Cover Note

This document was developed and used as an internal, working guide for Federal NITRD program participants. As a working guide, the document does not represent official Administration policy. This text is being released now (July, 2008) to provide background information for those interested in contributing to the development of a new, NITRD program strategic plan. It should be used for historical and informational purposes and should not be considered a model for a new strategic plan.

National Coordination Office

# INFORMATION TECHNOLOGY RESEARCH AND DEVELOPMENT (IT R&D) PROGRAMS

# FIVE-YEAR STRATEGIC PLAN FOR FY 2002-FY 2006

## Part I: Overview

Today, at the beginning of a new century and a new millennium, information technology (IT) is transforming our world, generating unprecedented U.S. prosperity and building revolutionary new infrastructures for commerce, communication, human development, and national security. In this remarkable period of transformation, the United States stands preeminent as the world's information technology pioneer, its research leader, and its foremost developer and deployer of cutting-edge computing, high-speed telecommunications, and IT systems.

"When historians look back a decade or so hence," Federal Reserve Board Chairman Alan Greenspan said in a March 6, 2000, address on the New Economy, "I suspect they will conclude we are now living through a pivotal period in American economic history. ... It is the growing use of information technology throughout the economy that makes the current period unique."

The New Economy arose from the Nation's immense industrial and entrepreneurial enterprise. But it was Federal investment in fundamental, long-term IT research and development (R&D) that launched the digital revolution, and that investment continues to play a critical role in generating the technological breakthroughs the country needs to meet vital national objectives and achieve the full promise of information technology in such public benefits as:

- Immediate on-site medical care, in the home and at remote locations
- Reliable, failure-resistant systems for such mission-critical applications as air-traffic control, defense, financial transactions, life support, and power supply
- Reduction of battlefield risk for military personnel

- Industrial process and product modeling, visualization, and analytical capabilities, such as in aircraft design and production, automotive efficiency and safety, and molecular synthesis of new drugs
- Expanded e-commerce with assured security and privacy of information
- On-demand universal access to education and knowledge resources
- Advanced computing capabilities that underpin the Nation's leadership in science and technology and the success of critical civilian and national security missions of the Federal government
- More accurate weather forecasting and improved environmental analysis
- High performance networking and information systems for emergency and disaster management
- Access to information anytime, anywhere, with any device

As the President's Information Technology Advisory Committee (PITAC) noted in its 1999 report on the status of U.S. information technology research, bipartisan support of Federal investment in fundamental IT R&D over the last several decades has produced "spectacular" returns for the economy and for society generally. But the Committee, made up of prominent IT industry leaders and university researchers, warned that Federal funding for IT R&D is now seriously inadequate, far outpaced by the explosive growth in societal needs for advanced IT capabilities. Measured in constant dollars, the Committee found, Federal research investment in critical IT areas – such as networking, software, and high performance computing – had been flat to declining for a decade, at the same time that IT-related business activity had grown to represent virtually a third of GDP growth. The PITAC concluded that the existing level of Federal IT R&D investment represented a significant strategic threat to the Nation's economic future.

The U.S. House of Representatives reached a similar conclusion in its findings on the Networking and Information Technology Research and Development Act (H.R. 2086) passed in 2000, saying: "Current Federal programs and support for fundamental research in information technology are inadequate if we are to maintain the Nation's global leadership in information technology."

There is also a growing nationwide need for trained IT scientists, engineers, educators, and technical workers. "Fundamental research in information technology has contributed to the creation of new industries and new, high-paying jobs," argued the House bill. "Scientific and engineering research and the availability of a skilled workforce are critical to continued economic growth driven by information technology."

The national stakes for the U.S. are high. In the past, the benefits of any single area of scientific research might be limited in scope – enabling, for example, development of one weapon or treatment for one disease. But information technology is by its nature pervasive, providing systems, tools, and capabilities that daily touch hundreds of millions of citizens. A balanced, diversified Federal IT R&D portfolio not only advances vital Federal missions but helps the Government support overarching public goals in education, environmental protection, health care, law enforcement, productivity, transportation safety, and many other dimensions of our national life.

The National Academy of Sciences, in a recent study of the Nation's IT research needs, noted that amid the deluge of new IT devices, "the critical role of the first half of the R&D process is overlooked: the research that uncovers underlying principles, fundamental knowledge, and key concepts that fuel development of numerous products, processes, and services." The Council concluded: "The Federal government should boost funding levels for fundamental IT research, commensurate with the growing scope of research challenges."

Corporate IT leaders strongly support a significant expansion of the Federal IT R&D enterprise on the ground that such fundamental, long-term work is critical to the national interest but will not be carried out by industry. Citing contemporary pressures on industry to focus on short-term product-related research, they argue that Federal IT R&D fills a gaping void in the Nation's IT research portfolio, complementing private-sector efforts with a focus on pre-competitive, long-term studies in such critical IT areas as advanced scientific computing, large-scale high-speed networks, and fundamental enabling information technologies. These areas, not addressed by industry, support essential government functions and effectively drive overall national innovation.

This Strategic Plan represents the collaborative research framework of the 12 Federal agencies whose critical missions require advanced IT R&D. These agencies participate in the Federal government's interagency Information Technology Research and Development Programs – successor to the High Performance Computing and Communications Program established by Congress in 1991. The Federal IT R&D agencies have established a 10-year record of highly successful collaborative accomplishments in multiagency projects and in partnerships with industry and academic researchers. The multiagency approach leverages the expertise and perspectives of scientists and technology users from many agencies who are working on a broad range of IT research questions across the spectrum of human uses of information technology.

Pursuing the Strategic Plan will enable the Federal IT R&D agencies to address the most significant scientific and technical challenges standing between today's networking and computing capabilities and the affordable advanced technologies and tools that both the Federal government and the Nation need. As Chairman Greenspan contended in his speech on IT, "We should ... persevere in policies that enlarge the scope for competition and innovation and thereby foster greater opportunities for everyone."

Key national IT research priorities proposed under this Strategic Plan are summarized in the table on the following page. The sections that follow describe the imperatives for Federal leadership in fundamental IT R&D; the technical elements of the Strategic Plan's five-year research agenda; examples of cutting-edge National Grand Challenge Applications that the IT R&D agencies propose to pilot, test, and/or demonstrate as part of the Strategic Plan; and the structure of the multiagency IT R&D Programs' coordinated administration and management.

# Research Priorities in Federal IT R&D Programs' Five-Year Strategic Plan

| Research Area | Research Goals | Technical Agenda |
|---|---|---|
| **Compact, teraops-scale supercomputing systems** | • Platforms capable of a trillion or more operations per second – with large global memory bandwidth, high-speed interconnects/switching, low latency<br>• Long-range scalability to petaflops computational speeds and 1,000 petabyte level storage | • Systems software and tools for terascale and beyond-terascale platforms<br>• Systems architectures, including configuration, new device and storage technologies, software for managing highly parallel computations, and hierarchical programming environments<br>• Advanced nonclassical computing concepts |
| **New processor technologies** | • Increase processor speeds to 1,000 or more times current levels<br>• Quantum and DNA computers for embedded systems, rapid design of target and therapeutics for pathogen combatants | • Innovative computational structures, 3-D architectures, hybrid technologies<br>• Computation at the molecular scale, microprocessor fabrics, quantum structures, biological substrate computing |
| **Reliable, universally accessible high-speed networks** | • Networks 1,000 or more times as fast as today's Internet<br>• Secure transmission, with guaranteed quality of service, of HDTV, sound, and terabytes of data<br>• Ubiquitous access from wireless, embedded, and wired devices<br>• New classes of applications<br>• Testbeds and supporting infrastructure | • Fundamental network research (optical and wireless networks, resource and network management, increased bandwidth requirements)<br>• Technologies for scalability and ubiquitous access<br>• Technologies for distributed data-intensive computing, collaboration, and computational steering, distance visualization and instrumentation, workflow management, management of large-scale distributed systems |
| **High-confidence software and systems** | • Fail-safe, secure, and reliable software and systems for mission-critical applications<br>• Technologies and tools for rigorous testing, validation, and certification | • Theoretical, scientific, and technological principles for high-confidence design<br>• Encryption, secure transmission, user I.D. systems<br>• Formal methods for specification and validation<br>• Technologies and tools to reduce the time and cost of assuring quality and security |
| **New paradigms for software design** | • Software governed by scientific and engineering principles<br>• Autonomous, self-programming software for embedded systems | • Computer languages, compilers<br>• Interoperability of applications<br>• Tools for integrated software and system design<br>• Reusable middleware for embedded systems<br>• Automation of software development<br>• Empirical testing of models and methods |
| **Large-scale information systems and data sets** | • Next-generation technologies for management and use of massive data sets and information archives<br>• Interoperability, accessibility, usability of data sets and data management systems | • Tools for collection, synthesis, curation, indexing, mapping, provisioning, and fusion<br>• Protocols for data compatibility, conversion, interoperability, interpretation<br>• Methods of preservation, archiving<br>• Interoperable interfaces, metadata systems<br>• Ultra-scale storage, management, and data-mining technologies |
| **Human-computer interaction** | • Improved integration of humans and computers in complex task environments<br>• Augmented human capabilities<br>• Universal accessibility to digital systems | • Technologies for language translation, speech-based interfaces, content extraction, multimodal systems<br>• Intelligent systems, such as "smart spaces," for ubiquitous computing with multiple interactions<br>• Universal designs integrating device-independence, usability, and accessibility considerations<br>• Ultra-rapid machine translation, prosodic processing, auditory modeling |
| **Social, economic, and workforce implications of IT** | • New knowledge about the co-evolution of IT and society, economic systems, education, the workforce, and workforce development<br>• Innovative applications of IT in education and training<br>• Infrastructure for SEW research | • Social and technical systems<br>• Internet governance and "citizenship"<br>• Intellectual property and information privacy<br>• Collaboration and learning<br>• Workforce development<br>• Universal participation |

## Part II: Why we need IT research

### The promise of information technology

No longer just a provider of tools for the sciences and engineering, information technology today is the uniquely interdisciplinary field at the very core of American innovation in every sector.

IT begins with fundamental research in the sciences and in engineering and stretches across the applied scientific and engineering knowledge it takes to design, construct, and maintain computing and telecommunications equipment. IT encompasses the mathematics and computer science expertise that goes into writing the complex sets of instructions – the software – that enable digital devices to do what people want them to do. IT also engages the thinking and imagination of scholars, students, government and business officials, and ordinary computer users in virtually every field who help figure out how to harness computing and communications capabilities to human needs, interests, and aspirations. All these scientific and technical skills and knowledge bases working together produce the complex digital systems that we have quickly come to rely on in our day-to-day lives.

Whether we are aware of it or not, we are surrounded by the results of this multidisciplinary R&D activity, in such applications as precision instrumentation and visualization capabilities for medical diagnosis and treatment; inventory-management systems for agile, just-in-time manufacturing; the Mars rover and astronomical images from the far reaches of the universe; monitoring and management of large-scale financial systems; standardized transmission protocols for electronic mail and audio, video, and sound files; international air-traffic communication and control systems; and weather forecasts based on collection and analysis of data from real-time observations of wind, water, and other environmental systems.

IT's rich mix of basic and applied science was showcased in October 2000, when Nobel Prizes in physics and chemistry were awarded for the first time in the program's history to six researchers, including four Americans, whose discoveries – the integrated circuit, the hetero semiconductor structure, and conductivity in plastics – involved information technology. The prizes also highlighted a key underpinning of U.S. scientific achievements that is not well understood. Three of the four American prizewinners are university-based scholars who received early and continuing research support from the Federal government.

### The Federal role in the IT revolution

The Nation's computer and telecommunications industry leaders are the first to acknowledge that Federal investments in fundamental IT R&D produced both the knowledge base and the technical workforce that are powering the New Economy and U.S. leadership in advanced computing and networking. As the corporate leaders on the President's Information Technology Advisory Committee (PITAC) put it in the Committee's 1999 report:

> "Federal funding has seeded high-risk IT research and yielded an impressive list of billion-dollar industries. Federally funded university research has trained most of our leading IT researchers. Information technology industries provide hundreds of thousands of jobs and much of the Nation's recent economic growth. The Federal investment to date has had tremendous benefits for our government, our Nation, and our economy."

Following is a sampling of the Federally sponsored IT R&D that has fueled the Information Age and dynamic business opportunities throughout the private sector:

- **The first operational, electronic stored-program computer (SEAC)** was developed for the U.S. Air Force by the predecessor of NIST; a similar machine, SWAC, built by the agency the same year for the U.S. Navy, was the fastest in the world at the time.
- **The Internet** grew out of ARPANET, the network invented by DARPA-funded researchers in the 1960's.

- **The first graphical Web "browser"** was developed by university-based researchers supported by NSF**;** Web search engines grew out of initial research investments by DARPA and NSF.
- **Java,** the programming language that supports interoperability across networks, is based on concepts first explored by Federally funded researchers.
- **The mouse and the graphical user interface (GUI),** now standard to desktop computers, stem from DARPA-funded research in the late 1960's.
- **High-speed optical networks**. The Federal government's Next Generation Internet (NGI) Initiative has produced the world's first prototype optical networks with end-to-end transmission speeds and carrying capacity a thousand times those of the current Internet. With $276 million in funding over three years, this program has stimulated development of new private-sector companies with a combined value of more than $50 billion – a near-2,000 percent return on the Federal investment.
- **The world's first and largest public medical database,** integrating research findings and medical-journal citations, was developed and is managed by NIH's National Library of Medicine.
- **Speech and spoken dialogue technologies** funded over decades by DARPA have led to new customer call center concepts and more efficient service for industry worldwide.
- **Parallel computing** concepts explored by Federally supported researchers for two decades laid the groundwork for the development of commercial high-end computing platforms in the late 1980's and 1990's.
- **Relational databases** – the industrial-strength software systems needed to store and manage large quantities of information, such as financial records, census data, and business inventories – were pioneered by university researchers funded by NSF in the 1970's.
- **Reduced instruction set computing (RISC) technology**, the basis for many of today's fastest microprocessors, was advanced by DARPA-funded research in the 1970's and early 1980's.
- **Machine learning research,** sponsored by DOE and NSF, was employed in decoding the human genome and also spawned the data-mining industry.
- **Numerical linear algebra libraries research sponsored by DOE, DARPA, and a number of other Federal agencies has produced high performance libraries of numerical linear algebra software that are used by thousands of researchers worldwide. These libraries have become a critical part of the world's scientific computing infrastructure.**

### Why Federal investment is key

*Federal IT R&D supports critical agency missions and national needs*

All of the projects cited above were funded in support of critical Federal missions, including national defense and national security, critical infrastructure protection, energy systems, aerospace engineering, weather and climate forecasting, and advanced biomedical and other scientific research. National defense and national security needs alone require advanced IT research efforts on a continuing basis to equip the military with cutting-edge weapons technologies and secure communications systems and to accurately model and design these advanced systems. Federal research responds to a basic reality of the interdisciplinary IT field: What can be accomplished using IT is determined by the weakest or the slowest technology, not by the strongest or the fastest. For that reason, Federal IT R&D pursues a balanced, diversified portfolio of research interests, reflecting the wide range of enabling technologies required for agency missions.

*The talent "pipeline" we need to continue making technological advances is in jeopardy*

The irony of the Nation's remarkable IT growth is that the commoditization of technologies in widely available, low-cost products has had a perverse effect on the fundamental-research engine of innovation, hollowing out its substance and thinning the ranks of the basic researchers. The flight of IT researchers into more lucrative jobs in industry – an acute and worsening problem today in both universities and the Federal government – combined with the private sector focus on product development, results in a strategic threat to the Nation's continuing leadership in advanced computing and communications. Judith Estrin, CEO of Packet Design and former CTO of Cisco Systems, Inc., made this point in a recent address, saying: "As a result, there is an architectural vacuum. Who will do the longer-term thinking for our industry?"

The Federal government plays a special role in our society as the primary supporter of research in many fields that generate innovations critical to the national interest and that expand the pool of highly trained scientists, engineers, and technicians needed to work on national challenges. A high-priority Federal IT research program will provide the opportunity to reverse the "brain drain," reinvigorating and repopulating the IT research community with fresh generations of talented people working on the most profound and challenging science and engineering problems of our era.

*Federal IT R&D produces broadly useful technologies and tools that spur innovation across the U.S. economy*

The coordination of Federal IT R&D investments across many agencies and private-sector partnerships leverages mission-related research, producing general-purpose, broadly useful, and interoperable technologies, tools, and applications. Federal IT R&D has thus been a powerful engine of technology transfer, the direct result of its focus on widely applicable solutions to basic IT problems and its mechanisms of funding R&D in universities, research institutes, and corporations. The large number of Federally funded breakthroughs subsequently commercialized in the private sector – often by graduates of U.S. research universities whose education was funded through the IT R&D Programs – leverage the Federal investments even further.

*No other sector does this fundamental scientific discovery work*

Many people incorrectly assume that the most significant IT R&D comes from private industry and that such research is best handled there. While it is true that total private IT R&D spending exceeds that of the Government, the lion's share of private-sector research is actually product-related development. In fact, private sector leaders are among the most ardent champions of Federal investment in long-term, fundamental IT research – precisely because the U.S. government is the only real source of support for that kind of work. IT executives emphasize that today's economic pressures – including international competition, stock market fluctuations, and short product lifecycles – push industry to concentrate resources on short-term, product-focused research rather than high-risk investigations with uncertain payoffs. Companies simply will not take on the responsibility for mid- and long-term fundamental research, particularly when the results are unlikely to produce an immediate proprietary economic benefit to their bottom line but rather one that accrues only to whole (sometimes new) industries.

Yet it is fundamental research that has driven the digital revolution. The Federally funded projects cited above explored core technical problems in IT that had to be solved to advance the capabilities of computers, networks, and information systems generally. These projects were not designed to result in commercial products within six months. They achieved results over years of experimentation and revisions that spread across the research community, enabling many scientists to join in the problem-solving. It is this ongoing foundational research process that has generated scientific, technical, and engineering breakthroughs that benefit us all.

*Venture capitalists do not finance fundamental research*

Some think IT R&D should be funded by private venture capital investment, which reportedly has risen over the last 10 years from $5 billion to $100 billion annually. But as the corporate representatives on the PITAC noted, venture capital flows only *after* "ideas freely flow from universities and national labs to existing and new companies." The leaders added, "The basic feedstock for these investments has been Government support of basic IT research. … If this feedstock is allowed to deplete, the economic growth engine could slow or disappear." David Morgenthaler, former president of the National Venture Capital Association, underscores the significance of this problem, noting that venture capitalists rarely invest to develop enabling technologies – all those bits and pieces of science and engineering that make the hardware and software innards of IT systems but do not stand to make a fortune by themselves. In addition, venture capital investments are usually made with the expectation of recovering the investment and profit within three years, not the longer timescale of high-risk R&D.

*Private-sector R&D bypasses the research most significant to Federal and national needs*

Private-sector investment strategies therefore bypass key technology areas that are the most critical to Federal government missions and that help support the continuing superiority of the U.S. IT industry. These areas include high-end computing, mass storage, optical networking, interoperable systems and applications, security, privacy, new generations of embedded and large scale systems, improved processes for developing new software, and effective human uses of IT. In fundamental IT R&D, the research time horizons are much longer and there is no guarantee of the success of any one research path.

**The value of the coordinated multiagency approach**

The breadth and diversity of Federal missions and activities uniquely equip the Government to lead the high-profile effort proposed in this Strategic Plan to assure U.S. IT leadership and economic competitiveness in the new century. The active interplay among computer science, engineering, mathematics, physical and biological sciences, social sciences, and technology users that IT research requires is rare in the private research community but a characteristic strength in Federal IT R&D activities. The Government's multiagency approach to IT R&D leverages the expertise and perspectives of scientists, engineers, and technology users from many agencies who are working on a broad range of IT research questions across the spectrum of human uses of information technology. Moreover, the research enterprise proceeds through multidisciplinary collaborations among university, government, and private-sector researchers, creating dynamic interactions among parties working on IT problems. Industry leaders concur with research scientists that this is an unparalleled resource for fundamental IT R&D.

The multiagency Federal effort proposed in the Strategic Plan will be coordinated by the Interagency Working Group on IT R&D, which is composed of representatives of the participating IT R&D agencies: AHRQ, DARPA, DOE/NNSA (National Nuclear Security Agency), DOE Office of Science, EPA, NASA, NIH, NIST, NOAA, NSA, NSF, and ODUSD/URI.

## Part III: What Federal IT R&D can accomplish

In the following sections on their strategic agenda, the IT R&D agencies describe the highest-priority IT research and development issues that must be addressed now to meet pressing government and national needs.

### *1. Developing the next generations of computing and data storage technologies*

Critical Federal missions and industry needs both call for new scientific and technical paradigms that significantly raise high-end computational speeds, provide adaptable and reconfigurable computing environments, and reduce the size, cost, and power requirements of high performance computing and data storage equipment. For example, the world's fastest computing platform today is DOE's "Option White" system at the Lawrence Livermore National Laboratory. A massively parallel system made up of 512 IBM multiprocessor nodes, it requires 13,000 square feet of floor space and more than 3.2 megawatts of electricity for power, cooling, and mechanical equipment. Option White is capable of 12.3 teraops (trillions of operations per second) in processing speed. But even such a system is not adequate for the massive computational requirements of the most complex scientific problems.

At the same time, the Nation's high-end computing sector – the companies that produce computing platforms that are much faster than the standard desktop computer – is a shrinking fraction of the U.S. marketplace. Business purchasers of high-end machines prefer less costly and physically demanding mid-range machines. As a result, the technical challenges of developing technologies that break through today's upper-end barriers in computing speed, storage capacity, and equipment are left orphaned.

Currently, the Government supports several dozen high-end computing platforms at academic computing centers and national laboratories, along with a number of mid-range machines, that are used by both academic and Federal researchers. But these are not nearly enough to support the high-end research and applications needs of university-based or government scientists. Nor do they offer a viable model for scalability to the processing speeds and storage capacity that future advanced applications will demand. Today's Option White platform, for example, has 160 terabytes of storage space spread over 7,000 disk drives. This amount of storage space represents about six times the contents of the entire Library of Congress, but it is only a small fraction of the scientific data that future research will call for.

Finding cost-effective solutions will require computational science research in disciplines such as physics, chemistry, materials science, and electrical engineering, as well as innovations in computer science and applied mathematics. Next-generation supercomputing architectures, systems software, and middleware must also address interoperability needs of Federal agencies. These technological breakthroughs will also aid U.S. competitiveness.

Under this Strategic Plan, the IT R&D Programs will sponsor research to increase the delivered performance of computing systems by 1,000 times the speeds of today's fastest systems, while reducing cost, energy consumption, and footprint, and to develop interoperable systems software and tools that will:

- Improve sustained application performance, ease of use, manageability, and high-speed network connectivity of teraops-scale systems
- Be scalable (expandable) to petaops-scale systems (petaops systems perform a thousand trillion calculations per second)
- Provide a unifying environment for high end scientific computing

**<u>Technical research agenda: Next-generation computing and data storage</u>**

- Systems software technologies (including operating systems, programming languages, compilers, memory hierarchies, I/O, and performance tools)
- Systems architectures that integrate device and component technology, systems software, and programming environments (including configuration, hardware, node functionalities, device technologies, software for managing highly parallel computations, and hierarchical programming), and network connectivity
- Effective software component technologies for high performance computing
- Advanced computing concepts (including nonconventional architectures, components, and algorithms)

### *2. Surmounting the silicon CMOS barrier*

The complementary metal oxide semiconductor (CMOS) chip, the two-dimensional miniature electronic map on a silicon wafer that is the standard building block of computing systems, is fast approaching its physical limits. That is, the electronic signals that can be routed through its pathways are finite in quantity and speed. Even the complex technical amassing of chips that produced Option White demonstrates these limitations in the machine's enormous size and power requirements. The IT R&D agencies propose to find new materials and methods to create wholly new designs for processors in computing devices. Both Federal missions and private-sector IT innovation require mid-term incremental improvements in computational speeds and long-term breakthroughs to radically new processor architectures capable of teraops and petaops speeds.

This Strategic Plan will fund research at the theoretical and empirical intersection of biology, information science, and micromechanics [Bio:Info:Micro]. Advances in photonics, micro-electromechanical systems (MEMS), sensors, actuators, opto-electronics, digital, analog, and mixed signal processing, and new fabrication technologies make it possible, for example, to conceive of integrated designs in 3-D on a chip with billions of transistors. This work will focus on design of new, modular hybrid architectures that include fault-tolerance, programmability (including novel approaches such as amorphous computing methods), and security features needed in embedded systems for defense.

A related research area is biological substrate computing, the potential in organic molecules – such as DNA, RNA, and proteins – to provide vast storage and processing capacities. For example, one gram of DNA contains $10^{21}$ DNA bases, which is equal to $10^{8}$ terabytes of information storage. Breakthroughs in this area could result in:

- High-volume, content-addressable storage
- Solutions to computationally hard problems that now are not solvable
- Self-assembly of nanostructures using DNA/RNA tiling. The nanostructures in turn could be used for nanoscience such as molectronics (described below)

This Strategic Plan will also support long-range research in quantum physics to explore the potential of atomic matter – such as quanta of light or molecular nuclei – to serve as high-speed processing mechanisms. This area holds great promise as a future means of providing:

- Ultrasecure communications over optical backbone networks
- Orders of magnitude increases in the speed of algorithms such as for searching unsorted databases or factoring large numbers
- Quantum computers that can give detailed and faithful simulations of molecular processes and phenomena in physics

**Technical research agenda: Surmounting the CMOS barrier**

- Innovative computational structures, 3-D architectures, hybrid technologies
- Reconfigurable systems on a chip, adaptive and polymorphous computing
- Processor in memory (PIM) and other efforts to provide memory performance commensurate with processor performance
- New computational substrates
  - Quantum computing
  - Biological substrate computing
  - "Smart fabric." Using technology for interweaving battery, fiberoptic cable, and metal connectors, scientists can produce fabric that can be embossed with enough processors to provide on-person processing on the order of tens of teraops (the size of today's larger supercomputers)
  - Molectronics: Computation at the molecular scale, which holds the potential of providing extremely fast, high-density processing power for the next generation of strategic computing for the military

### *3. Building versatile, scalable, secure networks for the 21st century*

The Internet is at the heart of the IT revolution, and Federally sponsored networking research plays a pivotal role in generating the technological advances critical to the Net's growth and evolution. Though the focus of Federal work is exploration of technologies and tools to support critical agency missions, the Federal research emphases on long-range needs – such as scalability, level and quality of service, reliability, security, interoperability, and flexible access – not surprisingly turn out to be the core research problems that must be solved to transition the Internet into a secure, reliable, expandable, very-high-speed communications system for the Nation in the new century.

The U.S. urgently needs a new generation of basic enabling technologies to "modernize" the Internet for rapidly growing traffic volumes, expanded e-commerce, and the advanced networked applications that will be possible only when next-generation networks are widely available. The Strategic Plan therefore proposes an ambitious research program to press ahead immediately to:

- Understand how to extend the network infrastructure so that it is available anytime and anywhere, and so that it includes ubiquitous networking that extends the network to millions and potentially billions of new devices and chips embedded in larger devices such as appliances, automobiles, and other elements of our transportation system
- Provide needed network services, such as management, reliability, security, and high-speed transmission rates

**Technical research agenda: Building versatile, scalable, secure networks**

- Fundamental network research
  - - Optical networking (flow, burst, and packet switching; access technology; gigabit per second interfaces; simplified protocol layering)
  - - Network dynamics and simulation (automated management, automated resource recovery, network modeling)
  - - Fault tolerance and autonomous management
  - - Resource management (discovery and brokering, advance reservation, co-scheduling, policy-driven allocation mechanisms)
  - - Wireless technologies (technical standards for discovery, co-existence, configuration)
  - - Assuring an increasing capability to support bandwidth requirements
  - - Enhancing and scaling networks to improve robustness and handling of transient interactions among billions of devices
  - - Enhancing and scaling networks (maximizing access from the "edges of the network" such as methods for ubiquitous broadband access, tether-free networking, network security and privacy, network management)
  - - Understanding global-scale networks and information infrastructure (end-to-end performance, backbone structures, applications)
- Enabling new classes of applications (distributed data-intensive computing; collaboration; computational steering of scientific simulations; distance visualization; operation of remote instruments; large-scale, distributed systems)
- Testbeds and infrastructure (extend the reach of high-performance networks, improve access technologies)

### *4. Exploiting advanced IT to sustain U.S. leadership in science and engineering*

The Federal investments proposed in this Strategic Plan include development and demonstration of the world's most advanced computational science and IT systems in the sciences and engineering. These high-performance IT capabilities, like all important innovations, will drive new waves of exploration and discovery at the leading edge of scientific and engineering knowledge, where the U.S. must remain in the years ahead. High-end scientific computation and visualization technologies and tools will enable researchers to "see," interact with, and analyze the structures and behaviors of organic and inorganic matter more precisely than previously possible – from the tiniest building blocks of the universe, to the tolerances of manufacturing designs, to the properties and interactions of the biosphere's large-scale phenomena. These exciting explorations will leverage Federal IT R&D investments to attract talented researchers into engineering and science and strengthen our national leadership in these fields.

Examples of the advanced science and engineering activities that will be possible with high performance IT systems include:

- Modeling and simulation in the biological, chemical, environmental, material, and physical sciences, such as:
  - - A dynamic integrated model of the Earth's atmosphere, oceans, and soil at scales ranging from kilometers to meters
  - - A model of the human body and its components at scales ranging from atoms to molecules, cells, and organs, to the whole body
  - - Complete engine simulation, including combustion, chemical mixing, and multiphase flow
  - - Simulation for controlled fusion to optimize the design of future nuclear reactors
  - - Design of new chemical compounds for biological and manufacturing applications

  - Models of chemical, manufacturing, and assembly plants for optimization
  - Simulations of automobile crash tests for different spatial configurations that reliably substitute for real tests
- Data assimilation, fusion, visualization, manipulation for modeling and simulation
- Modeling and simulation in IT
  - High-end computing systems
  - Network dynamics
  - Large-scale IT systems such as embedded systems and distributed heterogeneous applications
- Collaboration technologies in clinical medicine, scientific research, and professional education and training

### *5. Ensuring reliable operation of critical systems, with protection against failures and attacks*

The 1999 PITAC report correctly argued that fundamental research in software development should be an absolute national priority in Federal IT R&D. The Committee highlighted a reality of the Information Age: The software running today's computer systems and networks is a vast patchwork of often idiosyncratically designed, insecure, and non-interoperable code whose fragility manifests itself daily in unreliability, security breaches, performance lapses, errors, and difficulties in upgrading. Unlike the design of bridges and airplanes, for example, there exists today no framework of formal scientific and engineering principles governing software development. At the same time, the demand for software currently exceeds our capacity to produce it, and the software that is developed is very costly and increasingly complex, with many programs running to millions of lines of code – far too many to be closely validated or made secure from attack with today's technology.

If all that were at stake were the frustrations of home computer users, perhaps we could leave software development as a cottage craft rather than a formal scientific discipline. But with software already managing large-scale and mission-critical systems as aircraft and air traffic, medical devices including life-support systems, electrical power grids, international financial networks, and advanced weaponry, we must act immediately to turn software development into a science-based discipline. We must conduct the research necessary to develop software governed by formal principles and methods and structured so that its security and reliability can be assured through automated testing and validation. Mission-critical systems must be able to withstand hacker, criminal, and enemy attacks as well as unanticipated system interactions, "self-healing" so they can continue to function after an attack or system failure, and designed to guarantee predictably high levels of data integrity and security.

The Strategic Plan proposes to fund research to develop and demonstrate revolutionary high confidence software and systems development and assurance capabilities that balance risk, cost, and effort to achieve systems that behave in predictable and robust ways. The goals of this research effort are to:

- Provide a sound theoretical, scientific, and technological basis for assured construction of safe, secure systems
- Develop hardware, software, and system engineering tools that incorporate ubiquitous, application-based, domain-based, and risk-based assurance
- Reduce the time, effort, and cost of assurance and certification processes
- Provide a technological base of public domain, advanced prototype implementations of high confidence technologies to enable rapid adoption

## Technical research agenda: Ensuring reliable operation of critical systems

- Foundations of assurance and composition
  - Rigorous modeling and reasoning about high confidence properties
  - Intereoperable methods and tools

- System composition and decomposition
- Specification
- Safety and security foundations

- Scalable fault prevention, detection, analysis, and recovery
  - Robust system architectures
  - Monitoring, detection, and adaptive response
- Correct-by-construction software technologies
  - Programming languages, tools, and environments
  - Systems software, middleware, and networking, including reusable middleware services such as efficient, predictable, scalable, dependable protocols for timing, consensus, synchronization, and replication for large-scale distributed embedded applications and domain-specific services
- Evidence technologies for verification and validation
- Experimentation and reference implementations
  - Assured reference implementations and assurance cases, such as Public Key Infrastructure (PKI) for advanced networks, software control of physical systems, and mobile networked devices
  - Domain-specific certifications technologies, such as technologies for cost-effective verification and validation and verified hardware/software co-design technologies

### *6. Making software for the real world*

The PITAC contended that the longstanding "crisis" in software quality and productivity threatens U.S. security and economic viability. A conspicuous example of the enormous opportunities and challenges before us is embedded software – that is, software operating with and controlling the physical world. Embedded software is extremely hard to build because its design cannot be based on an idealized model of the real world. While the primary stakeholder is DoD (embedded software is the main reason for significant time and cost overruns in major weapon programs and presents a profound technical challenge for developers), embedded software has tremendous commercial significance. Examples of this may be found in automotive electronics (where it is predicted that the cost of the embedded computers and software will exceed that of the drive train and body by early 2003), consumer electronics such as personal digital assistants (PDA's,) cell phones, television sets, and other household devices, and industrial process control.

Given the staggering impact of the software industry on both the private sector — where personnel costs have reached $400 billion a year — and the Federal government, the Strategic Plan will sponsor fundamental research that will lead to more cost-efficient, productive software development methods. This will result in higher-quality software with predictable characteristics, as well as support the construction of advanced applications that stress and evaluate current and evolving best practices.

The National Research Council, in its new report "Making IT Better," argues that the single greatest challenge in IT research today is presented by large-scale systems, which now power society's most complex and critical infrastructures but which have not been the IT research community's primary focus to date. Citing the growing complexity, heterogeneity, distribution, and integration of these vast interconnected systems, the report urges that research to improve their design, development, and operation be made a national priority.

In large-scale systems, the validity of theoretical approaches is drastically challenged by scalability pressures and by the inherent heterogeneity of components. We cannot achieve improvements without evaluating the practical applicability of methods and techniques and actually testing them in large-scale application platforms. Therefore, this Strategic Plan proposes an aggressive research program that not only addresses the scientific foundations of software design, but also investigates the related engineering process and conducts substantial experimental evaluations.

## Technical research agenda: Making software for the real world

- Science of software and system design
  - Languages and compilers —for example, domain-specific languages to make software specification and development easy for end users and languages that are easier to use and harder to abuse
  - Effective methods for composing software and systems – better techniques for composing, analyzing, and verifying complex systems, and making them interoperable on widely distributed heterogeneous systems
  - Foundations for advanced frameworks and middleware – adaptive and reflexive components, composition frameworks and middleware, theoretical basis for the construction of scalable distributed software systems
- Automating the engineering process
  - Methods for putting together software "components" to reduce development time and increase reliability, including technologies for developing distributed, autonomous and/or embedded software; automation of software and systems development
  - Integrated software and systems development process, including methods for specifying, analyzing, testing, and verifying software and physical systems
  - Interoperability of applications running concurrently across wide area networks
  - Integrated configurable tool environments that enable rapid compostion and customization of integrated domain-specific development environments
- Pilot applications and empirical evaluation
  - Technologies for embedded software applications and other complex applications
  - Empirical studies of software and systems development projects

### *7. Expanding human capabilities and supporting universal human development*

Information technology holds the potential to help *all people* enhance their individual capacities and skills. The Federal research agenda outlined in this Strategic Plan aggressively pursues technical innovations that bring us closer to universal access to and usability of computing and communications systems. First, it focuses on investigation of ways to integrate advanced functionalities – i.e., computing technologies that input and output speech, translate languages, are activated by sensory data or remote instruction, and the like – so that they best support people performing multiple tasks in varying configurations within complex work environments. Second, it supports end user-focused research to re-invent such IT components as interfaces, search engines, and communications capabilities from the standpoint of expanding the user's capabilities and ease of use. Third, it supports development of technologies, tools, and devices that enable all individuals to live full and independent lives, whatever their age or physical capacities.

## Technical research agenda: Expanding human capabilities

- Development of advanced functionalities
  - Language-engineering technologies (including translation between languages and between spoken and written languages, and spoken-language query systems)
  - Spoken, aural, and multimodal interfaces – for hands-free and untethered computing in military and advanced aerospace applications and for computer access for the blind
  - Sensor technologies for use in such settings as health care, national defense, and emergency management, and for the severely physically disabled
  - Real-time interaction with databases to accelerate decisionmaking (for example, Web query response times of less than one second)

- Integration of advanced functionalities
    - Intelligent systems, such as "smart spaces," for ubiquitous computing with multiple interactions; collaborative mobile agents
    - Remote collaboration, visualization, and virtual-reality environments
    - Computer-assisted prosthetics for motion, sight, and hearing; monitoring systems; and remote consultation technologies to increase the independence of the elderly and disabled
    - Technologies and methods for modeling and sharing expertise; models and metrics for collaborative performance of complex tasks

### *8. Managing and enabling worlds of knowledge – Rx4*

Small Federal IT investments to date have pioneered development and implementation of digital repositories of information and such basic enabling technologies as search engines, record management systems, and linkages among distributed archives. Creating digital libraries across the range of human knowledge and developing the technologies and tools to make that knowledge universally available on demand is a core challenge in information technology whose advances benefit every profession, every academic discipline, every learner, and every citizen. Digital libraries form the basis of the Nation's 21st century knowledge network, but we also need advanced IT technologies for working with the information, from visualization, data fusion, and analysis capabilities to remote collaboration and metadata notation schemes, to advanced interoperable systems. This Strategic Plan proposes an expanded research program in this area to build on early Federal successes to reach next-generation technologies in archiving; data access, manipulation, management, and analysis; interoperability; remote collaboration; preservation; and information security.

This research will enable IT to provide the **right** information to the **right** people in the **right** form at the **right** time, a goal the IT R&D Programs call "**Rx4. "**

**Technical research agenda: Managing and enabling worlds of knowledge**

- Data storage and management technologies
    - Tools for collection, indexing, synthesis, and archiving
    - Protocols for data compatibility, conversion, interoperability, interpretation
    - Technologies and tools for fusion of databases, such as molecules and macromolecular structures in biology or disparate real-time weather observations, with remote access and analysis capabilities
    - Component technologies and integration of dynamic, scalable, flexible information environments
    - Digital representation, preservation, and storage of multimedia collections
    - Protocols and tools to address legal issues such as copyright protection, privacy, and intellectual property management
- Usability of large-scale data sets
    - Intelligent search agents, improved abstracting and summarization techniques, and advanced interfaces
    - Digital classification frameworks and interoperable search architectures
    - Metadata technologies and tools for distributed multimedia archives
    - Ultra-scale data-mining technologies
    - Testbeds for prototyping and evaluating media integration, software functionality, and large-scale applications

### *9. Supporting development of a world-class IT workforce*

U.S. employers in every sector as well as a variety of studies identify the growing shortage of skilled IT workers as the single greatest threat to U.S. competitiveness over the next 10 years. The Strategic Plan proposes to accelerate and expand research on issues in IT education and workforce development, with a focus on barriers and impediments to IT careers among women, minorities, and other underrepresented groups. This research will also foster promising IT applications for classroom and work-related learning by establishing research centers devoted to exploring and developing IT learning technologies.

As researchers representing many different disciplines, participants in the Federal IT R&D Programs know firsthand that the shortage of IT researchers is already jeopardizing their ability to carry out the research agenda that is crucial for the Nation's future. To address this problem, the Strategic Plan also proposes that the Federal research community strive to double the number of new IT researchers over the next five years and increase the support levels for existing faculty.

## Technical research agenda: Development of a world-class IT workforce

- Models of cognitive development
- Effects of IT systems on learning
- Software for self-instruction and collaborative learning
- Integration of technologies in learning environments
- Technology-based workforce development and training

### *10. Understanding the effects of IT to maximize its benefits*

New modes of learning, research, communication, commerce, and human services are proliferating so rapidly that we as a society have hardly paused to contemplate the changes or analyze their effects on people and institutions. Most IT research investments to date understandably have centered on development of the new technologies themselves. The PITAC report brought into focus, however, the need for "investment in research to identify, understand, anticipate, and address" the unintended consequences of the increasing pace of technology transformation. The Strategic Plan proposes a vigorous interdisciplinary research program to look much more closely at the nature and dynamics of the interactions between IT and social systems. It will do this by developing both baseline empirical maps of the landscape of social change and new theories and models to describe the complex process of adaptation and interchange between humans and large-scale technical systems.

The research agenda will address a major initial challenge: Development of an intellectual architecture for this new interdisciplinary research area. Researchers currently working on IT-related studies are scattered across many different disciplines without either a "magnetic" center to draw them together or a multidisciplinary communications network oriented to their work. Federal leadership will enable us to create research centers, build a national infrastructure for social, economic, and workforce-related (SEW) research, and attract additional developing scholars to the work to be done. This capacity-building effort will provide policymakers, for the first time, with current, research-based findings about IT's societal effects.

## Technical research agenda: Understanding the effects of IT

- Universal participation in a digital society, including such topics as the digital economy, modes of work, Internet governance and Internet citizenship, "digital divide" issues, and cybercrime and law enforcement

- Fundamental theoretic and legal analyses and empirical studies of intellectual property and privacy issues in the digital age
- Using large-scale social technologies for collaboration and learning in science, education, and the workplace
- Ethical principles in IT socio-technical designs
- IT for learning and research in education

## Part IV: Putting Federal research into action – National Grand Challenge Applications

Most of the IT enabling technologies the Nation needs – and that constitute the Federal research agenda proposed in this Strategic Plan – are invisible to the public. It is the combination of component technologies in far-reaching applications that marks the visible ultimate goal and crowning achievement of fundamental IT research. Many people think such applications *are the main focus* of IT research. But as this paper explains, applications are effectively *the final step* in an R&D process that begins with methodical, multidisciplinary investigations across a variety of basic and applied sciences.

The bulk of the budget for this five-year Strategic Plan will support fundamental research in enabling technologies. But the IT R&D Programs also propose to test and validate these technologies in prototypes and demonstrations of advanced IT applications. Representative National Grand Challenge Applications are described in the following sections. Several sections are devoted to specific IT applications. Others point to key areas of the national interest in which many advanced applications are needed and several Grand Challenge Applications will be prototyped.

### *Next-generation national defense and national security systems capabilities*

The R&D called for in this Strategic Plan will provide the base technologies to ensure that the U.S. maintains its dominant position in the application of information technologies to critical national defense and national security needs. The investments that are called for in this Plan will provide the national defense and national security communities with the advanced information technologies needed to support weapons programs, military and intelligence operations, and adverse information warfare environments. Systems with these capabilities will be able to perform the computationally intensive fine grain simulation of new aircraft and smart weapons, and will permit full maintenance and reliability simulation of the Nation's nuclear weapons stockpile. This R&D will enable the efficient design and development of robust and reliable software with the high fault tolerance and high levels of security assurance and intrusion resistance that are vital to the Defense command, control, communications, and intelligence infrastructure. R&D in both microsensors and embedded and autonomous devices will enable the modeling and the management of huge battlespaces involving hundreds of thousands of objects in dynamic combat, support, and intelligence operations. As a result, it will be possible to link autonomous sensor, surveillance, and combat weapon systems to battle management and cyber warfare systems in order to support both defensive and offensive operations with minimum risk of casualties.

The IT R&D Programs will develop and demonstrate new generations of highly secure, fault tolerant computing, networking, and storage technologies, including high end computing systems and distributed autonomous and embedded devices and systems, needed in weapons systems, battlespace, and national security applications.

### *Improved health care systems for all citizens*

Secure, high-speed networks and software that is reliable, interoperable, and safe from intrusion will enable basic improvements in the national health care infrastructure, such as high-confidence software for medical devices including life-support systems; management and usability of patient information; interactions between patients and health care providers; timely analysis of provider and institutional quality; and hospital systems, inventory, and procurement management.

More dramatic will be the extension of monitoring, diagnosis, care, emergency treatment, and even surgery to citizens in remote locations, or unable to reach the hospital, or housebound. Experimentation with telemedicine is showing the enormous promise in combining high-speed networking, two-way real-time video, embedded and robotic devices, and remote visualization and instrumentation to get needed care to citizens immediately wherever they are located. These capabilities will also make it possible to help maintain the independence of aging citizens and of citizens with physical limitations. In addition, this set of technologies will enable a whole new generation of techniques and practices in medical training and physician and health care professional continuing education.

The IT R&D Programs will prototype and demonstrate high-confidence medical devices; multimodal systems for remote and emergency on-site patient care; advanced home devices and services for individuals with physical limitations; and advanced, distributed multimedia capabilities for medical education, biomedical research, and clinical practice.

### *Creating scientifically accurate, 3-D functional models of the human body*

Advances in computational speeds, visualization software, and data storage capacities are bringing us closer to being able to generate large-scale 3-D models and simulations of enormously complex phenomena such as the human body. To suggest how computationally challenging such models are: It is taking the world’s fastest computing platforms in the Federal government’s national research laboratories to begin to create quantitatively accurate visualizations of the Nation’s nuclear weapons stockpile. It will take substantially more computational capacity to generate a precise 3-D visual model of the human body, starting from atoms, molecules, and cells, through organs and the vertebrate and circulatory systems. Federally funded researchers are working today on visualizing the neuronal structure of the brain. The scale of this problem alone is exemplified by the fact that one cubic millimeter of cerebral cortex may contain on the order of five billion interdigitated synapses of different shapes and sizes and a wide variety of subcellular chemical signaling pathways. Being able to visualize, manipulate, and test representations of structures and processes at this level of matter will mark an invaluable innovation for both scientific research and education.

The IT R&D Programs propose to harness IT advances to create a complete, functional digital model of the human body.

### *IT tools for environmental modeling and monitoring*

Advanced IT modeling, simulation, visualization, and analysis tools will also improve our ability to study and understand such complex phenomena as global warming, food shortages, energy depletion, drought, natural disasters, and human/environment interactions. More accurate measurement and analysis of such phenomena will provide better information for decision making in both the private and public sectors.

Developing a next-generation environmental monitoring, modeling, and prediction system will require real-time monitoring and observations above the Earth, on the Earth, and under ground. Because these real-time observations will be global in scale, the system will require high-speed digital connectivity and high-end computing platforms. The data must then be integrated with timely contextual knowledge in geophysics, biology, chemistry, and atmospheric and oceanic sciences. A key challenge in developing this application is the great complexity of assimilating observational data with models. Scientists will need new methods of visualization to understand the complexity and the spatial and time evolution of the underlying processes. Integration and synthesis of multidisciplinary data with advanced, high-resolution models will require coordination of component technologies, specialized languages for scientific software, storage strategies with very large capacities and good access characteristics, and metadata and search capabilities that include environmental semantics, data fusion, and data mining and/or automated pattern recognition.

The IT R&D Programs propose to prototype and demonstrate environmental monitoring and modeling systems to improve forecasting of hazardous weather, evolution of hazardous spills, response of ecosystems to environmental change, and impacts of earthquakes.

### *Integrated IT systems for crises management*

In a major natural or human-caused disaster, there is a great need for an instantaneous common communication system and a common capability for real-time distribution of precise information, disaster guidance and directives, situational updates and analyses, and instructions for distributed disaster workers. To date, we have not put development of such a coordinated crises management system on the national agenda. It is time to put the mobile wireless, nomadic, and satellite communications technologies now available together with scalable wireline networking capabilities, advanced microsensing technologies, data analysis and system-management software, and with our extensive multidisciplinary experience in crisis management (for example, public health, emergency response, medical triage, fire, and policing) to create a state-of-the-art crisis coordination and management system that can be deployed immediately and effectively in any kind of catastrophic situation.

The IT R&D Programs propose to support creation of a collaborative, interdisciplinary Enabling IT Center for Crises Management to develop and demonstrate this comprehensive technologies framework. Federal agencies, with state and local government and private-sector partners, have the technologies, the personnel, and the broad experience in major environmental and other disasters to successfully build this much-needed grand challenge application.

### *IT-enabled integrated intermodal transportation system*

The current national transportation system is made up of three main modes -- land (*e.g.,* pedestrian, highways, transit, motor carriers, rail, pipelines), water (maritime, waterways), and air and space. These modes are connected "intermodally" to provide for the transport of people, natural resources, and goods. But intermodal connections are not optimal today. Public emphasis on the value of time (and therefore, doorstep-to-destination speed) will take on increased importance early in the 21st century and will result in demand for faster, more efficient, and affordable transportation services. In addition, with the information revolution, a new mode of transport is emerging – the information or virtual mode. This "fourth" mode will provide global connectivity anywhere, anytime. While some physical transport needs will be reduced by the information revolution, throughout history increased communication ability has also resulted in increased demand for physical transportation. Information will not only make individual transportation modes more efficient, but could fundamentally change the ways in which we can conceive of totally integrated intermodal transportation systems in the 21st century.

The long-term goals for this IT investment are:

- An integrated national transportation system that can move anyone and anything, anywhere, anytime, on time at an affordable price
- A transportation system without fatalities and injuries resulting from system or operator error, or terrorist intervention
- A transportation system without transportation-related environmental impacts (e.g., noxious emissions, greenhouse gases, noise) and not dependent upon foreign energy

### *Integrated, advanced aviation system technology*

Aviation safety and capacity are national issues that are reported in the newspaper daily. The air transportation system is on the verge of gridlock, with delays and cancelled flights last summer reaching all-time highs and passenger rage skyrocketing. As demand for air transportation continues to increase, fueled by a strong economy and the package-delivery demands of e-commerce, the capacity of the air traffic control system needed to accommodate the anticipated growth is falling farther behind. It has become painfully apparent that the present air traffic control system cannot continue to be scaled up to provide the capacity increases required in the next 15 to 25 years. We need a fundamental change in the management of the aviation system and information technology is the key.

High-performance computational and networking,technologies, in combination with advanced applications in visualization, modeling, simulation, and distributed instrumentation make it possible now to design a fully integrated, large-scale aviation system in the air and on the ground. Such a next-generation IT infrastructure would vastly increase the capacity of the air transport system to move people and cargo through integrated airspace operations. This integrated system would enable real-time sharing of information from distributed sources such as weather stations, automated air-traffic management systems, flight controllers, passenger managers, and other transport-related nodes. IT challenges are to develop:

- The critical core component technologies to meet the requirements of the air transportation system
- A virtual airspace transportation environment for simulating the air traffic components at the system level with the requisite degree of fidelity
- Evaluation of candidate system-level concepts and architectures making use of the “virtual air transportation environment”

### *Creating a world-class infrastructure for lifelong learning*

Lifelong education, training, and development have become necessities of the Information Age. With human knowledge doubling every two years and dynamic work environments calling for continuous skills development and adaptability to new information, the ability to keep learning is perhaps this era's core requirement for successful employment and career development. We currently have, or will soon, the enabling technologies in high-speed networks, software for information management, real-time collaboration, 3-D visualization, and the like to create multifaceted learning environments and experiences for learners of every age with every kind of academic, vocational, or personal learning focus. IT can provide ubiquitous access to structured knowledge (systematic course work, laboratory activities, and rich digital libraries) as well as immersive environments for experiencing scientific phenomena and different cultures and environments. IT interfaces and experiences can be tailored to individual learning styles, ages, physical and mental capacities, and interests, with automated feedback systems to guide progress.

The IT R&D Programs propose to demonstrate prototypes of advanced learning systems for education, training, and development across age groups and needs.

## Part V: Realizing the IT promise

### The imperative for Federal leadership

As the developers of this five-year Strategic Plan, the Federal IT R&D Programs strongly urge the new Administration to build on the interagency effort's demonstrated 10-year record of success with this bold investment to make fundamental IT R&D a high-visibility national priority. Federal IT research not only is essential for critical Federal missions but also helps fulfill the promise of information technology in innovations and applications that benefit all Americans.

For all the reasons noted in the Strategic Plan, this vital fundamental research will not be undertaken by the private sector. But without it the Nation cannot achieve the scientific and technical breakthroughs urgently needed in mission-critical national defense and national security applications, advanced scientific research, manufacturing and services that lie at the heart of our economic competitiveness, and biomedical research and health care. All of these vital sectors now depend on effective communications networks, reliable computing systems, and information-rich digital archives.

The Strategic Plan details these enormous national benefits, and it sets out the technical challenges that Federal research priorities must address to drive substantial IT advances. The Federal IT R&D agencies agree with the President's Information Technology Advisory Committee, however, that it will take aggressive Federal leadership to press the IT research agenda that will maintain and strengthen the Nation's competitive edge in the global economy and assure that our national defense and national security systems are second to none.

**Management of the Federal IT R&D Programs' Strategic Plan**

The Interagency Working Group on Information Technology R&D (IWG/IT R&D, successor to the Subcommittee on Computing, Information, and Communications and before that the Subcommittee on High Performance Computing, Communications, and Information Technology) serves as the coordinating leadership body for the IT R&D Programs. Made up of representatives of the 12 Federal agencies in the Programs, plus representatives from the Office of Science and Technology Policy and the Office of Management and Budget (OMB) in the Executive Office of the President, the IWG provides IT R&D policy, program, and budget guidance for the Executive Branch and coordinates multiagency IT R&D activities. The IWG also works with other Federal agencies that need advanced IT to identify their requirements and accelerate development of appropriate technologies.

Six Coordinating Groups (CGs), representing the major research emphases of the IT R&D Programs and the program managers in participating agencies, report to the IWG. These groups confer regularly to coordinate the objectives and activities of the multiagency projects in their specialized research domains, called Program Component Areas (PCAs). The PCAs are:

- High End Computing and Computation (HECC), which includes both HEC (High End Computing) R&D and HEC Infrastructure & Applications (I&A)
- Human Computer Interface & Information Management (HCI&IM)
- Large Scale Networking (LSN)
- Software Design and Productivity (SDP)
- High Confidence Software and Systems (HCSS)
- Social, Economic, and Workforce Implications of IT and IT Workforce Development (SEW)

Funding for agency IT R&D activities is implemented through standard budgeting and appropriations processes that involve the participating agencies and departments, OMB, and the Congress. Some activities are funded and managed by individual agencies. Others involve multiagency collaboration, with mutual planning and mutual defense of budgets. For some highly complex, mission-critical R&D efforts, such as the thee-year Next Generation Internet Initiative begun in FY 1998 and the current HEC R&D program, agencies create integrated programs and budgets and detailed management plans. The work of the IWG and the Coordinating Groups, and interactions with OSTP, OMB, and the Congress, are supported by the National Coordination Office for IT R&D.

The 12 agencies that developed the Strategic Plan and their primary IT R&D interests are:

*AHRQ – the Agency for Healthcare Research and Quality* – focuses on developing state-of-the-art IT for use in health care applications such as computer-based patient records, clinical decision support systems, and standards for patient care data, information access, and telehealth.

*DARPA – the Defense Advanced Research Projects Agency* – is focused on future generations computing, communications, and software technologies, and human use of information technologies in national defense applications such as battlefield awareness.

*DOE/NNSA – Department of Energy National Nuclear Security Agency* – was established to develop new means of assessing the performance of nuclear weapon systems, predict their safety and reliability, and certify their functionality through high-fidelity computer simulations and models of weapon systems.

*The DOE Office of Science* is discovering, developing, and deploying the computational and networking tools that enable researchers in the scientific disciplines to analyze, model, simulate, and predict complex physical, chemical, and biological phenomena important to DOE. The office also provides support for the geographically distributed scientific teams and remote users of experimental facilities that are critical to the Department's missions.

*EPA – the Environmental Protection Agency* – has the IT R&D research goal of facilitating multidisciplinary ecosystem modeling, risk assessment, and environmental decision-making at the Federal, state, and local levels, and in corporations, through advanced use of computing and other information technologies.

*NASA – the National Aeronautics and Space Administration* – is extending U.S. technological leadership to benefit the U.S. aeronautics, Earth and space science, and spaceborne research communities.

*NIH – the National Institutes of Health* – is developing the basic knowledge for the understanding, diagnosis, treatment, and prevention of human disease, including the storage, curation, analysis, and retrieval of biomedical data and information.

*NIST – the National Institute of Standards and Technology* – is working with industry, educational, and government organizations to make IT systems more useable, secure, scalable, and interoperable; apply IT in specialized areas such as manufacturing and biotechnology; and encourage private-sector companies to accelerate development of IT innovations.

*NOAA – the National Oceanic and Atmospheric Administration* – is an early adopter of emerging computing technologies for improved climate modeling and weather forecasting, and of emerging communications technologies for disseminating weather warnings, forecasts, and environmental information to users such as policymakers, emergency managers, and the general public.

*NSA – the National Security Agency* – is addressing some of the most challenging problems in the country in computing, storage, communications, and information assurance in order to help ensure our national security.

*NSF – the National Science Foundation* – is the lead agency in the IT R&D Programs, with interest in developing new fundamental IT knowledge; applications in the biological, chemical, geophysical, physical, and mathematical sciences and engineering; educating world-class scientists and engineers and a knowledgeable IT workforce; and research infrastructure.

*ODUSD/URI – the Office of the Deputy Under Secretary of Defense's University Research Initiative* – focuses on IT R&D for Department of Defense applications, research infrastructure, and science and engineering education.

Other Federal agencies participate in information technology research and development, and coordinate with the IT R&D Programs, using funds that are not budgeted under the IT R&D Programs.