

1. Information Technology: Transforming Our Society

Information technologies are an integral part of people's lives, businesses, and society. Advances in microprocessors, memories, storage, software, and communication technologies make it possible to build computers and computing devices that are increasingly affordable, as well as to enable the development of increasingly powerful systems at reasonable costs. The wide acceptance of Internet standards and technologies is helping us build global computer networks capable of connecting everything and reaching everyone.

Since ancient times, networks have offered opportunities for growth and innovation and have supplied structure to our economic and social systems. From the roads and aqueducts of the Roman Empire, to nineteenth century continental railroad systems, to the telecommunications, broadcast, and satellite networks of the twentieth century, networked capabilities have allowed us to overcome barriers of time and space, and to access and open new frontiers for human interaction and ingenuity.

The free flow of information is essential to a democratic society. Advances in information technology have the potential to significantly enhance this flow of information, and thus strengthen the institutions of our society, from financial markets to government agencies. The flow of information must, however, not only be “free,” but “fair.” Financial markets, for example, have learned that they must guard against abuses, such as insider trading. Businesses and healthcare institutions must guard against the misuse of personal information put in their trust by their customers. As we have the opportunity to use information technology to strengthen our societal institutions, we must understand the potential pitfalls, and the safeguards we must put in place to achieve both a free and fair flow of information.

As we approach the new millennium, it is clear that the “information infrastructure”—the interconnected networks of computers, devices, and software—may have a greater impact on worldwide social and economic structures than all networks that have preceded them. The advances in computing and communications technologies of the last decade have already transformed our society in many ways. These advances have transformed the ways in which we view ourselves, our relationships with each other and with other communities, and the ways in which we obtain services, ranging from entertainment and commerce to education and health care. Even so, we have only just begun to grasp the opportunities and experience the transformations that will occur as these technologies mature.

Major technical advances are needed to build a smoothly functioning information infrastructure that links together all people, institutions, and relevant devices (e.g., cars, gas meters, home thermostats, air conditioners) in our Nation and beyond. Only vigorous information technology research and development programs will enable us to achieve our objectives.

But, hard as the technical challenges might be, we must keep in mind the great socioeconomic issues ahead of us on the road to becoming a fully networked society. Thus, we complement the call for research to support the required technical advances with a call for research programs to help us understand and enhance the positive effects of information technology on our economy, society, culture and political system.

The information revolution puts a premium on basic knowledge, not just information technology literacy, but basic skills in reading, writing, communications, and teamwork. Education and training have become lifelong pursuits for our workforce, as new jobs requiring new skills are created, and older jobs and skills become obsolete. The Nation must ensure that access to the benefits of the information infrastructure are available to everyone in our Nation: to those living in small towns and rural areas as well as in big cities, to those living in poor inner city neighborhoods and tribal reservations, as well as in well-to-do suburbs and those who face daily challenges from disabilities. We should use information technology to bridge the gaps in our society, not to create new ones.

A significant portion of our national progress in computing and communications over the past decade has been leveraged from the Federal research programs established by the High Performance Computing Act of 1991 (P.L. 102-194). These programs comprised the High Performance Computing and Communications (HPCC) initiative, which was responsible for moving the U.S. into an era of teraflop computers and gigabit networks. A major focus of the HPCC initiative was a set of Grand Challenges, difficult scientific and engineering problems whose solution were advanced by applying high performance computing and communications technologies and resources. Our recommendations build upon the solid foundation of the HPCC program and expand the HPCC vision to meet the challenges facing us in the 21st century.

To ensure a rapid, smooth, and extendible transition into the 21st century, the President's Information Technology Advisory Committee has identified ten critical "National Challenge Transformations." These information technology transformations will affect how we communicate, how we store and access information, how we become healthier and receive proper medical care, how we learn, how we conduct business, how we work, how we design and build things, how we conduct research, how we sustain a livable environment, and how we manage our government in the next millennium. Exploring these dynamic transformations enables us to identify common information technology challenges critical to our Nation's future and provides a framework for our recommendations for Federal research investments.

1.1 Transforming the Way We Communicate

Vision: At least one billion people worldwide can access the Internet simultaneously and engage in real-time electronic meetings, download the daily news, conduct secure financial transactions, or talk to friends and relatives around the world. This can be done regardless of the language the participants speak, since language translation can be done instantaneously, and regardless of physical limitations of the individual, because devices can accept and provide input and output in many different ways.

The Internet lies at the heart of our communications revolution. But, the current Internet must be expanded in scale to accommodate anticipated growth in use and demands for reliability comparable to that of the modern telephone system. New and improved modes of human interaction with computers must be developed to enrich and simplify the way we communicate. We must understand the behavior of extremely large and complex systems and address the potential fragility of large numbers of autonomously interacting software systems. Global networking raises a host of international issues and even poses questions about the nature of national boundaries as information flows across them invisibly and multinational corporations use worldwide networks to pursue their global interests. Perhaps the biggest challenge of all is to understand how human beings can best take advantage of the new electronic communication possibilities, both individually and in groups.

1.2 Transforming the Way We Deal With Information

Vision: An individual can access, query, or print any book, magazine, newspaper, video, data item, or reference document in any language by simply clicking a mouse, touching a computer screen, talking to a computer, or blinking an eye. Individuals can easily select among modes of presentation: data, text, images, or audio. Information can be referenced and derivations can be incorporated in many new ways, adding value and revealing insights through networked and software-enabled tools. Entertainment can be richer and more personalized, enabling individuals to access music, videos or live events that appeal to them.

This transformation requires significant improvements in data access methods, including high performance information systems and tools to help individuals locate information and present, integrate, and transform the information in meaningful ways. Systems will require interfaces accessible both to experts and novice or infrequent users regardless of physical ability, education, or culture. Multi-modal human-computer interaction technologies are needed including speech, touch, and gesture recognition and synthesis. There are research requirements for topics ranging from network reliability and bandwidth, to scalable software support, database structure and retrieval algorithms, high-performance computing, and robust, reliable, secure ways to deliver and to protect critical information. Providing high-quality entertainment over the Internet requires considerable more bandwidth, advances in audio and video streaming, and better tools to attract good content creators. Challenging issues regarding dissemination of information in electronic form including copyright, intellectual property rights, and the development of realistic business models remain important policy and research topics.

1.3 Transforming the Way We Learn

Vision: Any individual can participate in on-line education programs regardless of geographic location, age, physical limitation, or personal schedule. Everyone can access repositories of educational materials, easily recalling past lessons, updating skills, or selecting from among different teaching methods in order to discover the most effective ways of learning. Educational programs can be customized to each individual's needs, so that the information revolution reaches everyone and personal digital libraries provide a mechanism for managing ones accumulated knowledge resources. Learning involves all our senses, to help focus each student's attention and better communicate educational material.

Information technology is already changing how we teach, learn, and conduct research, but important research challenges in the field of education remain. In addition to research to meet the scalability and reliability requirements for information infrastructure, improvements are needed in the software technologies to enable development of educational materials quickly and easily and to support their modification and maintenance. We know too little about the best ways to use computing and communications technology for effective teaching and learning, in particular, how to effectively use multimedia capabilities to create a richer, and more appealing learning experience. We need to better understand what aspects of learning can be effectively facilitated by technology and which aspects require traditional classroom interactions with the accompanying social and interactive contexts. We also need to determine the best ways to teach our citizens the powers and limitations of the new technologies and how to use these technologies effectively in their personal and professional lives.

1.4 Transforming the Practice of Health Care

Vision: Telemedicine applications are commonplace. Specialists use videoconferencing and telesensing methods to interview and even to examine patients who may be hundreds of miles away. Computer-aided surgery with Internet-based video is used to demonstrate surgical procedures to others. Powerful high-end systems provide expert advice based on sophisticated analysis of huge amounts of medical information. Patients are empowered in making decisions about their own care through new models of interaction with their physicians and ever-increasing access to biomedical information via digital medical libraries and the Internet. New communications and monitoring technologies support treatment of patients comfortably from their own homes.

Future requirements for electronic medical records and health-system intranets will lead to increased reliance on the national infrastructure for communications, data sharing, and direct provision of care at a distance. Privacy and knowledge repositories are important research topics. Research in user interfaces is needed to understand how to make telemedicine applications not only efficient, but also satisfy the more human needs of both patient and physician. Robotics and remote visualization methods, supported by high-reliability, low-latency communications, are needed to support applications such as telepresence surgery.

1.5 Transforming the Nature of Commerce

Vision: Any company can be easily reached by its customers, regardless of location. It can receive immediate customer feedback, and rapidly adjust marketing strategies, prices, or product inventories based on that feedback. Consumers can shop for the best products, services, and prices from the convenience of their hotel room, home, or office. Electronic purchases can be made securely and with total privacy, providing suppliers and retailers with immediate access to cash generated by sales and consumers with automated statements detailing spending and purchases that allow for improved personal financial management.

Electronic communication is already dramatically changing how commercial transactions between companies are conducted, how digitally based goods and services are distributed, and how retail sales are made. Companies are using information technology to get closer to their customers and suppliers. Technology is also helping to reduce paper work and purchasing costs by streamlining the acquisition process and allowing companies to more efficiently find the best suppliers. Privacy and security are critical research topics if electronic commerce is ultimately to earn the full confidence of consumers. The reliability of the communication networks, computers, and business applications are vital to the success of U.S. companies. As the marketplace becomes increasingly global, understanding electronic commerce in the context of international trade relations will also become increasingly important.

1.6 Transforming the Nature of Work

Vision: The workplace is no longer confined to a specific geographic location, as workers can easily access their tasks and colleagues from alternate locations or while en route. Workers can do their jobs without regard to physical proximity to major metropolitan areas. They can choose where they live based on nearness to family or lifestyle preference rather than job market opportunities. A highly flexible workplace is able to accommodate each individual's needs, from working parents to workers with disabilities.

By some projections, as many as 15 million U.S. workers will become telecommuters over the next decade. This should enhance productivity and organizational flexibility as well as provide environmental benefits. To support large numbers of workers in non-traditional office settings, including the rapidly growing number of home businesses, we will need high-speed networking capability, equally available to many workers regardless of location or disability. Software technologies that allow work teams to collaborate effectively will be needed, and the privacy and reliability of the information infrastructure that permits this collaboration will be critical to success. The social and economic implications of telecommuting need to be studied. Computing and communications are also dramatically altering the skill base that workers need to perform their jobs. We need to determine how both employers, employees, and the self-employed can respond effectively to these changes.

1.7 Transforming How We Design and Build Things

Vision: Products and structures, from the highly complex, such as automobiles and buildings, to those used in everyday life, such as consumer appliances and fashion, can be designed with computer simulations that accurately represent the physical properties of the systems being built. Designers, manufacturers/builders, suppliers, and end-users participate in the design process, providing one another immediate feedback. Multiple designs and manufacturing processes can be rapidly explored yielding safer products, higher quality, and lower costs.

Global competition continues to press United States manufacturers to attract new customers and retain current customers by increasing productivity, reducing cost, improving quality, maintaining

maximum flexibility, and reducing design cycle time. Information technology has revolutionized the entire product development design cycle and will continue to do so. High-end computing technologies are needed for concept design, simulation, analysis with interactive control and computation steering, the mining of archived data, and the rendering of data for display and analysis. There is a critical need to link engineering development processes with business processes like planning, purchasing, scheduling, investment, and cost management. There is also a need for networked computers that allow simultaneous modification of a standard product to meet customers' needs. As computer prices continue to decrease, these design, engineering and manufacturing capabilities can be applied to many more products.

1.8 Transforming How We Conduct Research

Vision: Research is conducted in virtual laboratories in which scientists and engineers can routinely perform their work without regard to physical location—interacting with colleagues, accessing instrumentation, sharing data and computational resources, and accessing information in digital libraries. All scientific and technical journals are available on-line, allowing readers to download equations and databases and manipulate variables to interactively explore the published research.

High-speed computers and networks are enabling scientific discovery across a broad spectrum—from mapping the human brain to modeling climatic change. Research problems are becoming more complex and interdisciplinary in nature. As a result, researchers are finding innovative ways to collaborate with their colleagues across the globe. Key research technologies include high-end computing to allow higher fidelity models of complex physical phenomena, advances in collaborative environments, visualization of complex datasets, data mining techniques and management of very large datasets and databases.

1.9 Transforming Our Understanding of the Environment

Vision: Information technology can help us to improve a variety of problems from water and air quality to controlling the effects of toxic material. For example, reliable climate models permit us to determine the rate and regional distribution of climate change to support accurate projections by sector and region. Sophisticated models accurately predict the response of ecosystems to changes in temperature, water availability, and atmospheric composition. Fully integrated models allow scientists and policy makers to consider information on climate trends, population trends, resource utilization, and the value of natural and economic resources when making decisions regarding technically feasible and cost-effective options to reduce environmental impacts or adapt to climate change.

To better support national and international energy and environmental policy, the United States requires an unprecedented acceleration and extension of research into climate modeling in order to improve the accuracy of local and regional forecasting. Progress in this area depends on improvements in computational methods. This will require orders of magnitude increases in computing capability to deal with the immense size of these problems in both time and space. We also need

other advanced information technologies such as improved numerical methods and algorithms, tools for data storage, management, analysis and visualization, software development and testing techniques, and advanced networks for distributed computing.

1.10 Transforming Government

Vision: Government services and information are easily accessible to citizens, regardless of their physical location, level of computer literacy, or physical capacity. Intelligent systems guide citizens by providing a one-stop shopping experience for locating requested information. Documents and forms can be accessed, completed, and submitted electronically. Automated business processes allow nearly instantaneous response to citizens' requests. In times of natural emergencies, emergency crews have instant access to three-dimensional building models, risk analysis and assessment, high-resolution local weather predictions, stress analyses of damaged structures, rapid evacuation planning tools, and emergency agency coordination.

There is a huge potential to make all government institutions both more efficient and more responsive through information technologies. Technical challenges include significant improvements in systems and methods for accessing data, including high performance data storage and tools to locate and present information. Robust, reliable, and secure networks and software to deliver and protect critical information are important research topics. It is imperative that improvements in government be available to all citizens, so we must understand and surmount barriers to access.

Transforming the Way We...	Challenges	Benefits
1. Communicate	<ul style="list-style-type: none"> • Scaling for growth and reliability a la the telephone system. • Improving human interaction with computers. • Fragility of systems. • Global networking issues. • Finding best use of new communication possibilities, 1-on-1 and in groups. 	<ul style="list-style-type: none"> • One billion users can access the Internet simultaneously, regardless of language and physical limitations.
2. Deal with Information	<ul style="list-style-type: none"> • Improving data access methods. • Multi-modal human-computer interaction technologies. • Reliability and bandwidth, better audio and video streaming. • Scalable software support. • High-performance computing. • Delivering and protecting critical information. • Policy for electronic dissemination of information. 	<ul style="list-style-type: none"> • Everyone can access, query, and print any book, magazine, newspaper, video, data item, or reference document, regardless of language, using mouse, touch screen, speech, or eye blink. • Value is added to information through networked and software-enabled tools.
3. Learn	<ul style="list-style-type: none"> • Scalability and reliability of the information infrastructure. • Improving software technologies for development of education materials and support of their modifications and maintenance. • Determining the best use of computing and communication technology for effective teaching and learning. • Learning which traditional teaching methods to leave alone. • Learning how to teach citizens best use of these new technologies. 	<ul style="list-style-type: none"> • Regardless of location, age, handicaps, or schedule, anyone can participate in on-line education programs. • Everyone can access educational materials to discover the best learning style for them. • Customized educational programs exist for everyone, so no one is left behind.
4. Conduct Commerce	<ul style="list-style-type: none"> • Having sufficient privacy and security to ensure consumer confidence. • Reliability of communication networks, computers, and business applications needs to be high. 	<ul style="list-style-type: none"> • Customers can reach any company regardless of location. • Immediate feedback facilitates fast adjustment of marketing strategies and inventories. • Consumers shop at their convenience. • Companies can immediately access funds from sales. • Consumers have automated statements permitting improved financial management.

Transforming the Way We...	Challenges	Benefits
5. Work	<ul style="list-style-type: none"> • Developing high-speed networking for all, regardless of location or handicap. • Developing software to allow effective collaboration. • Ensuring privacy and reliability of the information infrastructure. • Determining how employers, employees, and the self-employed can respond to changes. 	<ul style="list-style-type: none"> • Workers have access to jobs regardless of proximity to population centers. • Workers can live where they want, not needing to be near jobs. • Workplace can better accommodate individual needs.
6. Practice Health Care	<ul style="list-style-type: none"> • Ensuring privacy of information repositories. • Developing robotics and remote visualization methods to support applications such as telepresent surgery. 	<ul style="list-style-type: none"> • Doctors use teleconferencing and telesensing to interview and examine patients. • Surgical procedures can be demonstrated with Internet-based video. • High-end systems provide expert advice. • Patients access biomedical information, gaining empowerment to make decisions.
7. Design and Build Things	<ul style="list-style-type: none"> • High-end computing technologies are needed for concept design, simulation, analysis with interactive control and computation steering, mining archived data, and rendering of data. • Need bi-directional engineering development processes linked with business processes. 	<ul style="list-style-type: none"> • Complex designs done via computer simulations. • All parties, including end users, participate in the process. • Safer products, higher quality, lower costs.
8. Conduct Research	<ul style="list-style-type: none"> • Research problems have become more complex and interdisciplinary. • Researchers need to find innovative ways to collaborate. 	<ul style="list-style-type: none"> • Research is conducted in virtual laboratories, interacting, accessing instrumentation, and sharing data and other resources, all regardless of physical location. • All journals are available on-line.
9. Deal with the Environment	<ul style="list-style-type: none"> • To accelerate and extend climate modeling research to improve forecasting. • Increasing computing capability by orders of magnitude. • Develop improved numerical methods and algorithms, tools for data storage, management, analysis and visualization, software development and testing, and advanced networks for distributed computing. 	<ul style="list-style-type: none"> • Reliable climate models. • Ecosystem models accurately predict responses to changes in conditions. • Fully integrated models facilitate decision making by scientists and policy makers.
10. Conduct Government	<ul style="list-style-type: none"> • Develop significant improvements in data access: high performance file systems and tools. • Develop reliable, secure networks and software to deliver and protect critical data. 	<ul style="list-style-type: none"> • Government services and information are available to all regardless of location, computer literacy, etc. • One-stop shopping for locating information. • Automated business processes accelerate responsiveness. • Enhanced responsiveness to natural disasters.