governmental Success in an Age of Transitions

In the Age of Transitions, the sheer volume of new products, new information, and new opportunities will keep people so limited in spare time that any real breakthrough in government and politics will have to meet several key criteria:

3. **Personal.** It has to involve a change that occurs in individual people's lives in order for them to think it is worth their while, because it will affect them directly. Only a major crisis such as a steep recession or a major war will bring people back to the language of politics. In the absence of such a national crisis, political leaders will not be able to attract people into the zone of government and politics unless they use the new technologies and new opportunities of the Age of Transitions to offer solutions that will dramatically improve people's lives.
- xxvii) **Big Ideas.** The changes offered have to be large enough to be worth the time and effort of participation. People have to be convinced that their lives or their families' lives will be affected significantly by the proposals, or they will simply nod pleasantly at the little ideas but will do nothing to get them implemented.
- xxviii) **Common Language.** New solutions have to be explained in the language of everyday life because people will simply refuse to listen to the traditional language of political and governmental elites. People have become so tired of the bickering, the conflict, and the reactionary obsolete patterns of traditional politics that they turn off the minute they hear them. New solutions require new words, and the words have to grow out of the daily lives of people rather than out of the glossary of intellectual elites or the slogans of political consultants.
- xxix) **Practical.** The successful politics of the Age of Transitions will almost certainly be pragmatic and practical rather than ideological and theoretical. People are going to be so busy and so harried that their first question is going to be "will it work?" They will favor conservative ideas that they think will work, and they will favor big government ideas that they think will work. Their first test will be, "Will my family and I be better off?" Their second test will be, "Can they really deliver and make this work?" Only when a solution passes these two tests will it be supported by a majority of people. Note that both questions are pragmatic; neither is theoretical or ideological.
- xxx) **Positive.** The successful politicians of the Age of Transitions will devote eighty percent of their time to the development and communication of large positive solutions in the language of everyday life and the gathering of grassroots coalitions and activists to support their ideas. They will never spend more than 20 percent of their effort on describing the negative characteristics of their opponents. When they do describe the destructive side of their opponents, it will be almost entirely in terms of the costs to Americans of the reactionary forces blocking the new solutions and the better programs (study FDR's 1936 and 1940 campaigns for models of this lifestyle definition of the two sides: the helpful and the harmful. FDR was tough on offense, but more importantly, he cast the opposition in terms of how they hurt the lives of ordinary people.)
- xxxi) **Electronic.** The successful large, personal, positive, practical movement of the Age of Transitions will be organized on the Internet and will be interactive. Citizens will have a stake in the movement and an ability to offer ideas and participate creatively in ways no one has ever managed before. The participatory explosion of the 1992 Perot campaign, in which tens of thousands of volunteers organized themselves, and the Internet-based activism of the closing weeks of the 1998 Ventura campaign are forerunners of an interactive, Internet-based movement in the Age of Transitions. None has yet occurred on a sustainable basis, for two reasons:
- a) First, no one has come up with a believable solution big enough to justify the outpouring of energy beyond brief, personality-focused campaign spasms lasting weeks or a few months.

- b) Second, no one has mastered the challenge of building a citizen-focused genuinely interactive system that allows people to get information when they want it, offer ideas in an effective feedback loop, and organize themselves to be effective in a reasonably efficient and convenient manner. When the size of the solution and the sophistication of the system come together, we will have a new model of politics and government that will be as defining as the thirty-second commercial and the phone bank have been.

The Political Challenge for the Coming Decade in America

For change to be successful, it is essential that we sincerely and aggressively communicate in ways that are inclusive, not exclusive. Our political system cannot sustain effectiveness without being inclusive. There are two principle reasons this strategy must be pursued:

4. A majority in the Age of Transitions will be inclusive. The American people have reached a decisive conclusion that they want a unified nation with no discrimination, no bias, and no exclusions based on race, religion, sex, or disability. A party or movement that is seen as exclusionary will be a permanent minority. The majority political party in the Age of Transitions will have solutions that improve the lives of the vast majority of Americans and will make special efforts to recruit activists from minority groups, to communicate in minority media, and to work with existing institutions in minority communities. For Republicans, this will mean a major effort to attract and work with every American of every background. Only a visibly, aggressively inclusive Republican Party will be capable of being a majority in the Age of Transitions.

xxxii) The ultimate arbiter of majority status in the next generation will be the Hispanic community. The numbers are simple and indisputable. If Hispanics become Republican, the Republican Party is the majority Party for the foreseeable future; if Hispanics become Democrat, the Republican Party is the minority Party for at least a generation. On issues and values, Hispanics are very open to the Republican Party. On historic affinity and networking among professional politicians and activist groups, Democrats have an edge among Hispanics. There should be no higher priority for American politicians than reaching out to and incorporating Hispanics at every level in every state. George W. Bush, when he was governor of Texas, and Governor Jeb Bush have proven that Republicans can be effectively inclusive and create a working partnership with Hispanics. Every elected official and every candidate should follow their example.

Conclusion

These are examples of the kind of large changes that are going to be made available and even practical by the Age of Transitions. The movement or political party that first understands the potential of the Age of Transitions, develops an understanding of the operating principles of that Age, applies them to creating better solutions, and then communicates those solutions in the language of everyday life will have a great advantage in seeking to become a stable, governing majority.

This paper outlines the beginning of a process as big as the Progressive Era or the rise of Jacksonian Democracy, the Republicans, the New Deal, or the conservative movement of Goldwater and Reagan. This paper outlines the beginning of a journey, not its conclusion. It will take a lot of people learning, experimenting, and exploring over the next decade to truly create the inevitable breakthrough.

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ZONE OF CONVERGENCE BETWEEN BIO/INFO/NANO TECHNOLOGIES: NASA'S NANOTECHNOLOGY INITIATIVE

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NASA's mission encompasses space and Earth science, fundamental biological and physical research (BPR), human exploration and development of space (HEDS), and a responsibility for providing advanced technologies for aeronautics and space systems. In space science, agency missions are providing deeper insight into the evolution of the solar system and its relationship to Earth; structure and evolution of the universe at large; and both the origins and extent of life throughout the cosmos. In Earth science, a fundamental focus is to provide, through observations and models, the role of the physical, chemical, and biological processes in long-term climate change as well as push the prediction capability of short-term weather. In addition, NASA's challenge is to understand the biosphere and its evolution and future health in the face of change wrought by humankind.

The goal of NASA for BPR is to conduct research to enable safe and productive human habitation of space as well as to use the space environment as a laboratory to test the fundamental principals of biology, physics, and chemistry. For HEDS, a long-term presence in low Earth orbit is being accomplished with the space station. In the longer term, humans will venture beyond low earth orbit, probably first to explore Mars, following a path blazed by robotic systems.

A critical element of science missions and HEDS is safe and affordable access to space and dramatically reduced transit times for in-space transportation systems. In pursuance of this mission, NASA needs tools and technologies that must push the present state of the art. NASA spacecraft must function safely and reliably, on their own, far from Earth, in the extremely harsh space environment in terms of radiation and temperature variance coupled with the absence of gravity. This places demands on NASA technologies that are highly unique to the Agency. NASA's aeronautics goals are focused on developing technology to support new generations of aircraft that are safer, quieter, more fuel efficient, environmentally cleaner, and more economical than today's aircraft; as well as on technology to enable new approaches to air systems management that can greatly expand the capacity of our air space and make it even safer than it is today.

Virtually all of NASA's vision for the future of space exploration — and new generations of aircraft — is dependent upon mass, power requirements, and the size and intelligence of components that make up air and space vehicles, spacecraft, and rovers. Dramatic increases in the strength-to-weight ratio of structural materials offers the potential to reduce launch and flight costs to acceptable levels. Such structural materials can also lead to increases in payload and range for aircraft, which can translate into U.S. dominance of the world marketplace. Packing densities and power consumption are absolutely critical to realizing the sophisticated on-board computing capability required for such stressing applications as autonomous exploration of Europa for evidence of simple life forms or their

precursors. The integration of sensing, computing, and wireless transmission will enable true health management of reusable launch vehicles and aircraft of the future.

To do this, NASA aircraft and space systems will have to be much more capable than they are today. They will have to have the characteristics of autonomy to “think for themselves”: they will need self-reliance to identify, diagnose, and correct internal problems and failures; self-repair to overcome damage; adaptability to function and explore in new and unknown environments; and extreme efficiency to operate with very limited resources. These are typically characteristics of robust biological systems, and they will also be the characteristics of future aerospace systems. Acquisition of such intelligence, adaptability, and computing power go beyond the present capabilities of microelectronic devices.

The current state-of-the-art microelectronics is rapidly approaching its limit in terms of feature size (0.1 microns). Future enhancements will need novel alternatives to microelectronics fabrication and design as we know them today. Nanotechnology will afford a new class of electronics. In addition to possessing the benefits inherent in smaller feature size, nanotechnology will harness the full power of quantum effects that are operable only at nanoscale distances. Hence, not only should we expect a performance enhancement at the quantitative level, due to the higher packing density of nanoscale components, but also the emergence of qualitatively new functionalities associated with harnessing the full power of quantum effects. The hybridization of nanolithography and bioassembly could serve as the basis of an engineering revolution in the fabrication of complex systems.

We are already seeing the potential of nanotechnology through the extensive research into the production and use of carbon nanotubes, nano-phase materials, and molecular electronics. For example, on the basis of computer simulations and available experimental data, some specific forms of carbon nanotubes appear to possess extraordinary properties: Young’s modulus over one Tera Pascal (five times that of steel) and tensile strength approaching 100 Giga Pascal (over 100 times the strength of steel). Recent NASA studies indicate that polymer composite materials made from carbon nanotubes could reduce the weight of launch vehicle — as well as aircraft — by half. Similarly, nanometer-scale carbon wires have 10,000 times better current carrying capacity than copper, which makes them particularly useful for performing functions in molecular electronic circuitry that are now performed by semiconductor devices in electronic circuits. Electronic devices constructed from molecules (nanometer-scale wires) will be hundreds of times smaller than their semiconductor-based counterparts.

However, the full potential of nanotechnology for the systems NASA needs is in its association with biology. Nanotechnology will enable us to take the notion of “small but powerful” to its extreme limits, but biology will provide many of the paradigms and processes for doing so. Biology has inherent characteristics that enable us to build the systems we need: selectivity and sensitivity at a scale of a few atoms; ability of single units to massively reproduce with near-zero error rates; capability of self-assembly into highly complex systems; ability to adapt form and function to changing conditions; ability to detect damage and self repair; and ability to communicate among themselves. Biologically inspired sensors will be sensitive to a single photon. Data storage based on DNA will be a trillion times more dense than current media, and supercomputers modeled after the brain will use as little as a billionth of the power of existing designs. Biological concepts and nanotechnology will enable us to create both the “brains and the body” of future systems with the characteristics that we require. Together, nanotechnology, biology, and information technology form a powerful and intimate scientific and technological triad.

Such technologies will enable us to send humans into space for extended durations with greater degrees of safety. While the vehicle they travel in will have much greater capability and display the same self-protective characteristics of spacecraft, nanotechnology will enable new types of human

health monitoring systems and healthcare delivery systems. Nanoscale, bio-compatible sensors can be distributed throughout the body to provide detailed information of the health of astronauts at the cellular level. The sensors will have the ability to be queried by external monitoring systems or be self-stimulated to send a signal, most likely through a chemical messenger. NASA is currently working with the National Cancer Institute (NCI) to conduct research along these specific lines.

Currently, NASA's program is split primarily between the Office of Aerospace Technology (OAT) with a focus on nanotechnology and the newly formed Office of Biological and Physical Research (OBPR) with a focus on basic research in nanoscience related to biomedical applications. Furthermore, the OAT Program integrates nanotechnology development in three areas:

5. materials and structures

xxxiii) nanoelectronics and computing

xxxiv) sensors and spacecraft components

A summary of the content of these programs follows.

Materials and Structures

A major emphasis for NASA over the next 5 years will be the production scale-up of carbon nanotubes; the development of carbon nanotube-reinforced polymer matrix composites for structural applications; and the development of analysis, design, and test methods to incorporate these materials into new vehicle concepts and validate their performance and life. NASA also will explore the use of other materials, such as boron nitride, for high-temperature applications and will research the use of crystalline nanotubes to ultimately exploit the full potential of these materials. In the long term, the ability to create biologically inspired materials and structures provides a unique opportunity to produce new classes of self-assembling material systems without the need to machine or process materials. Some unique characteristics anticipated from biomimetics (that is, "mimicking" biology) include multifunctional material systems, hierarchical organization, adaptability, self healing/self-repair, and durability. Thus, by exploiting the characteristics of biological systems, mechanical properties of new materials can be tailored to meet complex, rigorous design requirements and revolutionize aerospace and spacecraft systems.

Nanoelectronics and Computing

Biologically inspired neural nets have been developed in laboratory demonstrations that allow computers to rapidly account for loss of aircraft control elements, understand the resulting aerodynamics, and then teach the pilot or autopilot how to avoid the loss of the vehicle and crew by an innovative use of the remaining aerodynamic control. Such approaches, coupled with the advances in computing power anticipated from nanoelectronics, will revolutionize the way aerospacecraft deal with condition-based maintenance, aborts, and recovery from serious in-flight anomalies. While aircraft do not require electronic devices that can tolerate the space radiation environment, spacecraft exploration for the Space Science and HEDS Enterprises, e.g., vehicles exploring Mars, the outer planets, and their moons, will require such capabilities. NASA mission planners view such capability as enabling them to conduct *in-situ* science (without real-time Earth operators), where huge amounts of data must be processed, converted to useful information, and then sent as knowledge to Earth without the need for large bandwidth communication systems. A longer-term vision incorporates the added complexity of morphing devices, circuits, and systems whose characteristics and functionalities may be modified in flight. NASA will support work at the underlying device level, in which new device configurations with new functionalities may be created through intra-device switching.

Sensors and Spacecraft Components

NASA's challenge to detect ultra-weak signals from sources at astronomical distances make every photon or particle a precious commodity that must be fully analyzed to retrieve all of the information it carries. Nanostructured sensing elements, in which each absorbed quantum generates low-energy excitations that record and amplify the full range of information, provide an approach to achieve this goal. NASA will also develop field and inertial sensors with many orders of magnitude enhancement in the sensitivity by harnessing quantum effects of photons, electrons, and atoms. A gravity gradiometer based on interference of atom beams is currently under development by NASA with the potential space-based mapping of the interior of the Earth or other astronomical bodies. Miniaturization of entire spacecraft will entail reduction in the size and power required for all system functionalities, not just sensors. Low-power, integrable nano devices are needed for inertial sensing, power generation and management, telemetry and communication, navigation and control, propulsion, and *in situ* mobility, and so forth. Integrated nano-electro-mechanical systems (NEMS) will be the basis for future avionics control systems incorporating transducers, electromagnetic sources, active and passive electronic devices, electromagnetic radiators, electron emitters, and actuators.

Basic Nanoscience

Foremost among the technological challenges of long-duration space flight are the dangers to human health and physiology presented by the space environment. Acute clinical care is essential to the survival of astronauts, who must face potentially life-threatening injuries and illnesses in the isolation of space. Currently, we can provide clinical care and life support for a limited time, but our only existing option in the treatment of serious illness or injury is expeditious stabilization and evacuation to Earth. Effective tertiary clinical care in space will require advanced, accurate diagnostics coupled with autonomous intervention and, when necessary, invasive surgery. This must be accomplished within a complex man-machine interface, in a weightless environment of highly limited available space and resources, and in the context of physiology altered by microgravity and chronic radiation exposure. Biomolecular approaches promise to enable lightweight, convenient, highly focused therapies guided with the assistance of artificial intelligence enhanced by biomolecular computing. Nanoscopic, minimally invasive technology for the early diagnosis and monitoring of disease and targeted intervention will save lives in space and on Earth. Prompt implementation of specifically targeted treatment will insure optimum use and conservation of therapeutic resources, making the necessity for invasive interventions less likely and minimizing possible therapeutic complications.

BIOMEDICINE EYES 2020

John Watson, National Institutes of Health

I will present ideas from my experience with targeted, goal-oriented research programs and traditional investigator-initiated research projects. I strongly endorse both approaches. For NBIC to reach its potential, national science and engineering priorities should be set to complement investigator-initiated research projects. We should consider including in our NBIC thinking "human performance and health" (not just performance alone) to provide the most for our future quality of life.

How many of us know someone who has undergone angioplasty? A vision for ten and twenty years is under consideration: tomorrow's needs, tomorrow's patients, and tomorrow's diverse society. Well, what about today's needs, today's patients, and today's diverse society? It is riskier to talk about targeting a research goal to solve today's problems than to focus on promising basic research for solving as yet undefined problems.

We do not know what causes atherosclerosis. Surgically bypassing atherosclerotic plaques was shown to have clinical benefit. Using a small balloon to push the plaques into a coronary artery wall, thus opening the lumen, was met with lots of skepticism. If we had waited until we knew all the atherosclerosis basic science, millions of patients would not have benefited from angioplasty.

Picking up on Newt Gingrich's comments about providing some constructive unreasonableness to the conversation, let me suggest expanding our thinking to science and engineering, not science alone. Also, one can compliment our executive branch and Congress for setting national priorities. For discussion today, I will use the example of Congress establishing as a national priority use of mechanical systems to treat heart failure.

If NBIC is to blend into the fifth harmonic envisioned by Newt Gingrich, some national priorities are needed to complement unplanned, revolutionary discoveries. For instance, urinary incontinence a major health problem for today's patients. If the nation had a science and engineering capacity focused on urinary incontinence, this very personal problem would be virtually eliminated. As Mr. Gingrich stated, basic research can be associated with a specific goal.

Table A.1 is a list of the greatest engineering achievements of the past century. The primary selection criterion in constructing this list was worldwide impact on quality of life. Electrification was the number one selection, because the field was fully engineered to improve efficiency, lower cost, and provide benefit for virtually everyone. You will notice that healthcare technologies is number sixteen. NBIC technologies could focus on this field in this century and help move it into the top ten, to the enormous benefit of human performance, health, and overall quality of life.

Setting priorities involves national needs, process, and goals. The Congressional legislative process is quite effective for targeting priorities. The human genome is an example of a work in progress. Today I would like to focus on the field of prevention and repair of coronary heart disease (CHD), where the clinical benefits timeline for today's patients is a little clearer. Successfully addressing priorities such as these usually requires a few decades of sustained public (tax payer) support.

Table A.1. Greatest Engineering Achievements of the Twentieth Century

1. Electrification	11. Highways
2. Automobile	12. Spacecraft
3. Airplane	13. Internet
4. Water Supply	14. Imaging
5. Electronics	15. Household Appliances
6. Radio and TV	16. Health Technologies
7. Agricultural Mechanization	17. Petroleum Technologies
8. Computers	18. Laser and Fiber Optics
9. Telephones	19. Nuclear Technologies
10. Air Conditioning & Refrigeration	20. High-performance Materials

Following hearings in the 1960s, Congress identified advanced heart failure as a growing public health concern needing new diagnostic and treatment strategies. It called for NIH to establish the Artificial Heart Program. Following a decade of system component research, the National Heart, Lung, and Blood Institute (NHLBI) initiated the left ventricular assist device (LVAD) program in 1977. Research and development was targeted towards an implantable system with demonstrated two-year

reliability that improved patients’ heart function and maintained or improved their quality of life. A series of research phases based on interim progress reviews was planned over a fifteen-year timeline.

A few years earlier, the NHLBI established less invasive imaging of coronary artery disease as a top priority. A similar program was established that produced less invasive, high-resolution ultrasound, MRI, and CAT scanning for evaluating cardiac function and assessing obstructive coronary artery disease. While this was not an intended outcome, these imaging systems virtually eliminated the need for exploratory surgery. The purpose of long timelines for national programs is not to exclude individual or group-initiated research, and both can have tremendous benefit when properly nurtured.

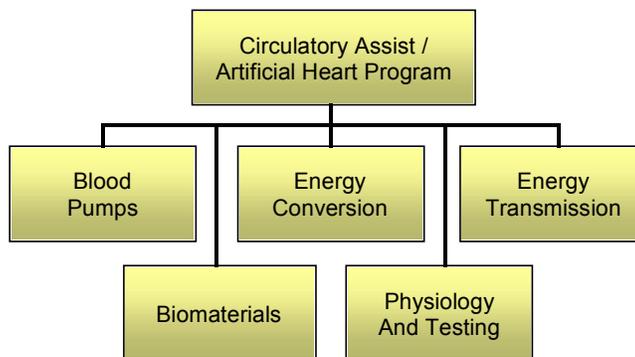


Figure A.4. NHLBI program organization.

Heart failure remains a public health issue. At any given time, about 4.7 million Americans have a diagnosed condition of this kind, and 250,000 die each year. The death rates and total deaths from cardiovascular disease have declined for several decades (Fig. A.5). However, during this same time frame, death rates from congestive heart failure (CHF) increased for men and women of all races (Fig. A.6). The most recent interim look at this field estimates that 50,000 to 100,000 patients per year could benefit from left ventricular assist (90% of the patients) and total artificial heart systems (10% of the patients), as reported by the Institute of Medicine in *The Artificial Heart* (1991).

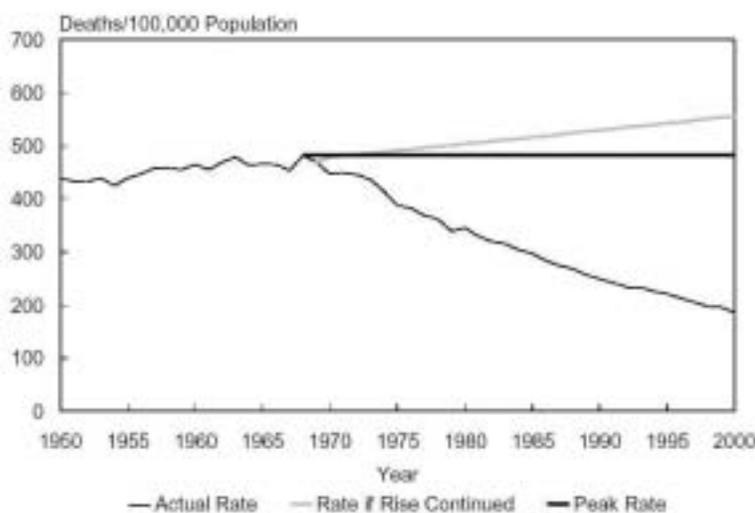


Figure A.5. Coronary heart disease statistics from 1950—1998, age-adjusted to the 2000 standard. CHD accounted for 460,000 deaths in 1998. It would have accounted for 1,144,000 if the rate had remained at its 1963 peak. Comparability ratio applied to rates for 1968-1978.

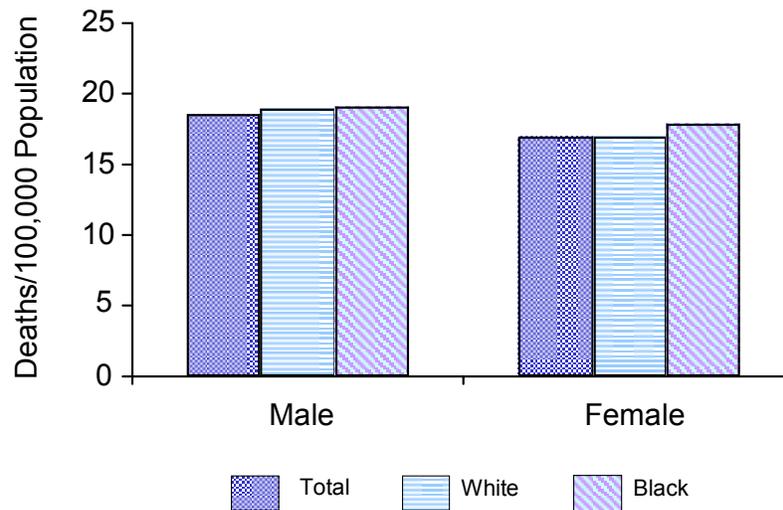


Figure A.6. Age-adjusted death rates for congestive heart failure by race and sex, U.S. 1997. Death rates for CHF are relatively similar in blacks and in whites, but are slightly higher in males than in females.

The first clinical systems were designed to support, for days or weeks, the blood circulation of patients with dysfunctional hearts following cardiac surgery. This short-term support would enable the hearts of some patients to recover and establish normal function. More than 4,000 patients treated by a product of this program resulted in 33% being discharged to their homes (Fig. A.7). Prior to this experience, only 5-10% of these patients were discharged.

- **BVS 5000**
- **4,250 patients**
- **33% Discharged**

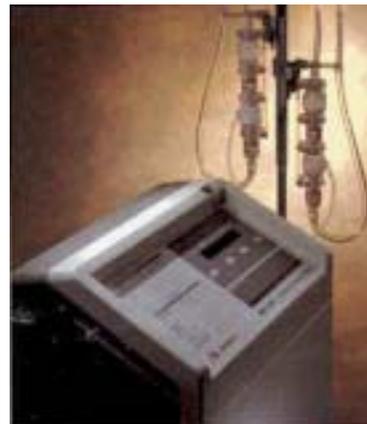


Figure A.7. Postcardiotomy heart dysfunction.

Clinicians learned that assist devices could “bridge” patients to cardiac transplant. For advanced heart failure and circulatory collapse, implantable ventricular assist devices restore the patient’s circulation, allowing patients to leave the intensive care unit and regain strength before undergoing cardiac transplantation. Many patients received support for over one year, some for two or three years, with one patient supported for over four years. Table A.2 lists a tabulation of some 6,000 patients and the assist device used to discharge them to their homes (50-70% with cardiac transplants). The question

remains, will these systems meet the overall program objective of providing destination therapy for heart failure patients?

Table A.2. Bridge-to-Cardiac Transplant

Device	Number of Patients
Heartmate	3000
Novacor	1290
Thoratec	1650
Cardiowest	206
Discharged	50-70%

To answer this question, the Randomized Evaluation of Mechanical Assistance for the Treatment of Congestive Heart Failure (REMATCH) clinical trial was conducted. The Heartmate left ventricular assist (LVAD) system was used (Fig. A.8). This trial was a true cooperative agreement based on mutual trust between academia, the private sector, and the government. This was a single blind trial, with the company and the principle investigator blinded to the aggregate results of the trial as it was underway. The NHLBI established a Data and Safety Monitoring Board (DSMB) to confidentially review the progress of the trial and evaluate every adverse event. At each meeting, the DSMB recommended to NHLBI if the trial should continue and what was needed to improve recruitment and the quality of the data. The final decisions about the conduct of the trial were made by the NHLBI.

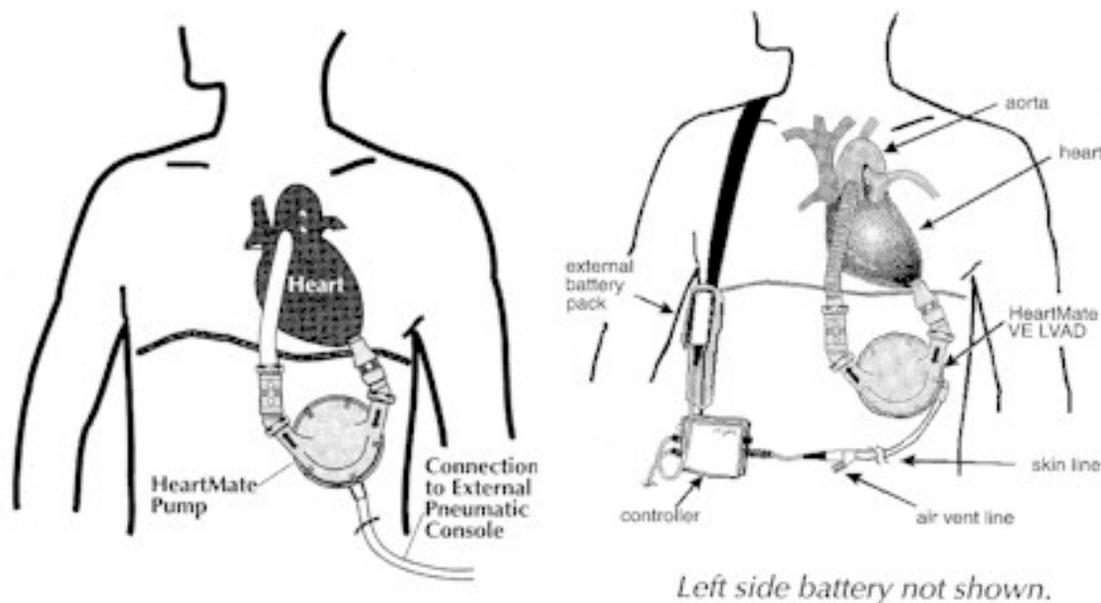


Figure A.8. HeartMate IP and VE.

It should be noted here that the burden of heart failure on healthcare is increasing. Heart transplants provide remarkable survival and quality of life, but only for some patients, because the limited donor pool provides hearts for only about 2000 patients a year. Figure A.9 is based on a registry of some 52,000 heart transplant patients. The mean survival is nine years, with some patients surviving fifteen years or more. These patients serve as the guideline for improved function, quality of life, and survival for alternative therapies (Fig. A.9).

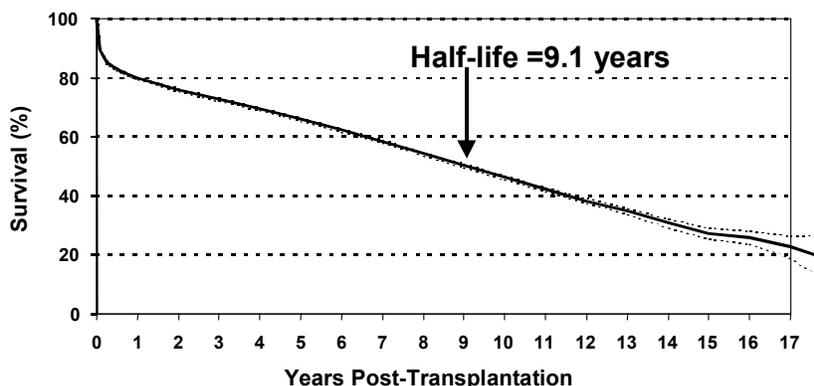


Figure A.9. Heart transplant survival.

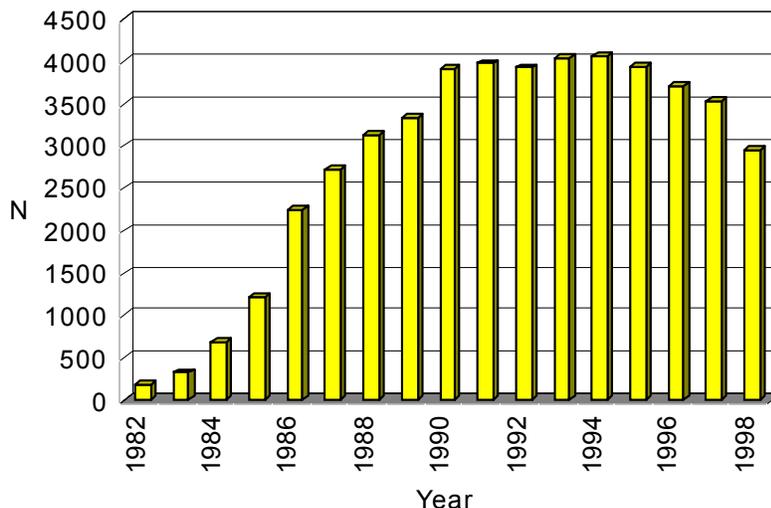


Figure A.10. ISHLT Registry of annualized heart transplant volume.

The REMATCH primary end-point was set at a 33% improvement in survival for LVAD patients who are not eligible for cardiac transplantation over two years. The goal was for patients to experience improved function without a decrement in quality of life compared to the randomized control group. Cost and cost-effectiveness will also be analyzed as the data becomes available.

The LVAD patients demonstrated a 48% improvement in survival (Fig. A.11), significant functional gains, and suggestions of improved quality of life (Fig. A.12), compared with patients receiving optimal medical management (OMM). The LVAD patients also experienced increased adverse events of infections, bleeding, and technical device problems (Table A.3). At two years, updated data (not shown) showed a 200% increase in survival but also a high number of device failures.

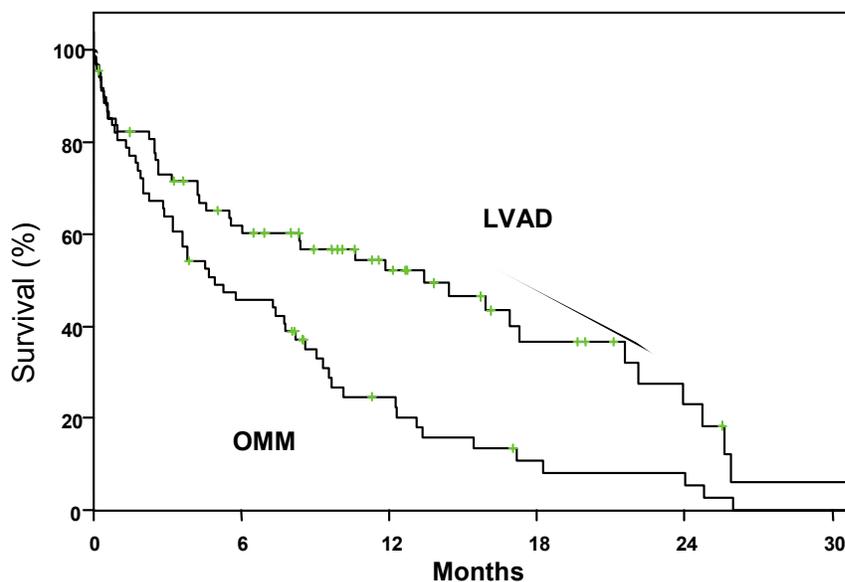


Figure A.11. The LVAD patient improvements in survival.

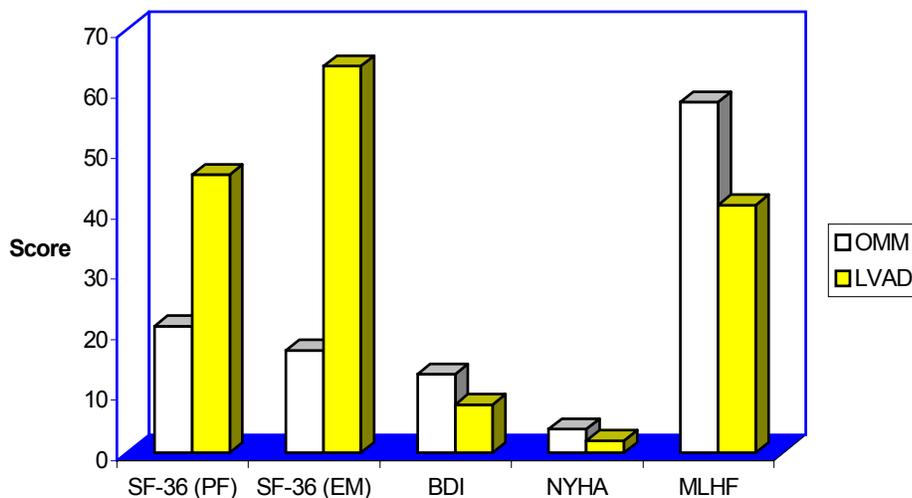


Figure A.12. The LVAD patient improvement in quality of life.

Table A.3. LVAD Patients' Adverse Events

Event	Rate per patient-year		
	OMM (n=60)	LVAD (n=67)	Ratio (95% CI)
All	2.75	6.45	2.35 (1.86-2.95)
Bleeding (Nonneurological)	0.06	0.56	9.47 (2.3-38.9)
Neurological Dysfunction	0.09	0.39	4.35 (1.31-14.5)
Peripheral Embolic Event	0.06	0.14	2.29 (0.48-10.8)
Sepsis	0.3	0.6	2.03 (0.99-4.13)

Overall, REMATCH patients have a higher mortality than is measured for AIDS or breast, colon, and lung cancer. Based on REMATCH results, LVAD systems will prevent 270 deaths annually per 1000 patients treated — four times as effective as beta blockers and ace inhibitors, with a quality of life similar to ambulatory heart failure patients (Table A.4). All of the evidence suggests that these factors could improve, with fewer adverse events, following further research and clinical experience.

Table A.4. REMATCH Results for LVAD Systems

LVAD Mortality Impact	Quality of Life	Adverse Events
LVAD Rx would avert 270 deaths annually per 1000 patients treated	Improved compared to ESHF, yet normalcy not restored	LVAD morbidity still considerable
Nearly 4 times the observed impact of beta-blockers and ACEI (70 deaths prevented per 1000 patients)	Physical function scores similar to hemodialysis and ambulatory heart failure	Infections and mechanical failure obvious targets for device and management improvement
Magnitude of effect commensurate with complexity of intervention	Emotional role scores better than clinical depression and similar to ambulatory heart failure	Rate of neurological events encouraging

The potential of LVAD systems is highlighted in the following two examples of patients from the REMATCH trial. The first example is a 35-year-old women. Following her implant, she has married and is enjoying her husband, home, and dogs. The second patient is a 67-year-old man who collapsed on the golf course. He now claims he is playing better golf than ever against those “40-year-old flat bellies.”

This program would not have occurred without priority-setting by Congress. The clinical need is still substantial. Without sustained public support, the needed research and development capacity would not have materialized. NBIC holds even greater promise but will not achieve its potential without setting some national long-term research objectives.

BALANCING OPPORTUNITIES AND INVESTMENTS FOR NBIC

R. Stanley Williams and Philip J. Kuekes, Hewlett Packard Labs

Over the course of the last several millennia, human beings have learned that major tasks can be performed much more efficiently by dividing up the workload and sharing it among individuals and groups with specialized skills. Larger and more complex tasks require societies with more capable tools and communications skills. As we view the beginning of the 21st century, the tasks we want to perform have become so complex and the tools we have created so sophisticated, that we are challenged to even describe them coherently. It is time to take a holistic view of how we relate to our technologies and develop strategic approaches to integrating them in a fashion that makes them more adaptable and responsive to human desires and capabilities.

In 2001, we are seeing the simultaneous beginnings of three great technological and industrial revolutions that will spring from advances in fundamental research during the past two decades:

Information Science — the understanding of the physical basis of information and the application of this understanding to most efficiently gather, store, transmit, and process information.

Nanoscale Science — the understanding and control of matter on the nanometer length scale to enable qualitatively new materials, devices, and systems.

Molecular Biology — the understanding of the chemical basis of life and the ability to utilize that chemistry.

The knowledge base in each of these areas has the capacity to increase exponentially for several decades into the future, assuming that the research enterprise is maintained. Each field, by itself, offers tremendous opportunities and potential dangers for society, but the fact that there are three simultaneous technology revolutions is literally unprecedented in human history.

The greatest prospects and challenges will occur in the overlap areas that combine two or all three of the new technologies. The great difficulties are that (1) each area by itself is so large and intricate that no single human being can be an expert in all of it, and (2) that each area has developed a language and culture that is distinct and nearly incomprehensible to those working in the other areas. Thus, we find that the most significant problems are often not those related to any particular technology but are based on the basic inadequacies of human understanding and communication. This all-important human factor requires that we better understand and apply cognition. *Cognitive science* will become an increasingly important field for research and utilization in order to more effectively employ the technologies springing from information, nanoscience, and molecular biology. In turn, these technologies will enable major advances in the study and applications of cognition by allowing the construction and emulation of physical models of brain function.

A concrete example can help to illustrate the potential of these overlapping technologies. Since 1960, the efficiency of computing has increased approximately two orders of magnitude every decade. However, this fact has rarely been factored into solving a grand challenge by trading off computation for other types of work as an effort proceeded. This is largely because humans are used to maintaining a particular division of labor for at least a human generation. When paradigms change at a rate that is faster, humans have a difficult time adjusting to the situation. Thus, instead of a smooth adoption of technological improvements, there are often revolutionary changes in problem-solving techniques. When the human genome project began, the shotgun approach for gene sequencing was not employed, because the speed of computing was too slow and the cost was too high to make it a viable technique at that time. After a decade of steady progress utilizing, primarily, chemical analysis, advances in computation made it possible to sequence the genome in under two years utilizing a very different procedure. Thus, the optimum division of labor between chemical analysis and computation changed dramatically during the solution of the problem. In principle, that change could have been exploited to sequence the genome even faster and less expensively if the division of labor had been phased in over the duration of the effort.

As long as technologies progress at an exponential pace for a substantial period of time, those improvements should be factored into the solution of any grand challenge. This will mean that the division of labor will constantly change as the technologies evolve in order to solve problems in the most economical and timely fashion. For computation, the exponential trend of improvement will certainly continue for another ten years, and, depending on the pace of discovery in the nano- and information-sciences, it could continue for another four to five decades. Similar advances will occur in the areas of the storage, transmission, and display of information, as well as in the collection and processing of proteomic and other biological information. The route to the fastest solution to nearly any grand challenge may lie in a periodic (perhaps biannual) multivariate re-optimization of how to allocate the labor of a task among technologies that are changing exponentially during execution of the challenge.

These thrusts in twenty-first century science are being recognized by those in academia. Some university deans are calling them the “big O’s”: *nano*, *bio*, and *info*. These are seen as the truly hot areas where many university faculty in the sciences and engineering want to work. In looking further into the future, we believe that *cogno* should join the list of the big O’s.

One way in which academe responds to new opportunities is by creating new disciplines at the intersections between the established divisions. Materials science was created early in the last century at the boundary between chemistry and structural engineering and has evolved as a separate and highly rigorous discipline. Computer science was created in the middle of the last century at the boundary of electrical engineering and mathematics. Now we are beginning to see new transdisciplinary groups coming together, such as chemists and computer scientists, to address new problems and opportunities. One of the problems we face at the turn of this century is that as device components in integrated circuits continue to shrink, they are becoming more difficult to control, and the factories required to build them are becoming extraordinarily expensive. The opportunity is that chemists can inexpensively manufacture components, i.e., molecules, very precisely at the nanometer scale and do so at an extremely low cost per component. Therefore, the new discipline of molecular electronics is arising out of the interactions between computer scientists and chemists. However, developing this new field requires the rigor of both disciplines, the ability to communicate successfully between them, and the proper negotiation process that allows them to optimally share the workload of building new computers. Chemists can make relatively simple structures out of molecules, but they necessarily contain some defects, whereas computer scientists require extremely complex networks that operate perfectly. Economic necessity brings these two very different fields together in what is essentially a negotiation process to find the globally optimal solution of building a working computer from nanometer scale objects at a competitive cost.

There are other very interesting examples of different sciences just beginning to leverage each other. In the bio-info arena, Eric Winfree at the California Institute of Technology is using DNA for self-assembly of complex structures by designing base-pair sequences to construct nano-scaffolding. There is also the whole area of the interaction between biology and information science known as bioinformatics. With the discovery and recording of the human genome and other genomes, we essentially have the machine language of life in front of us. In a sense, this is the instruction set of a big computer program that we do not otherwise understand: we have only the binary code, not the source code. There is a huge amount of work to reverse-engineer this binary code, and we are going to have to rely on computing power to understand what these programs are doing.

Another arena of extreme importance is the bio-nano intersection, since at the fundamental level these both deal with the same size scale. There will be tremendous opportunities to design and build measurement devices that can reach to the scale of molecules and give us a lot more knowledge about biology than we have now. But the reverse is also true. We are going to learn new ways to manipulate matter at the nanoscale from our huge investment in biology. The current goal of molecular electronics is to combine simple physical chemistry with computer design. But biomolecules have incredible functionality based on four billion years of R&D on very interesting nano-structures. The world is going to make a huge investment over the next few years in the biosciences, and we will be able to leverage much of that knowledge in engineering new nanoscale systems.

Work on the relationship between cognition and information goes back the Turing test (i.e., a test that determines if a computer can fool a human being into thinking it is a person during a short conversation) — ideas Turing had even before computers existed. As more powerful computers have become cheaper, we now have cars that talk to us. How will the next generation of people respond when all kinds of devices start talking to them semi-intelligently, and how will society start reacting to the “minds” of such devices? As well as the coming impact of info on cogno, we have already seen the impact of cogno on info. Marvin Minsky, in his *Society of Mind*, looked at the cognitive world and what we know about the brain and used that to work out a new model of computation.

With nanotechnology literally trillions of circuit elements will be interconnected. There is a set of ideas coming out of the cognitive science community involving connectionist computing, which only starts to make sense when you have such a huge number of elements working together. Because of

nanotechnology, we will be able to start experimentally investigating these connectionist computing ideas. The other connection of nanotechnology with the cognitive sciences is that we will actually be able to have nonintrusive, noninvasive brain probes of conscious humans. We will be able to understand tremendously more about what is going on physically in the brains of conscious minds. This will be possible because of measuring at the nanoscale, and because quantum measurement capability will provide exquisitely accurate measurements of very subtle events. Over the next couple of decades, our empirical, brain-based understanding in the cognitive sciences is going to increase dramatically because of nanotechnology. The hardest challenge will be the bio-cogno connection. Ultimately, this will allow us to connect biology to what David Chalmers recognizes as the hard problem — the problem of the actual nature of consciousness.

The topic of discussion at this workshop is literally “How do we change the world?” What new can be accomplished by combining nanoscience, bioscience, information science, and cognitive science? Will that allow us to qualitatively change the way we think and do things in the 21st century? In the course of discussions leading up to this workshop, some of us identified nano, bio, and information sciences as being the key technologies that are already turning into 21st century industrial revolutions. Where do the cognitive sciences fit in? One of the major problems that we have in dealing with technology is that we do not know how we know. There is so much we do not understand about the nature of knowledge and, more importantly, about the nature of communication. Behind innovative technologies and industrial revolutions there is another dimension of human effort. In order to harness the new scientific results, integrate them, and turn them into beneficial technologies, we need to strengthen the cognitive sciences and begin the task of integrating the four big O’s.

THE IMPACT OF CONVERGENT TECHNOLOGIES AND THE FUTURE OF BUSINESS AND THE ECONOMY

James Canton, Institute for Global Futures

The convergence of nanotechnology, biotechnology, information technology, and cognitive science, which together is referred to here as “convergent technologies,” will play a dominant role in shaping the future economy, society, and industrial infrastructure. According to the Commerce Department, over one third of GDP is contributed by information technology. This data would suggest that with new technology being introduced daily, the share of GDP driven by technology will increase. Emerging technologies, especially convergent technologies discussed here, are the engines of the future economy. The objective of enhancing human performance is vital to the well-being of individuals and to the future economic prosperity of the nation. The convergent technologies model has yet to be fully mapped. The convergence of nano, bio, and information technologies and cognitive science is in the embryonic stages of our understanding. We need to examine the factors driving convergent technologies and the possible impacts on business and the economy. There is a need to better prepare the nation, coordinate efforts, and work collaboratively towards a national initiative to focus our efforts. How we manage the realtime impact of radical innovation on the social and economic infrastructure of the United States will determine the future wealth, prosperity, and quality of life of the nation. This is no less important than the capacity of the United States to play a global leadership role via the leveraging of next-generation innovations like convergent technologies.

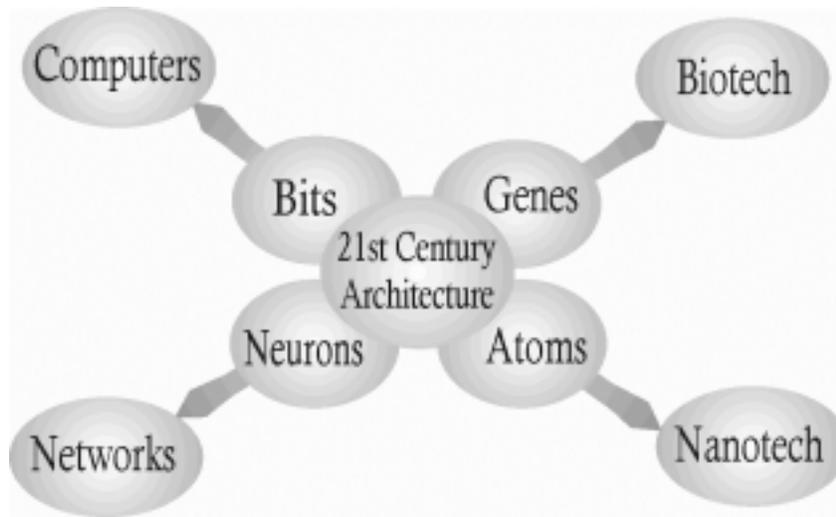


Figure A.13. 21st century architecture.

Inventing the Future

Already, massive socio-economic new directions have appeared due to emerging technologies. Examples include the Internet's impact on business, genomics' impact on healthcare, and the wireless impact on personal communications. Some convergence is happening organically, as the evolution of interdisciplinary science, a systems-approach, and the necessity of sharing tools and knowledge is bringing separate disciplines together. The tyranny of reductionism, too long the unwritten law of modern science, is changing, incorporating a more holistic convergent model. We need to take this effort to a new level of fast innovation, inter-science coordination, and action.

The enhancement of human performance via the deployment of convergent technologies requires new work to focus on the synergy of interdependent arenas of science. The benefits to the nation and its citizens may be great in offering lifestyle choices for individuals and incentives for business that do not exist today. New lifestyles, workstyles, and economic business models may be born of this work. The benefits, the payoff we envision, should be the betterment of people and the sustainability of our economy.

It may be possible to influence the process of how convergent technologies will change economics and society, on a national scale, by providing leadership and support for a nationwide, collaborative development effort. A national initiative to enhance human performance will be needed. This effort should have many stakeholders in education, healthcare, pharmaceuticals, social science, the military, the economy, and the business sector to name a few. No less than a comprehensive national effort will be required to meet the challenges of a future shaped by convergent technologies.

The daunting challenge of managing rapid and complex technological-driven change is increasingly a disruptive force on today's markets, business, economics, and society. Disruptions will cut deeper as innovations fostered by convergent technologies emerge faster. At the same time, opportunities will be present that offer unprecedented market leadership for those prepared to exploit them.

Many things will require change: educational curricula, workforce skills, business models, supply chains, and the post-industrial infrastructure, to name a few. New thinking will be required that is savvy about the real potential of convergent technology, not just on an individual scale but also relative to the nation's competitive advantages in a global marketplace.

A comprehensive and interdisciplinary strategy needs to be developed that will open up new national policy directions, that can leverage convergent technologies and support the enhancement of human performance and the quality of human life. The future wealth of nations, certainly that of the United States, may well be based on the national readiness we set in motion today to facilitate the adaptation of our society to the challenges and opportunities of convergent technologies.

Managing Fast Change: The Power Tools of the Next Economy

The exponential progress in technology undeniably influences every aspect of business, the economy, and society. Accelerated change is the daily reality we face — and events are speeding up. These convergent technologies are exponentially increasing in months, not years or decades. Consider that Internet traffic doubles every six months; wireless capacity doubles every nine months; optical capacity doubles every twelve months; storage doubles every fifteen months; and chip performance (per Moore's Law) doubles every eighteen months.

Will we as a nation be ready to adapt to this pace of change? Will we as a nation be ready to be a global leader in a world where radical technological, social, and economic change occurs overnight, not over a century as in the past? There are vast social policy questions and challenges we have yet to ponder, yet to debate, and yet to understand.

Trying to manage fast and complex change is always a messy business for organizations and people, and even more so for nations. Large systemic change most often happens around a crisis like war or the identification of a potential threat or opportunity. Planned change can backfire. So can policy that attempts to predict the future rather than allow the market economy and free enterprise to rule. Yet there is a role for raising awareness and better directing science policy and private sector coordination that must reflect the changing times.

One would argue that the need to bridge the gap between policy and the fast-changing global market economy may be critically important to the nation's future prosperity and global leadership. A more directed technology policy that is both in sync with the marketplace and capable of rapid responsive change — enabling all sectors of society — would be the preferred direction for the future.

There have been instances where a planned change process was beneficial for the nation such with government management of telecommunications giant ATT as a regulated monopoly. Some innovations are too valuable not to promote in the public's interest. Certainly, supply has driven demand often, such as with the telegraph, train routes, and the telephone. Even the Internet, though never considered by its inventors as the power tool it is today, was built ahead of demand. Enlightened public policymakers understood the immense value of these technologies to shape the economic opportunity of a nation. There are some today who argue with merit for turning the next generation of the Internet, broadband, into a utility so that all Americans can gain access and enhance their productivity.

We are again at this crossroads. The convergence of these critical technologies, nano, bio, info, and cogno, may cause deeper disruptions sooner than any prior technologies. We may not have generations or decades to foster national collaboration. We may have a brief period, perhaps a few years, to raise awareness and committed actions at the national scale before serious global competitive challenges arise.

Convergent Technologies and Human Resources

There already is a crisis of inadequate qualified human resources to manage the future opportunities that may lay before us. Already we confront low math and science test scores in our students. Most of

the doctoral students in the technical sciences are from abroad. We have close to one million high-tech jobs a year that go begging. Immigration policy cannot keep pace with attracting the number of skilled knowledge workers our economy needs to grow — and this is only the beginning of the talent wars. Clearly, the emergence of radical innovations in science, such as the convergent technology paradigm described here, will accelerate the nation's need for deep science and technical human resources.

How are we as a nation to compete in the super-charged high-tech global economy of the future if we do not have the skilled human resources? Consider the stakeholders of this crisis and what we must do today to rectify this problem before it becomes the nation's Waterloo. Too long has this message been ignored or simply not addressed with the resources required to make a difference for institutions, the private sector, and individuals.

In our modern era we have seen large transformations in nations due to the globalization of trade, emergence of communications technologies, and the expansion of offshore manufacturing. Increasingly, the emergence of new technology is emerging as the key driver of change where once the train, the telephone, and before that the steamship, drove economic opportunity.

Given the prospects of advanced NBIC technologies, efforts towards large-systems-managed change represent a daunting task for policymakers across all sectors of society. In some ways, the social policymaking process has lagged behind scientific and technological progress. It is time that the social policymaking process catches up and reaches further to explore the technological vectors that will shape our nation's economic future.

Preparing For the Next Economy

No society has ever had to deal with tools as massively powerful as those that are emerging today. The convergence of the NBIC technologies promise to realign the nation's economic future. These power tools are the key arbiters of the next economy, but they will seem tame compared to what is to come. It could be argued that we have passed over the threshold where it is clear that these power tools will be definitive shapers of nations, economies, and societies. How might we guide the emerging future? How might we invent the preferred future by investing in readiness on a national scale? How might we raise awareness of the radical nature of these technologies so that we can be more productive and focused on enhancing human performance?

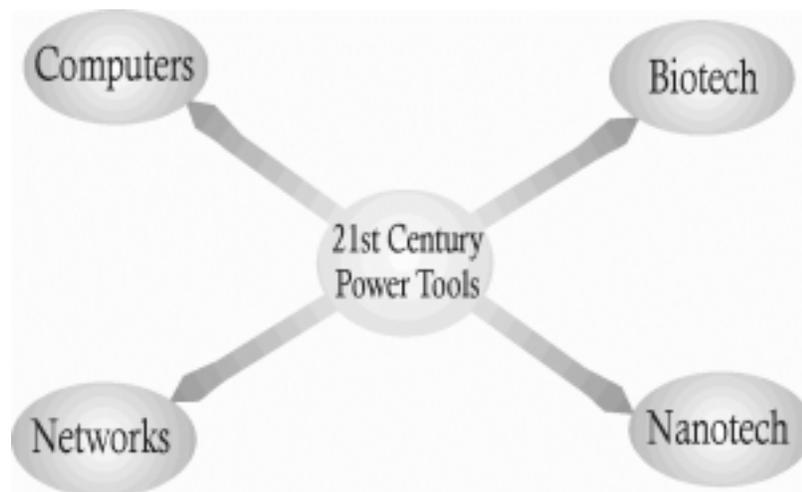


Figure A.14. 21st century power tools.

An entirely new infrastructure is emerging. This new infrastructure will need to accelerate knowledge exchange, networked markets, fast collaborative work, and workforce education. The building blocks of the next economy will be born from the convergent technologies. They represent the shift from the steel and oil of the past and point us towards a radical reshaping of the economy, now in an embryonic stage. The next economy's building blocks — bits, atoms, genes and neurons (Fig. A.15) — will be followed by photons and qubits, as well.

The nations that understand this and that support the growth and development of government and private sector collaboration will thrive. This will enable those economies prepared to pursue new economic growth horizons. The future wealth of nations will be based on the change-management readiness that we set in motion today by enabling the social adaptation to convergent technology.

How might we direct, encourage, and ultimately shape this desired future for the nation, given the emergence of convergent technologies? We can start by developing a plan and setting objectives committed to answering this question. How might we enhance human performance, as a national objective, given the emergence of these convergent technologies? A coordinated and strategic approach will be necessary to create effective long-term results. New thinking will be required that recognizes the necessity of building a collaborative and interdisciplinary strategy for integrating national policy and programs and private and public sector cooperation as never before.

Convergent Technologies: Towards a New Model for Interdisciplinary Policy, Systems-Research, and Inter-Science

Convergent technologies offer an opportunity to design a new model for policyplanners, research scientists, and business executives to consider what the probable outcomes of this work may be. Will we create longevity for the Baby Boomers? Will a new era of convergent knowledge workers be nurtured? How should the private venture community prepare to attract more capital to fuel convergent technology deals? What might healthcare do with enhanced human performance as a medical “product”? What of the ethical and social issues concerning who in our society gets enhanced? These issues and many more are waiting for us in the near future, where convergent technologies will dominate the agenda with breakthroughs too numerous to forecast with any accuracy.

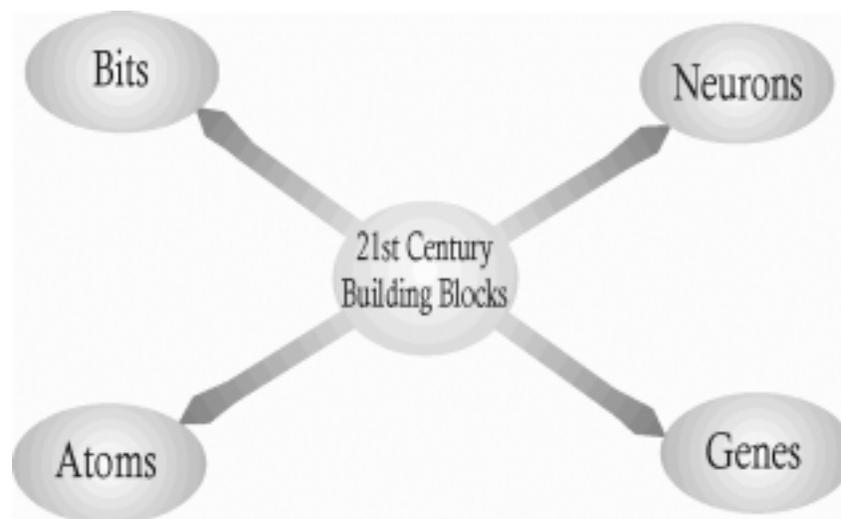


Figure A.15. 21st Century building blocks.

Will we have ready a comprehensive and integrated science policy framework that is visionary enough to consider the development of human potential and the enhancement of human performance? This is the challenge before us, to build a framework that can nurture and experiment but that has the proper controls in place.

The central challenge may well be that we desire a higher quality of life for the nation, as well as building our competitive readiness, given the emergence of convergent technologies. Some may argue against these as non-essential. The quality of life of Americans, it could be easily argued, is influenced heavily by their easy access to leading technologies. American companies and their workers enjoy a global competitive advantage over other less tech-tool-enabled, less human performance-enabled resources. If anything, this may be predictive of the future. We need to continue innovating as a nation and as the leader of the free world. There are security issues not far removed from this argument.

How might we best leverage convergent technology for enhancing the competitive advantage of the nation's businesses and citizens? Nothing less than a comprehensive rethinking of national technology policy, national education policy, and strategic R&D policy should be considered to create the necessary long-term impact that we desire. The U.S. economy is not a planned economy, nor should it be. Yet our nation needs to formulate a new interdisciplinary, inter-science, and systems-wide collaborative model based on converging NBIC technologies in order to move forward to create productive and efficient change. We need to map out the scenarios with all sectors as we stake out our visions of a preferred future.

Convergent Technology Impact Factors

Convergent technologies will be a catalyst for large-systems social change impacting the following domains, all of which will require forward-thinking leadership to facilitate and manage the transition:

- 6. Workforce Training
 - xxxv) Educational Curricula
 - xxxvi) Market and Supply Chain Infrastructure
 - xxxvii) Government R&D
 - xxxviii) Private Sector R&D
 - xxxix) Private Sector Product Development
 - xl) Next Generation Internet

Economic Readiness and Convergent Technology: Key Policy Questions

It could be argued that a nation's technological innovations shape the destiny of that nation. They certainly shape the security, economics, and social well-being of nations. The economic prosperity of the modern nation state cannot be de-linked from technological adaptation and leadership. But there are other less well-defined issues that we should consider in a global realtime market shaped by convergent technology. Here are some of the arenas yet to be addressed:

- 7. How can we use the Internet to encourage the high-level knowledge exchange and collaborative work required by convergent technology?
 - xli) What knowledge management resources and large-scale efforts might be mission-essential to facilitating the work with convergent technology?

- xlii) How should private and public sectors work together to facilitate change and adaptation to convergent technology?
- xlili) What new business and economic models might we foster to better enhance productivity in convergent technology?
- xliv) How might we best prepare the nation to compete in a global marketplace shaped by convergent technology?
- xlv) How might we rethink social policy given the future impact of convergent technology?
- xlvi) What are the best ways to raise private sector awareness and support for convergent technologies initiatives?
- xlvii) Given the emergence of convergent technology, how might we rethink a more holistic inter-science model to better increase our understanding and enhance human performance?
- xlviii) How do we define human performance and enhanced human performance given convergent technologies?
- xlix) What is the basis for formulating a national convergent technology initiative to foster private sector and government collaboration, increase citizens' awareness, and coordinate and conduct R&D?

A Proposal for a Convergent Technologies Enterprise Knowledge Network

A convergent technologies Enterprise Knowledge Network (EKN) could provide an online resource bank of information and jobs, a marketplace and clearinghouse for innovations in different vertical industries such as manufacturing, financial services, and entertainment. This network could coordinate information about innovations and intellectual property, and most importantly, connect people using the power of the Internet. This virtual community would be able to build upon, share, and collaborate on new developments in convergent technologies. This network would be linked to research and the marketplace to be able to quickly disperse information, available capital, breakthroughs, and communications relevant to the convergent technologies community.

Next Steps: Advancing Convergent Technologies to Enhance Human Performance

Convergent technology represents an opportunity to address the need to better share innovations, ideas, knowledge, and perhaps, as is our thesis here, to create more effective breakthroughs in enhancing human performance. This is a process that will have to untangle the silo thinking that has been at the heart of science, government, academia, and research. Given the emerging paradigm of convergent technologies, how might we conceptualize a new systems approach to science?

An adoption of a systems approach is already being explored in many areas: Information technology is considering genetic models; telecommunications is experimenting with self-healing networks; biotechnology is edging towards systems-biology; quantum computing and nanotechnology are destined for a convergence.

An area that will require much policy and research work is how we define “enhancing human performance.” For the physically-challenged the definition may entail gaining sight or mobility. For the aged, it may entail having access to one’s memory. Even bolder, the definition of human enhancement may entail providing people with advanced capabilities of speed, language, skill, or

strength beyond what humans can perform today. Just as plastic surgery and pharmacology have given new choices to human beings today, enhancement treatments will no doubt shape tomorrow.

Cybernetic Enhancement

Inevitably, the cybernetic enhancement of human performance is sneaking up on society. We already are “enhanced.” We wear contact lens to see better, wear hearing aids to hear better, replace hips to improve mobility. We are already at the point of embedding devices in the heart, brain, and body to regulate behavior and promote health. From braces that straighten teeth to plastic surgery that extends youthful appearance, humans are already on the path towards human performance enhancement. Yet, the next generation of human performance enhancement will seem radical to us today .

Well beyond anticipating the sightless who will see, the lame who will walk, and the infertile couples who will be able to conceive children, we will be faced with radical choices. Who will have access to intelligence-enhancing treatments? Will we desire a genetic modification of our species? The future may hold different definitions of human enhancement that affect culture, intelligence, memory, physical performance, even longevity. Different cultures will define human performance based on their social and political values. It is for our nation to define these values and chart the future of human performance.

Summary

Research into convergent technologies may provide insight into better productivity, enhanced human performance, and opportunities to advance the betterment of individuals. No doubt the business sector will need to be a full player in the strategies to further this approach. Better collaboration within government and between government and the private sector would be a worthwhile endeavor.

The destiny of our nation and the leadership that the United States provides to the world will be influenced by how we deal with convergent technologies and the enhancement of human performance.

Convergent technologies will be a key shaper of the future economy. This will drive GDP higher while the health, prosperity, and quality of life of individuals is improved.

A national initiative that can accelerate convergent technology collaboration and innovation while fostering better inter-agency work and public or private sector work will lead to a prosperous future. Without a strategy that enable collaboration, the development of a true systems approach, and an inter-science model, future success maybe be haphazard. The future destiny of the nation as a global leader may be at risk unless a coordinated strategy is pursued to maximize the opportunity that lies inherent in convergent technologies.

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COHERENCE AND DIVERGENCE OF MEGATRENDS IN SCIENCE AND ENGINEERING

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Scientific discoveries and technological innovations are at the core of human endeavor, and it is expected that their role will increase over time. Such advancements evolve into coherence, with areas of temporary confluence and divergence that bring both synergism and tension for further developments. Six increasingly interconnected megatrends (Fig. A.16) are perceived as dominating the science and engineering (S&E) scene for the next several decades: (a) information and computing, (b) nanoscale science and engineering, (c) biology and bio-environmental approaches, (d) medical sciences and enhancement of human physical capabilities, (e) cognitive sciences and enhancement of intellectual abilities, and (f) collective behavior and systems approaches.

This paper presents a perspective on the process of identifying, planning, and implementing S&E megatrends, with illustration for the U.S. research initiative on nanoscale science, engineering, and technology. The interplay between coherence and divergence that leads to unifying science and converging technologies does not develop only among simultaneous scientific trends but also over time and across geopolitical boundaries. There is no single way to develop S&E: here is the value of visionary thinking, to anticipate, inspire, and guide development. Scientists with a view of societal implications should be involved from the conceptual phase of any program that responds to an S&E megatrend.

Introduction

Discoveries and advancements in science and technology evolve into coherence reflecting the trends towards unifying knowledge and global society, and has areas of both enduring confluence and temporary divergence. These dynamics bring synergism and tension that stimulate further developments following, on average, an exponential growth. Besides addressing societal needs for wealth, health, and peace, a key driver for discoveries is the intrinsic human need for intellectual advancement, to creatively address challenges at the frontiers of knowledge. A few of the most relevant discoveries lead to the birth of megatrends in science and engineering after passing important scientific thresholds, then building up to a critical mass and inducing wide societal implications. After reaching this higher plateau, such discoveries spread into the mainstream of disciplines and are assimilated into general knowledge. S&E megatrends always are traceable to human development and societal needs, which are their origin and purpose (Fig. A.16). We speak about both science and engineering, because engineering skills provide the tools to implement scientific knowledge and thus the capability to transform society.

Funding a megatrend means enhancing the chance of support of researchers moving into the respective field while maintaining most of the investment in the original research fields. The goals are to increase the research outcomes of the total investment, obtain the benefits sooner, and create a suitable infrastructure for the new field in the long term.

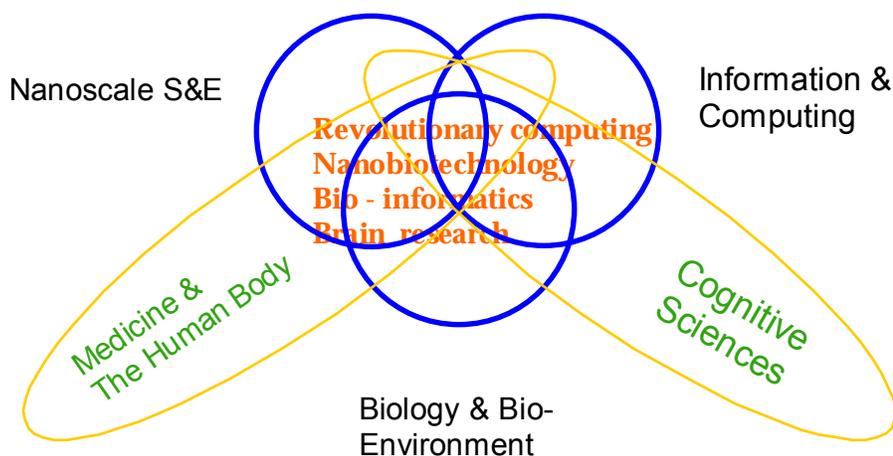


Figure A.16. Coherence and synergism at the confluence of NBIC science and engineering streams.

At times, groups of researchers argue, targeted funding of S&E megatrends could present a threat to open science and technology advancement. We agree that targeted funding may present a threat to the uniform distribution of R&D funding and could present a larger threat to scientific advancement if the megatrend selection were arbitrary. With proper input from the scientific community to identify the megatrend to support, the primary purpose of a focused S&E effort at the national level is the big payoff in terms of accelerated and synergistic S&E development at the frontiers of science and at the interfaces between scientific disciplines. Without such divergent developments, the entire S&E dynamics would be much slower. There is a need for synergy and cooperative efforts between the disciplines supporting a new field of science or engineering, as well as the need to focus on and fund the key contributing disciplines in a timely fashion.

How should society identify an S&E megatrend? A megatrend is usually motivated by a challenge that may appear unfeasible and even unreasonable at the beginning, as were flying, landing on the Moon, or going into the nanoworld. The goals must be sufficiently broad, the benefits sufficiently valuable, and the development timeframe sufficiently long to justify the national attention and expense. This paper presents an overview of what we see as key national S&E trends in the United States and illustrates the process of identifying a new megatrend in the recent “National Nanotechnology Initiative” (NNI). Finally, the paper discusses the coherence and synergism among major S&E trends and the role of macroscale management decisions.

Six Increasingly Interconnected Megatrends

The S&E communities and society at large share a mutual interest in advancing major new areas of technological focus in response to objective opportunities, with the goal of accelerating the progress of society as a whole. Six increasingly interconnected scientific megatrends, some closely followed by engineering and technology advancements, are expected to dominate the scene for the coming decades in the United States:

- (a) *Information and computing.* The bit-based language (0,1) has allowed us to expand communication, visualisation, and control beyond our natural intellectual power. Significant developments beginning in the 1950s have not slowed down, and it is expected that we will continue the exponential growth of opportunities in this area. The main product is in the form of software.

- (b) *Nanoscale science and engineering.* Working at the atomic, molecular, and supramolecular levels allows us to reach directly the building blocks of matter beyond our natural size limitation, that is, on orders of magnitude smaller than what we can see, feel, or smell. At this moment, this is the most exploratory of all megatrends identified in this list. The field was fully recognised in the 1990s and is just at the beginning of the development curve. The main outcome of nanotechnology is in the form of hardware, that is, in the creation of new materials, devices, and systems. The nanoscale appears to be the most efficient scale for manufacturing, as we understand its nature now, promising the smallest dissipation of energy, material consumption, and waste and the highest efficiency in attaining desired properties and functions.
- (c) *Modern biology and bioenvironmental approaches.* Studying cells, their assemblies, and their interactions with their surroundings presents uniquely challenging issues because of their unparalleled complexity. Biology introduces us to self-replicating structures of matter. It uses the investigative methods of information and nanoscale technologies. One important aspect is genetic engineering, another is the connection between life and its environment, including topics such as global warming. Modern biology began its scientific ascendance in the 1970s, and its role continues to expand.
- (d) *Medical sciences and enhancement of the human body.* The goals are maintaining and improving human physical capabilities. This includes monitoring health, enhancing sensorial and dynamical performance, using implant devices, and extending capabilities by using human-machine interfaces. Healthcare technology is a major area of R&D; it has general public acceptance, and its relative importance is growing as the population ages.
- (e) *Cognitive sciences and enhancement of intellectual abilities.* This area is concerned with exploring and improving human cognition, behavior, and intellect. Enhancing communication and group interaction are an integral part of improving collective behavior and productivity. This area has received little public recognition, even though increasing cognitive capabilities is a natural objective for a large section of the population.
- (f) *Collective behavior and systems approach.* This area uses concepts found in architecture, hierarchical systems, chaos theory, and various disciplines to study nature, technology, and society. It may describe a living system, cultural traits, reaction of the society to an unexpected event, or development of global communication, to name a few examples. Recognition of the value of systems approaches increased in the late 1990s.

If one were to model the evolution of the entire society, none of these six S&E megatrends could be disregarded. The nano, bio, and information megatrends extend naturally to engineering and technology, have a strong synergism, and tend to gravitate towards one another. Among these three trends, nanoscale S&E is currently the most exploratory area; however, it is a condition for the development of the other two. Information technology enhances the advancement of both the others. A mathematical formulation of the coherent evolution of research trends could be developed based on a systems approach and time-delayed correlation functions.

Figure A.16. shows a simplified schematic of the complex interaction between the main elements of the scientific system of the beginning of the 21st century. Bits (for computers and communication to satisfy the need for visualization, interaction, and control), genes and cells (for biology and biotechnology), neurons (for cognition development and brain research), and atoms and molecules (to transform materials, devices, and systems), are all interactive components (part of a system approach). But it is important to note that there is a melding of human and S&E development here: human development, from individual medical and intellectual development to collective cultures and globalization, is a key goal.

The main trends of this 21st century scientific system overlap in many ways; their coherence and synergy at the interfaces create new research fields such as bioinformatics, brain research, and neuromorphic engineering. Let's illustrate a possible path of interactions. Information technology provides insights into and visualization of the nanoworld; in turn, nanotechnology tools help measure and manipulate DNA and proteins; these contribute to uncovering brain physiology and cognition processes; and brain processes provide understanding of the entire system. Finally, the conceived system and architecture are used to design new information technology. *Four transforming tools have emerged: nanotechnology for hardware, biotechnology for dealing with living systems, information technology for communication and control, and cognition-based technologies to enhance human abilities and collective behavior.*

Unifying Science and Engineering

There are several reasons why unifying principles in science and engineering are arising now:

- Scientists have increased depth of understanding of physical, chemical, and biological phenomena, revealing the fundamental common ground in nature.
- Significant advances exist at the interfaces among disciplines, in such a way that the disciplines are brought closer together and one can more easily identify the common principles, fractal patterns and transforming tools.
- There is a convergence of principles and methods of investigation in various disciplines at the nanoscale, using the same building blocks of matter in their analysis. Now it is possible to explore within human cell and neural systems.
- There is a need to simulate complex, simultaneous phenomena, and hierarchical processes where the known physico-chemico-biological laws are too specific for effective multiscale modeling and simulation. An obvious illustration is the requirements for modeling of many-body interactions at the nanoscale, where the laws are specific for each material, and variable within bodies and at the boundaries, at different environmental parameters, and for different phenomena.

The unifying science may manifest in three major ways:

- Unification of the basic understanding of various natural phenomena and bringing under the same umbrella various laws, principles, and concepts in physical, chemical, biological, and engineering sciences using cause-and-effect explanation. For example, in physics, there is an increasing awareness that weak, strong, electromagnetic, and gravitational forces may collapse into the same theory in the future (Grand Unified Theory). Mathematical language and other languages for improved communication at S&E interfaces and the system approach offer general tools for this process. Furthermore, unification of knowledge of natural sciences with social sciences and humanities forms *a continuum across levels of increasingly complex architectures and dynamics*.
- Observation of collective behavior in physics, chemistry, biology, engineering, astronomy, and society. *Integrative theories are being developed* using the concepts of self-organized systems, chaos, multi-length and time-scale organizations and complex systems.
- *Convergence of investigative methods to describe the building blocks of matter at the nanoscale.* The nanoscale is the natural threshold from the discontinuity of atoms and molecules to the continuity of bulk behavior of materials. Averaging approaches specific to each discipline collapse in the same multibody approach.

Identifying and using unifying science and engineering has powerful transforming implications on converging technologies, education, healthcare, and the society in the long term.

National S&E Funding Trends

The foundation of major S&E trends are built up over time at the confluence of other areas of R&D and brought to the front by a catalytic development such as a scientific breakthrough or a societal need. For example, space exploration has grown at the confluence of developments in jet engines, aeronautics, astronomy, and advanced materials and has been accelerated by global competitiveness and defense challenges. Information technology advancement has grown at the confluence of developments in mathematics, manufacturing on a chip, materials sciences, media, and many other areas and has been accelerated by the economic impact of improved computing and communication. Nanotechnology development has its origins in scaling down approaches, in building up from atomic and molecular levels, and in the confluence of better understanding of chemistry, biosystems, materials, simulations, and engineering, among others; it has been accelerated by its promise to change the nature of almost all human-made products. Biotechnology development has grown at the confluence of biology, advanced computing, nanoscale tools, medicine, pharmacy, and others and has been accelerated by its obvious benefits in terms of improved healthcare and new products.

Development of initiatives for such fields of inquiry has led to additional funding for these and similar initiatives. The last two national research initiatives are the Information Technology Research (ITR) initiative, announced in 1999, and the National Nanotechnology Initiative (NNI), announced in 2000. For ITR, there is a report from the President's Information Technology Advisory Committee (PITAC), a committee with significant participation from industry, that shows new elements and expectations. According to this report, the Internet is just a small token development on the way to larger benefits.

How is a new trend recognized for funding? There is no single process for raising an S&E trend to the top of the U.S. national priorities list. One needs to explore the big picture and the long term. It is, of course, important to identify a significant trend correctly; otherwise, either a gold mine may not be exploited, or a wasteful path may be chosen. We note that major U.S. R&D initiatives are designed to receive only a relatively small fraction of the total research budget, because the country must provide support for all fields, including the seeds for future major trends. Generally, one must show a long-term, cross-cutting, high-risk/high-return R&D opportunity in order to justify funding a trend. However, this may be insufficient. Of the six major trends listed above, only the first two have led to multiagency national research initiatives, although there is de facto national priority on the fourth trend — that related to human health. Information technology and nanotechnology received national recognition through the National Science and Technology Council (NSTC). In another example, the driving force for support for a program for global change has been international participation.

Table A.5 summarizes the main reasons for national recognition and funding of several S&E programs. A few years ago, NSF proposed a research focus on biocomplexity in the environment, a beautiful (and actual) subject. This topic so far has not received attention from other funding agencies; a reason may be that no dramatic scientific breakthrough or surge of societal interest was evident at the date of proposal to justify reallocating funds at the national level. On the other hand, cognitive sciences are key for human development and improvement, and it is expected that this area will receive increased attention. Converging technologies starting from the nanoscale is another area for future consideration.

We could relate the S&E developments to the perception and intellectual ability of the contributing researchers. The left-brain handles the basic concepts; the right-brain looks into pictures and assemblies. “Your left-brain is your verbal and rational brain; it thinks serially and reduces its thoughts to numbers, letters, and words. Your right brain is your non-verbal and intuitive brain; it

thinks in patterns, or pictures, composed of “whole things” (Bergland 1985). Accordingly, the brain combines reductionist elements with assembling views into a cooperative and synergistic thinking approach. Those two representations of thinking may be identified as development steps for each S&E megatrend, as illustrated in Table A.6.

**Table A.5. Reasons for national recognition for funding purposes:
No unique process of identification of U.S. national R&D programs**

(PITAC: Presidential Information Technology Advisory Committee; NSTC: National Science and Technology Council)

S&E Funding Trends in U.S.	Main reasons for recognition at the national level
Information Technology Research (1999 -)	Economic implications; proposed by PITAC; promise of societal implications; recognized by NSTC
National Nanotechnology Initiative (2000 -)	Intellectual drive towards the nanoscale; promise of societal implications; recognized by NSTC
Medicine (NIH)	Public interest in health, and aging population; focus at the National Institutes of Health
Biology and bioenvironment	Distributed interest; NSF focus on biocomplexity
Cognitive	Not yet well recognized; included in education
Collective behavior	Not yet well recognized; not focused, part of others
Others in the last 50 years:	
Nuclear program	National security
Space exploration	International challenge
Global change research	International agreements
Partnerships for a new generation of vehicles	Economic competitiveness; environment

Table A.6. S&E megatrends as related to human representation

Left-brain focus	Right-brain focus	S&E trend
DNA, cell (from natural environment)	Biosystems, organisms	Modern biology
Atom, molecule (from natural environment)	Patterns, assemblies	Nanoscale S&E
Bits (chosen language)	Visualization, networking	Information and computing

It is relevant to keep track of this connection when developing a new research program. For example, the basic concepts originating in the left brain allow individuals and groups to develop representations further from their primary perception (point of reference). Let’s consider the human representation of length scale. Initially, we used our hands to measure and developed representations at our natural length scale; then we used mechanical systems, and our representation moved towards the smaller scale of exact dimensions; later, optical tools helped us move into the microscale range of length representation; and electron microscopes and surface probes have helped us move into the nanoscale range. This process continues into the arena of nuclear physics and further on. In a similar manner, abstract concepts handled by the left brain have helped humans move into larger representation scales, beginning with the representation of a building and geography of a territory; later moving to representation of the Earth (useful in sustainable development and global change R&D), then of the universe (needed in space exploration).

The left brain tends to favor reductionist analysis and depth in a single field, which may contribute to “divergent” advancements. Within finite time intervals, such advancements tend to develop faster, to diverge, to take on a life of their own. Meantime, the “whole think” approach is favored by right-brain activities. It is the role of the right brain to assemble the global vision for each initiative and see the coherence among initiatives. This coherence leads to unifying concepts and converging technologies.

Societal feedback is the essential and ultimate test for the nation to establish and assimilate S&E megatrends. There are clear imperatives: increasing wealth, improving healthcare, protecting a sustainable environment, enhancing the culture, and providing national security. When one looks from the national point of view and in the long term, scientific communities, government, and society at large all have the same goals, even if the R&D funds for a megatrend favor some S&E communities in short-term.

Motivation, Preparation, and Approval Process of the National Nanotechnology Initiative

Four imperatives define the National Nanotechnology Initiative:

8. *There is a need for long-term fundamental research leading to systematic methods of control of matter at the nanoscale.* All living systems and man-made products work at this scale. This is because all basic building blocks of matter are established and their basic properties are defined in the range between one and a hundred molecular diameters. The first level of organization in biosystems is in the same nanometer range. For example, our body cells typically include nanobiomotors converting energies to the forms needed, such as chemical, electrical, or mechanical. The typical size of the organelles (see Fig. A.17) in a cell is ten nanometers, which corresponds approximately to ten shoulder-to-shoulder molecules of water. Fundamental understanding of matter at the nanoscale may change our long-term strategies concerning healthcare, the way we manage the environment, our manufacturing practices. This is the first initiative at the national level motivated by and focused on fundamental research.

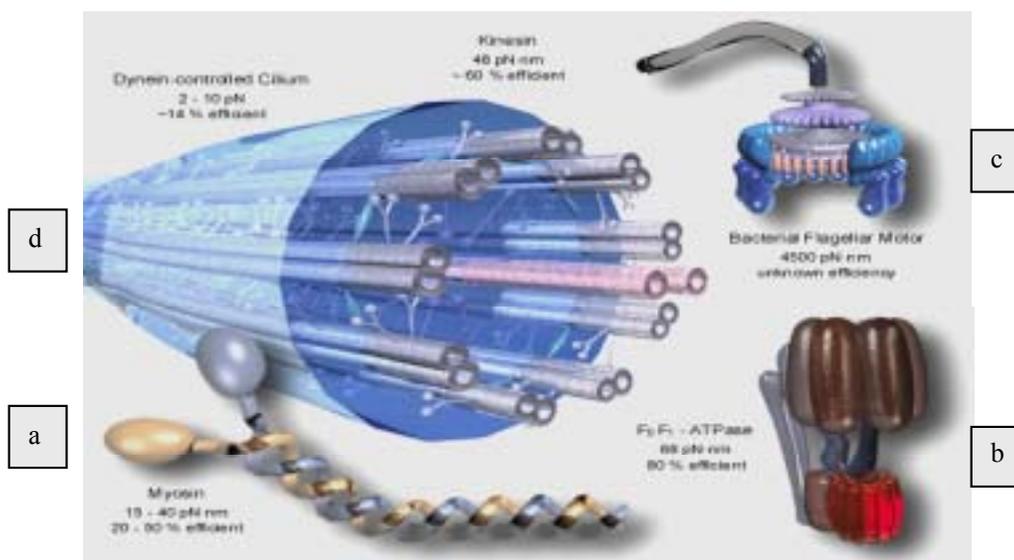


Figure A.17. All living systems work at the nanoscale: illustration of cellular nanomachines (after Montemagno 2001): (a) Myosin, the principle molecular motor responsible for muscle movement (characteristic dimension L about a few nm); (b) ATP synthase, a chemical assembler (L about 10 nm); (c) Bacterial flagella motor (L about 20 nm); (d) A dynein-microtubule complex assembled to form a cilium (L about 50 nm).

- l) *Nanotechnology promises to become the most efficient length scale for manufacturing.* While we know that the weak interactions at the nanoscale would require small amounts of energy for manufacturing and that precise assembly of matter would lead to products with high performance and no waste, we do not yet have systematic, economic manufacturing methods for production at the nanoscale. Again, a focus on fundamental research is essential in this regard.
- li) *Large societal pay-offs are expected in the long term in almost all major areas of the economy* (see Roco and Bainbridge 2001). Material properties and system functions are adjustable at the nanoscale, a function of size, shape, and pattern. For this reason, nanoscale sciences have created tremendous scientific interest. However, this alone would have not been sufficient to start a national research initiative. Nanotechnology has acquired national interest only in the last two years because of our increasing ability to manufacture products with structures in the nanometer range, as well as to change life and environmental ventures. This possibility promises a new industrial revolution leading to a high return on investments and to large benefits for society.
- lii) *Nanoscience and nanotechnology development are necessary contributing components in the converging advancements in S&E*, including those originating in the digital revolution, modern biology, human medical and cognitive sciences, and collective behavior theory. The creation of “hardware” through control at the nanoscale is a necessary square in the mosaic. The future will be determined by the synergy of all six research areas, although in the short term, the synergy will rely on the information, nano- and bio- sciences starting from the molecular length scale. The developments as a result of the convergent technologies will be significant, but are difficult to predict because of discontinuities.

NNI was the result of systematic preparation. It was done with a similar rigor as used for a research project, and documents were prepared with the same rigor as for a journal article. In 1996-1998, there was an intellectual drive within various science and engineering communities to reach a consensus with regard to a broad definition of nanotechnology. In the interval 1997-2000, we prepared detailed materials answering several defining questions:

- What are the research directions in the next 10 years? (See *Nanotechnology research directions. A vision for nanotechnology research and development in the next decade.* Roco, Williams, and Alivisatos 1999/2000; <http://nano.gov/nsetrpts.htm>.)
- What is the national and international situation? (See *Nanostructure science and technology, A worldwide study.* Siegel et al. 1999; <http://nano.gov/nsetrpts.htm>.)
- What are the societal implications? (See *Societal implications of nanoscience and nanotechnology.* NSF 2000; <http://nano.gov/nsetrpts.htm>.)
- What are the vision and implementation plans for the government agencies? (See NNI, Budget request submitted by the president to Congress. NSTC 2000; <http://nano.gov>.)
- How do we inform and educate the public at large about nanotechnology? (See *Nanotechnology. Reshaping the world atom by atom,* NSTC/CT 1999; <http://nano.gov/nsetrpts.htm>.)

The approval process began with various S&E communities, and advanced with the positive recommendations of the Presidential Council of Science Advisory and Technology and of the Office of Management and Budget. The president proposed NNI on January 21, 2000, in a speech at the California Institute of Technology. The proposed budget was then approved by eight congressional committees, including those for basic science, defense, space, and health-related issues. Finally, the Congress appropriated \$422 million for NNI in fiscal year 2001 (see Roco 2001a).

The Role of Macroscale Management Decisions

It is essential that we take time to explore the broad S&E and societal issues and that we look and plan ahead. These activities require information at the national level, including macroscale management decisions, which must be sufficiently flexible to allow creativity and imagination to manifest themselves during implementation of planning and programs. (Firm predictions are difficult because of the discontinuities in development and synergistic interactions in a large system.) Industry provides examples of the value of applying visionary ideas at the macroscale and making corresponding management decisions. At General Electric, for example, Jack Welch both articulated a clear vision and spearheaded measures structured at the level of the whole company for ensuring long-term success. R&D activities depend on the decisions taken at the macroscale (national), S&E community (providers and users), organization (agency), and individual levels. In addition, the international situation increasingly affects results in any individual country. An international strategy would require a new set of assumptions as compared to the national ones (Roco 2001b).

- a) **Strategic macroscale decisions taken at the national level.** These have broad, long-term implications. Different visions and implementation plans may lead to significantly different results. Examples and principles follow.
- NSF collects information on the evolution of sources of R&D funding like the one shown in Fig. A.18. Federal funding is relatively constant from 1992 to 2000. In the same time interval, private R&D funding has increased and approximately doubled as compared to federal funding. The federal government share of support for the nation's R&D decreased from 44.9% in fiscal year 1988 to 26.7% in fiscal year 1999. Also, more funds in industry are dedicated to funding development and applied research. That is, society spends more overall for shorter-term outcomes and less for long-term outcomes. Government needs to direct its funding more on complementary aspects: fundamental research (see Bohr's quadrant, Fig. A.19) and mission-oriented projects that encourage depth of understanding, synergism, and collaboration among fields (see Pasteur's quadrant, Fig. A.19). Frequently, the focus in this last quadrant is on developing a generic technology.

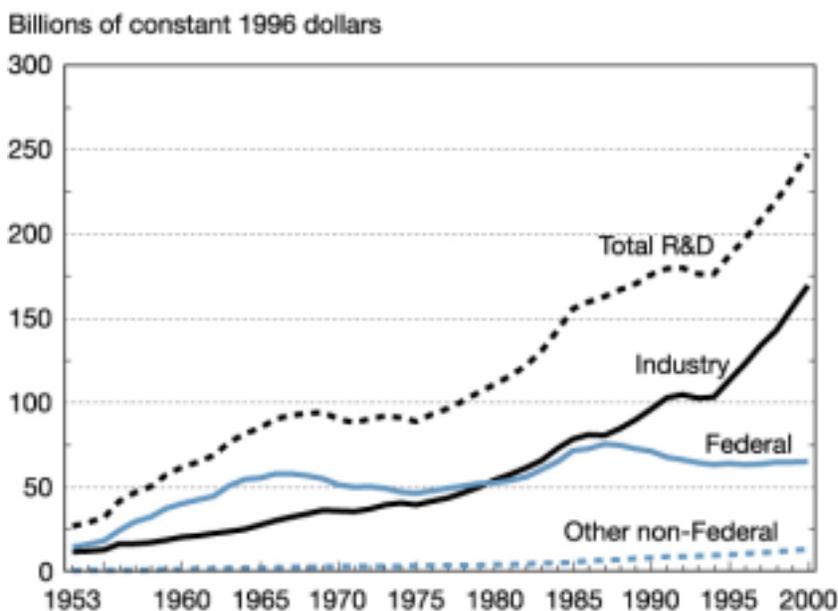


Figure A.18. National R&D funding by source (NSF 2002)

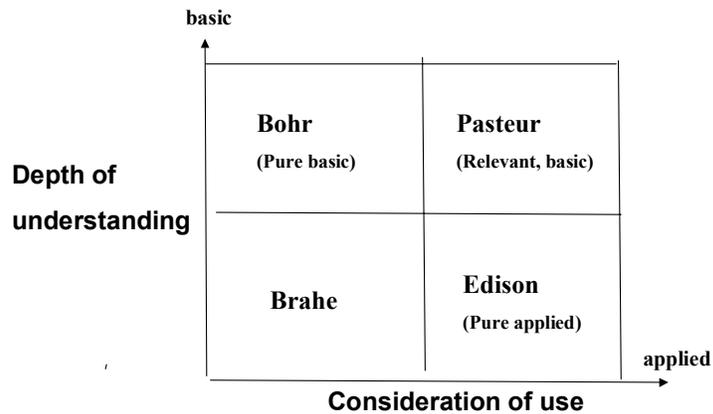


Figure A.19. Pasteur's Quadrant (schematic after Stokes 1997): Redirecting R&D investments with a new role for engineering.

The Federal Government provides funds for industry only under limited programs such as SBIR (Small Business Innovative Research), STTR (Small Technology Transfer), and ATP (Advanced Technology Program at National Institute of Standards and Technology), or for special purposes such as DARPA (Defense Advanced Research Program Agency). If total funding is constant, supporting applied research often means that a large number of exploratory research projects cannot be funded.

- Since 1970, the proportion of life sciences in the U.S. federal research funding portfolio has increased by about 13%, while the engineering sciences have decreased by the same. Relative funding for physical and chemical sciences has decreased, too. This has changed not only the research outcomes, but also the education contents and the overall infrastructure. One way to address this imbalance is to prepare national programs in complementary areas.
- The measures need a collective discipline and flexibility in implementation. A bio-inspired funding approach within the major NNI research areas has been adopted. The funding agencies have issued solicitations for proposals addressing relatively broad R&D themes identified by panels of experts according to the agency missions. In their proposals, researchers respond to those solicitations with specific ideas in a manner suggesting a bottom-up assembly of projects for each theme.
- The coherence among various S&E areas should be evaluated periodically in order to create conditions for convergence and synergism. Figure A.20 suggests that the major trends identified in this paper will play an increased role, beginning with the synergism of nanoscience, modern biology, information technology, and neuro-cognitive sciences, integrated from the molecular level up, with the purpose of enhancing cognitive, human body, and social performance. This coherence will create an unprecedented transformational role for innovation. Organizations will augment creative, knowledge-based activities, with larger conceptual versus physical work components.
- Macroscale measures should address the increased role of the partnerships between the government-sponsored research providers and industry.

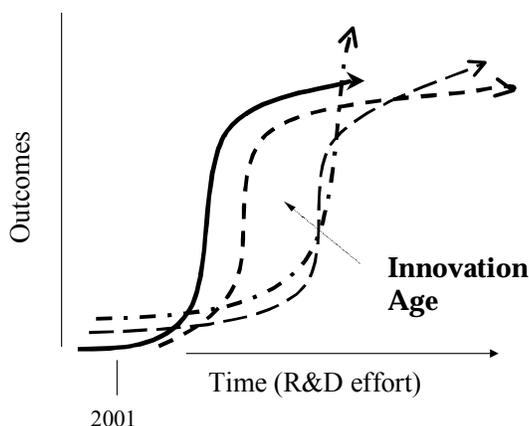


Figure A.20. The “Innovation Age.” Organizations will change the focus from repetitive to creative, innovation-based activities, and transfer efforts from machines to human development.

- The measures should encourage international collaboration based on mutual interest. The U.S. investments in the areas of nanoscience and nanotechnology represent about one-third of the global investment made by government organizations worldwide. At NSF, support is made available to investigator-initiated collaborations and through activities sponsored by the Foundation.
 - National and cultural traditions will provide the diverse support for a creative society, and their role appears to also provide the continuity and stability necessary for a prosperous society.
 - The chief aim of taking visionary and macroscale measures is to create the knowledge base and institutional infrastructure necessary to accelerate the beneficial use of the new knowledge and technology and reduce the potential for harmful consequences. To achieve this, the scientific and technology community must set broad goals; involve all participants, including the public; and creatively envision the future. The implementation plans must include measures for stimulating the convergence and beneficial interaction among the S&E megatrends, including coordinated R&D activities, joint education, and infrastructure development.
- b) **Strategic decisions taken at the level of R&D providers and users of an S&E megatrend.** The main goal of the strategy adopted by the National Nanotechnology Initiative is to fully take advantage of this new technology by coordinated and timely investment in ideas, people, and tools. A coherent approach has been developed for funding the critical areas of nanoscience and engineering, establishing a balanced and flexible infrastructure, educating and training the necessary workforce, promoting partnerships, and avoiding unnecessary duplication of efforts. Key investment strategies are
- *Focusing on fundamental research.* This strategy aims to encourage revolutionary discoveries and open a broader net of results as compared to development projects for the same resources.
 - *Maintaining a policy of inclusion and partnerships.* This applies to various disciplines, areas of relevance, research providers and users, technology and societal aspects, and international integration.
 - *Recognizing the importance of visionary, macroscale management measures.* This includes defining the vision of nanotechnology, establishing the R&D priorities and interagency

implementation plan, integrating short-term technological developments into the broader loop of long-term R&D opportunities and societal implications, using peer review for NNI, developing a suitable legal framework, and integrating some international efforts. Work done under NSTC (the White House) has allowed us to effectively address such broader issues.

- *Preparing the nanotechnology workforce.* A main challenge is to educate and train a new generation of skilled workers in the multidisciplinary perspectives necessary for rapid progress in nanotechnology. The concepts at the nanoscale (atomic, molecular, and supramolecular levels) should penetrate the education system in the next decade in a manner similar to that of microscopic approach over the last forty to fifty years.
 - *Addressing the broad goals of humanity.* Nanoscale science and engineering must be designed to lead to better understanding of nature, improved wealth, health, sustainability, and peace. This strategy has strong roots, and, it is hoped, may bring people and countries together. An integral aspect of broader goals is increasing productivity by applying innovative nanotechnology for commerce (manufacturing, computing and communications, power systems, energy).
 - *Identifying and exploiting coherence with other major S&E trends.* As part of an S&E trend, one may address a scientific and technological “grand challenge” at the national level.
- c) **Strategic decisions taken at the organizational level.** The organization level is concerned with optimum outcome in each department, agency, national laboratory, or other organization.
- d) **Strategic decisions taken at the level of the individual.** The individual level addresses issues related to education, motivation, productivity, and personal involvement.

Common Ground for the Science Community and Society at Large

- e) We envision the bond of humanity driven by an **interconnected virtual brain** of the Earth’s communities searching for intellectual comprehension and conquest of nature (Roco 1999). In the 21st century, we estimate that scientific and technological innovation will outperform for the first time the societal output of the physical activities separated by geographical borders. Knowledge and technologies will cross multiple institutional boundaries on an accelerated path before application, in a world dominated by movement of ideas, people, and resources. National and cultural diversity will be a strength for the new creative society. The interplay between information, nano-, bio- and healthcare technologies, together with cognitive sciences and cultural continuity will determine the share of progress and prosperity of national communities, no matter their size.
- f) **Researchers need the big picture of different disciplines.** The current focus on reductionism and synthesis in research will be combined with and partially overtaken by a recognition of various aspects of unity in nature and a better understanding of complexity, crossing streams in technology, crossing national and cultural borders. The ability to see complex systems at the molecular and atomic level will bring a New Renaissance. Leonardo da Vinci, equally brilliant in the art of painting and in mechanical, hydraulic, military, and civil engineering, embodied the quintessence of the original Renaissance. The laboratory investigations that began in the 17th century led researchers to separate, reductionist pathways. Today, all disciplines share a common ability to work at the molecular and nano length scales using information technology and biology concepts. The reductionist divergence of sciences and engineering of old seems to be regrouping and finding a confluence. The collective multiphenomena and multiscale behavior of systems between single atoms and bulk become the center of attention in order to extract new properties, phenomena, and function — like a new alchemy. For researchers to acquire a “big picture” approach requires depth in each discipline and good communication across disciplines.

- g) **Visionary R&D planning pays off.** It is essential to take the time to courageously look into the future. “The best way to predict the future is to create it” according to Alan Kaye of Xerox Park. Technological progress may be accelerated by a wise structuring of science and engineering that helps the main trends (or megatrends) be realized sooner and better. Why do all of this? We cite U.S. Federal Reserve Chairman Allen Greenspan (1999), who credits our nation’s “phenomenal” economic performance to technological innovation that has accelerated productivity: “Something special has happened to the American economy in recent years . . . a remarkable run of economic growth that appears to have its roots in ongoing advances in technology.”

We have seen in the last twenty years that industrial productivity has steadily increased. This is the key reason why the U.S. economy is growing, indicating the strong connection between science, engineering, and development. The productivity growth rate increased from 0.8% during the Carter administration, to 1.6% during the Reagan administration, 1.7% during the first Bush administration, and 2.1% during the Clinton administration. These increases are attributed to technological innovation. Several case studies show that investment in research at the national level also brought about 20% additional benefits in the private sector and 50% in social return.

Because there is no single or proven way of successfully developing S&E, the role of visionary R&D planning is to set priorities and provide the infrastructure for major promising projects at the national level. The coherence and synergism of various S&E trends and the rate of implementation and utilization are affected by management decisions at the macroscale. The measures must be based on good understanding of the global societal environment and long-term trends. Professors do not leave their students to do everything they like in academic research. On the contrary: if a research project goes well, more resources are guided in that direction. This idea should be held true at the national level, where there are additional advantages such as synergistic and strategic effects.

- h) **The risk of S&E developments should be evaluated in the general context of potential benefits and pitfalls in the long term.** Significant S&E developments inevitably have both desired and undesired consequences. Dramatic discoveries and innovations may create a tension between societal adoption of revolutionary new technologies in the future and our strong desire for stability and predictability in the present. Important research findings and technological developments may bring undesirable negative aspects. Bill Joy has raised such issues with the public, presenting scenarios that imply that nanoscale science and engineering may bring a new form of life, and that their confluence with biotechnology and the information revolution could even place in danger the human species.

In our opinion, raising this general issue is very important, but several of Joy’s scenarios are speculative and contain unproven assumptions (see comments from Smalley 2000) and extrapolations. However, one has to treat these concerns responsibly. For this reason we have done studies and tasked coordinating offices at the national level to track and respond to unexpected developments, including public health and legal aspects. So far, we all agree that while all possible risks should be considered, the need for economic and technological progress must be counted in the balance. We underscore that the main aim of our national research initiatives is to develop the knowledge base and to create an institutional infrastructure to bring about broader benefits for society in the long term. To this end, it is essential to involve the entire community from the start, including social scientists, to maintain a broad and balanced vision.

- i) **Contributions to the broader vision and its goals are essential** at any level of activity, including organizational and individual levels. Researchers and funding agencies need to recognize the broad societal vision and contribute to the respective goals in a useful and transforming manner, at the same time allowing the unusual (divergent) ideas to develop for future

discoveries and innovations. The funded megatrends provide temporary drivers that seem to be part of the overall dynamics of faster advancements in S&E. The vision and goals should be inclusive, and equally well understandable by top researchers, the productive sector, and society at large. In a similar manner, one needs to observe the international trends and respond accordingly. Internationalization with free movement of ideas, people, and resources makes impossible long-term advances only in one country. Cultural and national diversity is an asset for the creative, divergent developments in S&E.

In a system with R&D management structured at several levels as discussed above, the macroscale measures have major implications, even if they are relatively less recognized by an S&T community that tends to be more focused on specific outcomes at the organizational and individual levels and on distribution of the funds. The recognition system centered on individual projects in R&D universities and other research organizations may be part of the reason for the limited recognition of the role of macroscale measures.

- j) **Maintaining a balance between continuity and new beginnings (such as funding S&E megatrends) is an important factor for progress at all levels.** Coherence and convergence are driven by both intrinsic scientific development (such as work at the interfaces) and societal needs (such as the focus on healthcare and increased productivity). The divergence tendencies are driven also by both internal stimuli (such as special breakthrough in a scientific and engineering field) and external stimuli (such as political direction). We need to stimulate the convergence and allow for temporary divergences for the optimum societal outcomes, using, for example, the mechanisms of R&D funds allocation and enhancing education based on unity in nature. Such activities need to be related to the individual capabilities, where the left-brain (new beginnings) and right-brain (coherence) have analogous dual roles as the drivers of S&E trends.
- k) **The societal importance of innovation is growing**, where innovation is defined as “knowledge applied to tasks that are new and different.” In many ways, science and engineering have begun to affect our lives as essential activities because of innovation that motivates, inspires and rewards us. While the ability to work has been a defining human quality, and increasing industrial productivity was the motor of the 20th century, we see innovation as being the main new engine joining other key humanity drivers in the 21st century. The coherence and divergence of major S&E trends is an intrinsic process that ensures more rapid progress in science and technology, enhancing human performance and improving the quality of life. We envision the S&E trends converging towards an **“Innovation Age”** in the first half of the 21st century, where creativity and technological innovation will become core competencies. Current changes are at the beginning of that road. They are triggered by the inroads made in understanding the unity of nature manifested equally at the nanoscale and in broad complex systems, by reaching a critical mass of knowledge in physical and biological sciences and their interface, and by the increased ability to effectively communicate between the scientific and engineering fields.

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