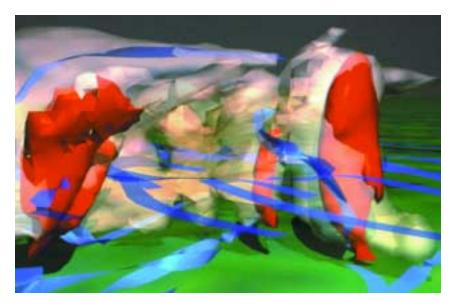




To understand the changes brought by the Internet, one has only to go back a few decades, to a time when researchers networked in person, and collaboration meant working with colleagues in offices down the hall. From the beginning, computer networks were expected to expand the reach—and grasp—of researchers, providing more access to computer resources and easier transfer of information. NSF made this expectation a reality. Beginning by funding a network linking computer science departments, NSF moved on to the development of a high-speed backbone, called NSFNET, to connect five NSF-supported supercomputers. More recently NSF has funded a new backbone, and is playing a major role in evolving the Internet for both scientists and the public. The Internet now connects millions of users in the United States and other countries. It has become the underpinning for a vibrant commercial enterprise, as well as a strong scientific tool, and NSF continues to fund research to promote high-performance networking for scientific research and education.

A Constellation of Opportunities

- A solar wind blasts across Earth's magnetic field, creating ripples of energy that jostle satellites and disrupt electrical systems. Satellite data about the storm are downlinked through Goddard Space Flight Center in Greenbelt, Maryland, passed on to a supercomputer center, and uploaded by NSF-funded physicists at the University of Maryland and at Dartmouth College in Hanover, New Hampshire. Using the Internet, researchers work from their own offices, jointly creating computer images of these events, which will lead to better spaceweather forecasting systems.
- An NSF-funded anthropologist at Penn State
 University uses his Internet connection to
 wade through oceans of information. Finally,
 he chooses the EMBL-Genbank in Bethesda,
 Maryland, and quickly searches through huge
 amounts of data for the newly deciphered DNA
 sequence of a gene he's studying. He finds it,
 highlights the information, downloads it, and
 logs off.
- It's time to adjust the space science equipment in Greenland. First, specialized radar is pointed at an auroral arc. Then an all-sky camera is turned on. The physicist controlling the equipment is part of a worldwide team of researchers working on NSF's Upper Atmospheric Research Collaboratory (UARC). When she's finished making the adjustments, the physicist pushes back from her computer in her Ann Arbor, Michigan, office, knowing the job is done.
- The Laminated Object Manufacturing (LOM) machine's camera, or LOMcam, puts a new picture on the Web every forty-five seconds, and the molecular biologist watches. From his office, he can already tell that the tele-manufacturing system is creating an accurate physical model of the virus he is studying. The San Diego Supercomputer Center's LOMcam continues to post pictures, but the biologist stops watching, knowing that he will soon handle and examine the physical rendering of the virus, and learn more about it than his computer screen image could ever reveal.



This is the Internet at work in the lives of scientists around the globe. "The Internet hasn't only changed how we do science, it permits entirely new avenues of research that could not have been contemplated just a few years ago," says George Strawn, executive officer of NSF's Directorate for Computer and Information Science and Engineering (CISE) and former division director for networking within CISE. "For example, the key to capitalizing on biologists' success in decoding the human genome is to use Internet-based data engines that can quickly manipulate even the most massive data sets."

A Public Net

The Internet, with its millions of connections world-wide, is indeed changing the way science is done. It is making research more collaborative, making more data available, and producing more results, faster. The Internet also offers new ways of displaying results, such as virtual reality systems that can be accessed from just about anywhere. The new access to both computer power and collaborative scientists allows researchers to answer questions they could only think about a few years ago.

Working from one of the NSF-supported supercomputing centers, researcher Greg Foss used the Internet to collect weather data from many sites in Oklahoma. He used the data to create this three-dimensional model of a thunderstorm.

It is not just the scientists who are enthralled. While not yet as ubiquitous as the television or as pervasive as the telephone, in the last twenty years, the Internet has climbed out of the obscurity of being a mere "researcher's tool" to the realm of a medium for the masses. In March 2000, an estimated 304 million people around the world (including nearly 137 million users in the United States and Canada) had access to the Internet, up from 3 million estimated users in 1994. U.S. households with access to the Internet increased from 2 percent in 1994 to 26 percent in 1998, according to the National Science Board's (NSB) Science and Engineering Indicators 2000. (Every two years, the NSB—NSF's governing body reports to the President on the status of science and engineering.)

In today's world, people use the Internet to communicate. In fact, for many, email has replaced telephone and fax. The popularity of email lies in its convenience. No more games of telephone tag, no more staying late to wait for a phone call. Email allows for untethered connectivity.

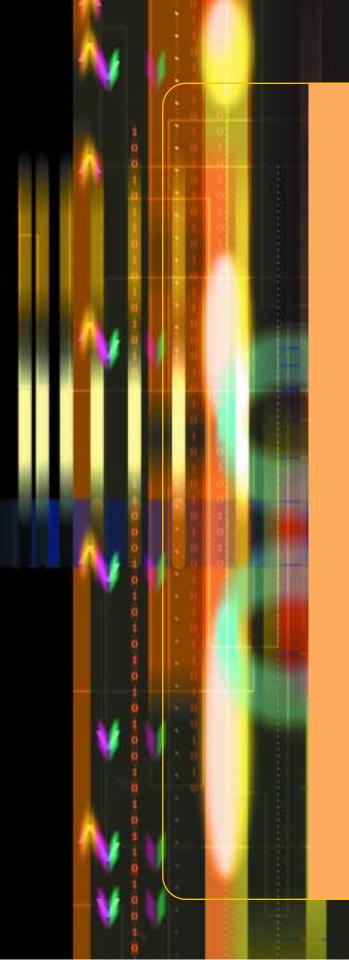
The emergence of the World Wide Web has helped the Internet become commonplace in offices and homes. Consumers can shop for goods via the Web from virtually every retail sector, from books and CDs to cars and even houses. Banks and investment firms use the Web to offer their clients instant account reports as well as mechanisms for electronic financial interactions. In 1999, the U.S. Census Bureau began collecting information on e-commerce, which it defined as online sales by retail establishments. For the last three months of 1999, the bureau reported nearly

\$5.2 billion in e-commerce sales (accounting for 0.63 percent of total sales), and nearly \$5.3 billion for the first quarter of 2000. More and more, people are going "online to shop, learn about different products and providers, search for jobs, manage finances, obtain health information and scan their hometown newspapers," according to a recent Commerce Department report on the digital economy. The surge of new Internet business promises to continue, with some experts estimating \$1.3 trillion in e-commerce activity by 2003.

Among the Web's advantages is the fact that it is open twenty-four hours a day. Where else can you go at four in the morning to get a preview of the upcoming art exhibit at the New York Museum of Modern Art . . . fact sheets on how to prepare for an earthquake or hurricane . . . a study on the important dates of the Revolutionary War . . . or hands-on physics experiments for elementary school teachers?

With all of this information, the Internet has the potential to be a democratizing force. The same information is readily available to senior and junior researchers, to elementary school students, and to CEOs. Anyone who knows how and has the equipment can download the information, examine it, and put it to use.

While the original Internet developers may not have envisioned all of its broad-reaching capabilities, they did see the Internet as a way of sharing resources, including people, equipment, and information. To that end, their work has succeeded beyond belief. The original backbone rates of 56 kbps (kilobytes per second) are now available in many homes.



PACI: Computer Partnerships

In March 1997, NSF launched its
Partnerships for Advanced Computational Infrastructure (PACI) program.
"This new program will enable the
United States to stay at the leading
edge of computational science,
producing the best science and
engineering in all fields," said Paul
Young, former head of NSF's Directorate
for Computer and Information Science
and Engineering.

The program consists of the National Computational Science Alliance (the Alliance), led by the University of Illinois at Urbana-Champaign, and the National Partnership for Advanced Computational Infrastructure (NPACI) led by the San Diego Supercomputer Center. The partnerships offer a breadth of vision beyond even what NSF has hoped for. They will maintain the country's lead in computational science, further the use of computers in all disciplines of research, and offer new educational opportunities for people ranging from kindergartners through Ph.D.s.

The Alliance's vision is to create a distributed environment as a prototype for a national information infrastructure that would enable the best computational research in the country. It is organized into four major groups:

- Application Technologies Teams that drive technology development;
- Enabling Technologies Teams that convert computer science research into usable tools and infrastructure.
- Regional Partners with advanced and mid-level computing resources

- that help distribute the technology to sites throughout the U.S.
- Education, Outreach, and Training Teams that will educate and promote the use of the technology to various sectors of society.

In addition, the leading-edge site at the University of Illinois at Urbana-Champaign supports a variety of highend machines and architectures enabling high-end computation for scientists and engineers across the country.

NPACI includes a national-scale metacomputing environment with diverse hardware and several high-end sites. It supports the computational needs of high-end scientists and engineers across the country via a variety of leading-edge machines and architectures at the University of California at San Diego. It also fosters the transfer of technologies and tools developed by applications and computer scientists for use by these high-end users. Another major focus includes data-intensive computing, digital libraries, and large data set manipulation across many disciplines in both engineering and the social sciences.

NSF recently announced an award to the Pittsburgh Supercomputing Center to build a system that will operate at speeds well beyond a trillion calculations per second. The Terascale Computing System is expected to begin operation in early 2001, when Pittsburgh will become PACI's latest leading-edge site. Through these partnerships, PACI looks to a strong future in computational science.

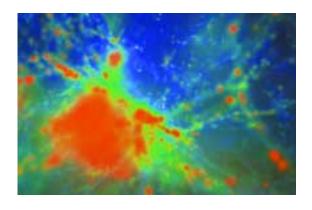
Satellites, the Hubble Space Telescope, and observatories around the world provide data to Earth-bound scientists. Once received, the data are sent, via the Internet, to researchers around the country. At the University of Illinois-based National Center for Supercomputing Applications, Frank Summers of Princeton University used the data to create a model of a galaxy formation.

From Modest Beginnings

In the 1970s, the sharing of expensive computing resources, such as mainframes, was causing a bottleneck in the development of new computer science technology, so engineers developed networking as a way of sharing resources.

The original networking was limited to a few systems, including the university system that linked terminals with time-sharing computers, early business systems for applications such as airline reservations, and the Department of Defense's ARPANET. Begun by the Defense Advanced Research Projects Agency (DARPA) in 1969 as an experiment in resource-sharing, ARPANET provided powerful (high-bandwidth) communications links between major computational resources and computer users in academic, industrial, and government research laboratories.

Inspired by ARPANET's success, the Coordinated Experimental Research Program of the Computer Science Section of NSF's Mathematical and Physical Sciences Directorate started its own network in 1981. Called CSNET (Computer Science Network), the system provided Internet services, including electronic mail and connections to ARPANET. While CSNET itself was just a starting point, it served well. "Its most important contribution was to bring together the U.S. computer science community and to create the environment that fostered the Internet," explains Larry Landweber, a professor at the University of Wisconsin and a CSNET principal investigator. In addition, CSNET was responsible for the first Internet gateways between the United States and many countries in Europe and Asia.



From the outset, NSF limited the amount of time it would support CSNET. By 1986, the network was to be self-supporting. This was a risky decision, because in 1981 the value of network services was not widely understood. The policy, which carried forward into subsequent NSF networking efforts, required bidders to think about commercialization from the very start. When the 1986 deadline arrived, more than 165 university, industrial, and government computer research groups belonged to CSNET. Usage charges plus membership fees ranged from \$2,000 for small computer science departments to \$30,000 for larger industrial members. With membership came customer support.

The Launch of NSFNET

While CSNET was growing in the early 1980s, NSF began funding improvements in the academic computing infrastructure. Providing access to computers with increasing speed became essential for certain kinds of research. NSF's supercomputing program, launched in 1984, was designed to make high performance computers accessible to researchers around the country.

The first stage was to fund the purchase of supercomputer access at Purdue University, the University of Minnesota, Boeing Computer Services, AT&T Bell Laboratories, Colorado State University, and Digital Productions. In 1985, four new supercomputer centers were established with NSF support—the John von Neumann Center at Princeton University, the San Diego Supercomputer

Center on the campus of the University of California at San Diego, the National Center for Supercomputing Applications at the University of Illinois, and the Cornell Theory Center, a production and experimental supercomputer center. NSF later established the Pittsburgh Supercomputing Center, which was run jointly by Westinghouse, Carnegie-Mellon University, and the University of Pittsburgh.

In 1989, funding for four of the centers, San Diego, Urbana-Champaign, Cornell, and Pittsburgh, was renewed. In 1997, NSF restructured the supercomputer centers program and funded the supercomputer site partnerships based in San Diego and Urbana-Champaign.

A fundamental part of the supercomputing initiative was the creation of NSFNET. NSF envisioned a general high-speed network, moving data more than twenty-five times the speed of CSNET, and connecting existing regional networks, which NSF had created, and local academic networks. NSF wanted to create an "inter-net," a "network of networks," connected to DARPA's own internet, which included the ARPANET. It would offer users the ability to access remote computing resources from within their own local computing environment.

NSFNET got off to a relatively modest start in 1986 with connections among the five NSF university-based supercomputer centers. Yet its connection with ARPANET immediately put NSFNET into the major leagues as far as networking was concerned. As with CSNET, NSF decided not to restrict NSFNET to supercomputer researchers but to open it to all academic users. The other wide-area networks (all government-owned) supported mere handfuls of specialized contractors and researchers.

The flow of traffic on NSFNET was so great in the first year that an upgrade was required. NSF issued a solicitation calling for an upgrade and, equally important, the participation of the private sector. Steve Wolff, then program director for NSFNET, explained why commercial interests eventually had to become a part of the network, and why NSF supported it.

"It had to come," says Wolff, "because it was obvious that if it didn't come in a coordinated way, it would come in a haphazard way, and the academic community would remain aloof, on the margin. That's the wrong model—multiple networks again, rather than a single Internet. There had to be commercial activity to help support networking, to help build volume on the network. That would get the cost down for everybody, including the academic community, which is what NSF was supposed to be doing."

To achieve this goal, Wolff and others framed the 1987 upgrade solicitation in a way that would enable bidding companies to gain technical experience for the future. The winning proposal came from a team including Merit Network, Inc., a consortium of Michigan universities, and the state of Michigan, as well as two commercial companies, IBM and MCI. In addition to overall engineering, management, and operation of the project, the Merit team was responsible for developing user

In 1996, researchers and artists envisioned the information superhighway this way. Since then, individuals, schools and universities, organizations, and government agencies have added millions of connections to the Internet.



support and information services. IBM provided the hardware and software for the packet-switching network and network management, while MCI provided the transmission circuits for the NSFNET backbone, including reduced tariffs for that service.

Merit Network worked quickly. In July 1988, eight months after the award, the new backbone was operational. It connected thirteen regional networks and supercomputer centers, representing a total of over 170 constituent campus networks and transmitting 152 million packets of information per month.

Just as quickly, the supply offered by the upgraded NSFNET caused a surge in demand. Usage increased on the order of 10 percent per month, a growth rate that has continued to this day in spite of repeated expansions in data communications capacity. In 1989, Merit Network was already planning for the upgrade of the NSFNET backbone service from T1 (1.5 megabits per second or Mbps) to T3 (45 Mbps).

"When we first started producing those traffic charts, they all showed the same thing—up and up and up! You probably could see a hundred of these, and the chart was always the same," says Ellen Hoffman, a member of the Merit team. "Whether it is growth on the Web or growth of traffic on the Internet, you didn't think it would keep doing that forever, and it did. It just never stopped."

The T3 upgrade, like the original network implementation, deployed new technology under rigorous operating conditions. It also required a heavier responsibility than NSF was prepared to assume. The upgrade, therefore, represented an organizational as well as a technical milestone—the beginning of the Internet industry.

In 1990 and 1991, the NSFNET team was restructured. A not-for-profit entity called Advanced Networks and Services continued to provide backbone service as a subcontractor to Merit Network, while a for-profit subsidiary was spun off to enable commercial development of the network.

The new T3 service was fully inaugurated in 1991, representing a thirtyfold increase in the bandwidth on the backbone. The network linked sixteen sites and over 3,500 networks. By 1992, over 6,000 networks were connected, one-third of them outside the United States. The numbers continued to climb. In March 1991, the Internet was transferring 1.3 trillion bytes of information per month. By the end of 1994, it was transmitting 17.8 trillion bytes per month, the equivalent of electronically moving the entire contents of the Library of Congress every four months.

An End and a Beginning

By 1995, it was clear the Internet was growing dramatically. NSFNET had spurred Internet growth in all kinds of organizations. NSF had spent approximately \$30 million on NSFNET, complemented by in-kind and other investments by IBM and MCI. As a result, 1995 saw about 100,000 networks—both public and private—in operation around the country. On April 30 of that year, NSF decommissioned the NSF backbone. The efforts to privatize the backbone functions had been successful, announced Paul Young, then head of NSF's CISE Directorate, and the existing backbone was no longer necessary.

From there, NSF set its sights even higher. In 1993, the Foundation offered a solicitation calling for a new, very high performance Backbone Network Service (vBNS) to be used exclusively for research by selected users. In 1995, Young and his staff worked out a five-year cooperative agree-



ment with MCI to offer the vBNS. That agreement was recently extended to keep the vBNS operating through March 2003. The vBNS has met its goal of pushing transmission speed from its starting point of 155 Mbps to speeds in excess of 2.4 billion bits per second by the turn of the century.

The vBNS originally linked the two NSF super-computing leading-edge sites that are part of the Foundation's Partnerships for Advanced Computational Infrastructure (PACI) program. NSF soon tied in another thirteen institutions. By 2000, the network connected 101 institutions, including 94 of the 177 U.S. universities that have received high-performance computing awards from the Foundation.

"In ensuring that vBNS will be available at least through March 2003, NSF is living up to its Next-Generation Internet commitments while charting the course for new research applications that capitalize on that infrastructure," says NSF's Strawn. "The new Information Technology Research program—begun in fiscal year 2000—has spurred an overwhelming response of proposals from the academic community, which proves that these tools have become critical to research in science and engineering."

Research on Today's Internet

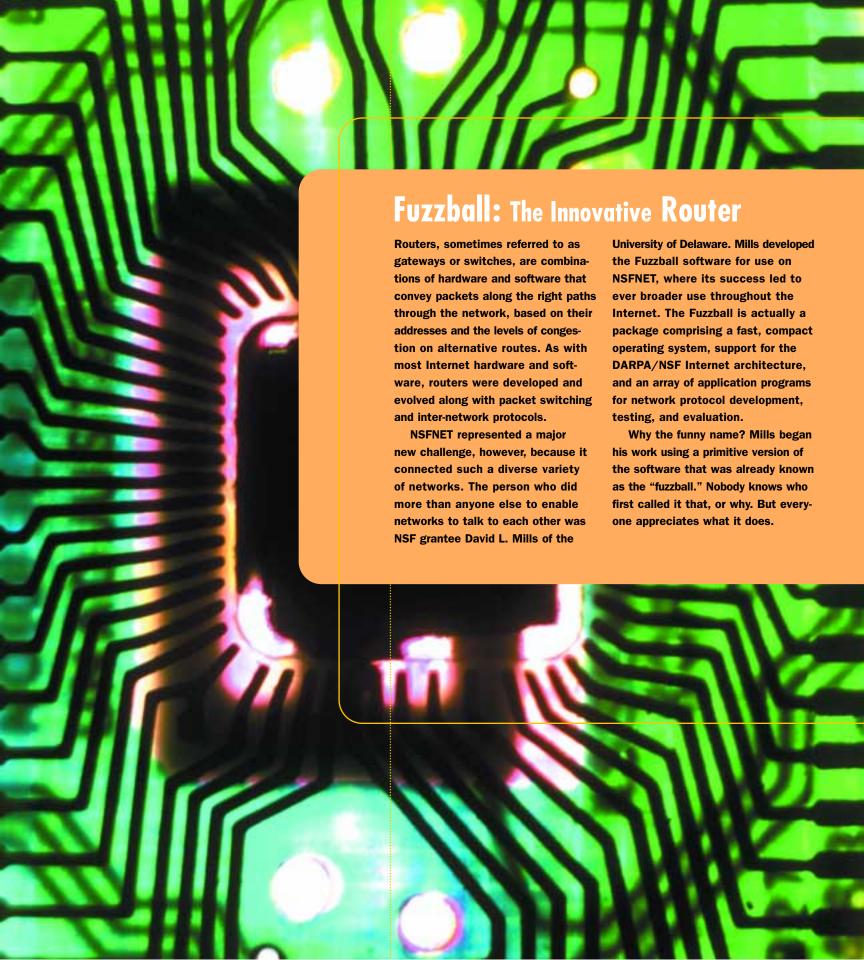
For researchers, the expanding Internet means more—more data, more collaboration, and more complex systems of interactions. And while not every university and research institution is hooked up to the vBNS, all forms of the Internet have brought radical changes to the way research is conducted.

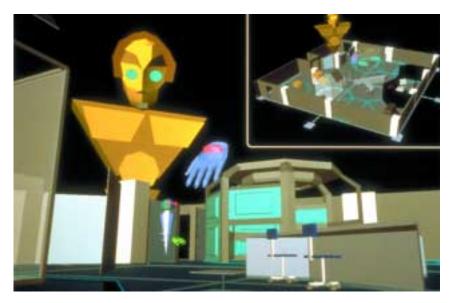
Ken Weiss is an anthropologist at Penn State University and an NSF-supported researcher studying the worldwide genetic variability of humans. While he is not actively seeking a hook-up to the vBNS, he says the Internet has had a significant impact on his research. For example, he uses email constantly, finding it more convenient than the phone ever was. And he has access to much more data. He can download huge numbers of gene sequences from around the world and do research on specific genes.

Weiss is an active user and enthusiast, but he does not necessarily agree that more is always better. "The jury is still out on some aspects, such as the exponential growth of databases, which may be outpacing our ability for quality control. Sometimes the data collection serves as a substitute for thought," says Weiss.

Other disciplines are seeing an equally phenomenal surge of information. Researchers can now get many journals online when they once needed to work geographically close to a university library. The surge of data is both a boon and a problem for researchers trying to keep on top of their fields. But no one is asking to return to the pre-Internet days, and no one is expecting the information growth to end.

On a more profound level, the Internet is changing science itself by facilitating broader studies. "Instead of special interest groups focusing on smaller questions, it allows people to look at the big picture," says Mark Luker, who was responsible for high-performance networking programs within CISE until 1997 and is now vice president at EDUCAUSE, a nonprofit organization concerned with higher education and information technology.





A networked virtual laboratory allows scientists to work remotely on a design project. This virtual laboratory and lab worker were created by specialists at the University of Illinois at Chicago.

By "special interest groups," he means the more traditional, individualistic style of science where a researcher receives a grant, buys equipment, and is the sole author of the results. The current trend is for multiple investigators to conduct coordinated research focused on broad phenomena, according to Tom Finholt, an organizational psychologist from the University of Michigan who studies the relationship between the Internet and scientists.

This trend, Finholt and others hasten to add, has existed for a long time, but has been greatly enhanced by the Internet's email, Web pages, and electronic bulletin boards. In addition, formal collaboratories—or virtual laboratories of collaborators—are forming around the globe. The Space Physics and Aeronomy Research Collaboratory (SPARC) is one of these. Developed as the Upper Atmospheric Research Collaboratory (UARC) in Ann Arbor, Michigan, in 1992 and focused on space science, this collaboratory has participants at sites in the United States and Europe. Scientists can read data from instruments in Greenland, adjust instruments remotely, and "chat" with colleagues as they simultaneously view the data.

"Often, space scientists have deep but narrow training," says Finholt. SPARC allows them to fit specialized perspectives into a bigger picture. "Space scientists now believe they have reached a point where advances in knowledge will only be produced by integrating information from many specialties." Furthermore, the collaboration is no longer as physically draining as it once was. Now, scientists like Charles Goodrich of the University of Maryland and John Lyon of Dartmouth College can continue collaborating on space-weather research, even when one person moves away. While Goodrich admits that the work might be done more easily if it could be done in person, he is sure that both the travel budget and his family life would suffer if he tried. "You can put your data on the Web, but not your child," he quips.

Expectation for the Internet of Tomorrow

If the past is a guide, the Internet is likely to continue to grow at a fast and furious pace. And as it grows, geographic location will count less and less. The "Information Superhighway" is not only here, it is already crowded. As Luker says, it is being divided, as are the highways of many cities, allowing for the equivalent of HOV lanes and both local and express routes. The electronic highway now connects schools, businesses, homes, universities, and organizations.

And it provides both researchers and business leaders with opportunities that seemed like science fiction no more than a decade ago. Even now, some of these high-tech innovations—including virtual reality, computer conferencing, and telemanufacturing—have already become standard fare in some laboratories.

Tele-manufacturing allows remote researchers to move quickly from computer drawing boards to a physical mock-up. At the San Diego Supercomputer Center (SDSC), the Laminated Object Manufacturing (LOM) machine turns files into models using either plastic or layers of laminated paper. The benefits are especially pronounced for molecular biologists who learn how their molecules actually fit together, or dock. Even in a typical computer graphics depiction of the molecules, the docking process and other significant details can get lost among

the mounds of insignificant data. SDSC's models can better depict this type of information. They are also relevant to the work of researchers studying plate tectonics, hurricanes, the San Diego Bay region, and mathematical surfaces.

To make the move from the virtual to the physical, researchers use the network to send their files to SDSC. Tele-manufacturing lead scientist Mike Bailey and his colleagues then create a list of three-dimensional triangles that bound the surface of the object in question. With that information, the LOM builds a model. Researchers can even watch their objects take shape. The LOMcam uses the Web to post new pictures every forty-five seconds while a model is being produced.

"We made it incredibly easy to use so that people who wouldn't think about manufacturing are now manufacturing," says Bailey. For some researchers, the whole process has become so easy that "they think of it no differently than you do when you make a hard copy on your laser printer," he adds. SDSC's remote lab has moved out of the realm of science fiction and into the area of everyday office equipment.

While other remote applications are not as far along, their results will be dramatic once the bugs are ironed out, according to Tom DeFanti of the University of Illinois at Chicago and his colleagues. DeFanti and many others are manipulating the computer tools that provide multimedia, interaction, virtual reality, and other applications. The results, he says, will move computers into another realm. DeFanti is one of the main investigators of I-WAY, or the Information Wide Area Year, a demonstration of computer power and networking expertise. For the 1995 Supercomputer Conference in San Diego, he and his colleagues, Rick Stevens of the Argonne National Laboratory and Larry Smarr of the National Center for Supercomputing Applications, linked more than a dozen of the country's fastest computer centers and visualization environments.

The computer shows were more than exercises in pretty pictures; they demonstrated new ways of digging deeply into the available data. For example, participants in the Virtual Surgery demonstration were able to use the National Medical Library's Visible Man and pick up a "virtual scalpel" to cut "virtual flesh." At another exhibit, a researcher demonstrated tele-robotics and tele-presence. While projecting a cyber-image of himself into the conference, the researcher worked from a remote console and controlled a robot who interacted with conference attendees.

Applications such as these are just the beginning, says DeFanti. Eventually the Internet will make possible a broader and more in-depth experience than is currently available. "We're taking the computer from the two-dimensional 'desktop' metaphor and turning it into a three-dimensional 'shopping mall' model of interaction," he says. "We want people to go into a computer and be able to perform multiple tasks just as they do at a mall, a museum, or even a university."

To Learn More

NSF Directorate for Computer and Information Science and Engineering

www.cise.nsf.gov

National Computational Science Alliance www.access.ncsa.uiuc.edu/index.alliance.html

National Partnership for Advanced Computational Infrastructure

www.npaci.edu

Pittsburgh Supercomputing Center

www.psc.edu

vBNS (very high performance Backbone Network Service) www.vbns.net

Defense Advanced Research Projects Agency www.darpa.mil

25th Anniversary of ARPANET
Charles Babbage Institute at University of Minnesota
www.cbi.umn.edu/darpa/darpa.htm