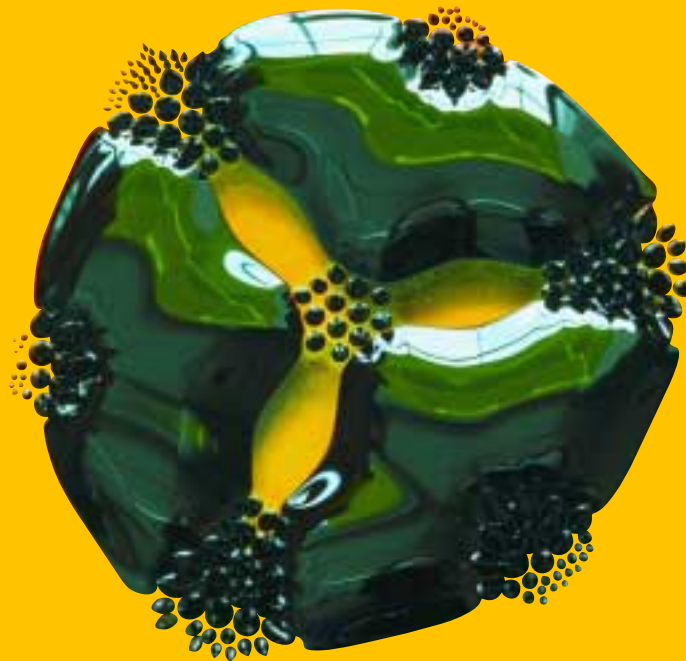


National Science Foundation



America's Investment in the Future

N S F C E L E B R A T I N G

Foreword by Walter Cronkite

5 0 Y E A R S

Photos by Felice Frankel

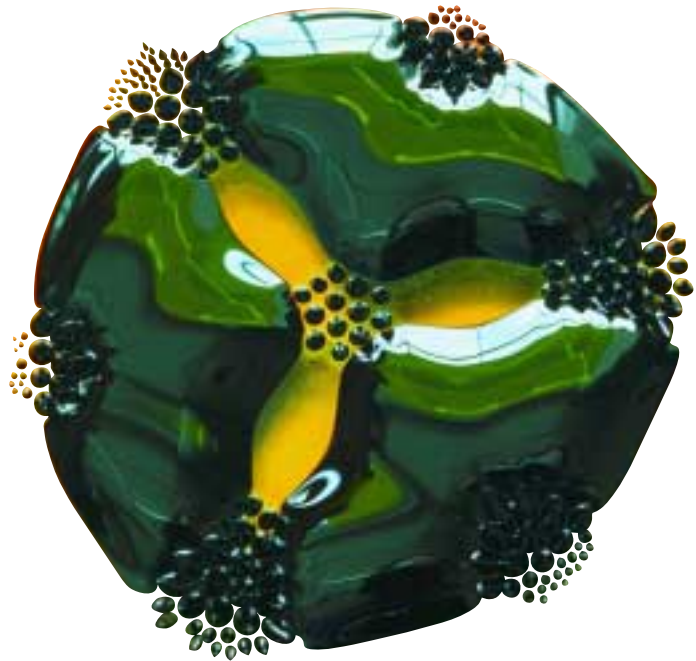


On the cover

Part liquid, part magnet, this ferrofluid serves as a symbol of NSF's dual mission—research and education. Precisely ground particles of magnetite in the ferrofluid remain loose and suspended in an oil. When the ferrofluid is placed in a magnetic field, it recalls its magnetic heritage. Here, a drop of ferrofluid rests on a glass sheet placed above a piece of yellow paper. Photographer Felice Frankel then placed seven small magnets under the paper. The attraction between the magnetite and the magnets creates the beautiful flower-like form.



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Foreword by Walter Cronkite

It may seem ironic that I—a man who failed first-year physics at the University of Texas—am writing the foreword to a book about the National Science Foundation.

I'm not a scientist. I'll never experience the thrill of formulating a new algorithm or unlocking a new gene sequence. But you don't have to be a scientist (or even have passed a physics course) to understand and appreciate the National Science Foundation. If you've ever surfed the Web or sent an e-mail, thank NSF. NSF also played a role in the development of wireless communications, advanced medical diagnostics, and more accurate weather forecasting. The list of scientific discoveries and engineering feats that NSF has supported over the past fifty years will surprise you.

In 1982 I had the good fortune to accompany marine biologists on a deep-sea dive off the coast of Mexico. It was an NSF-funded research mission. As *The Alvin* descended deeper and deeper into the ocean, I observed a world that I never knew existed, a world beneath the surface that is vast and varied.

This book, like my adventure on *The Alvin*, opened my eyes. Eighteen years ago, I was so awed by the ocean's secrets I didn't stop to think about how they were revealed. Today, when we read a story about cloning sheep or about amazingly strong molecules, most of us don't stop to think about the years of trial and error, experimentation

and analysis it took to get to the headline. Even though we're not scientists, this book can help us all to see beneath the surface of things and to appreciate how NSF enables researchers to advance the frontiers of knowledge in every direction.

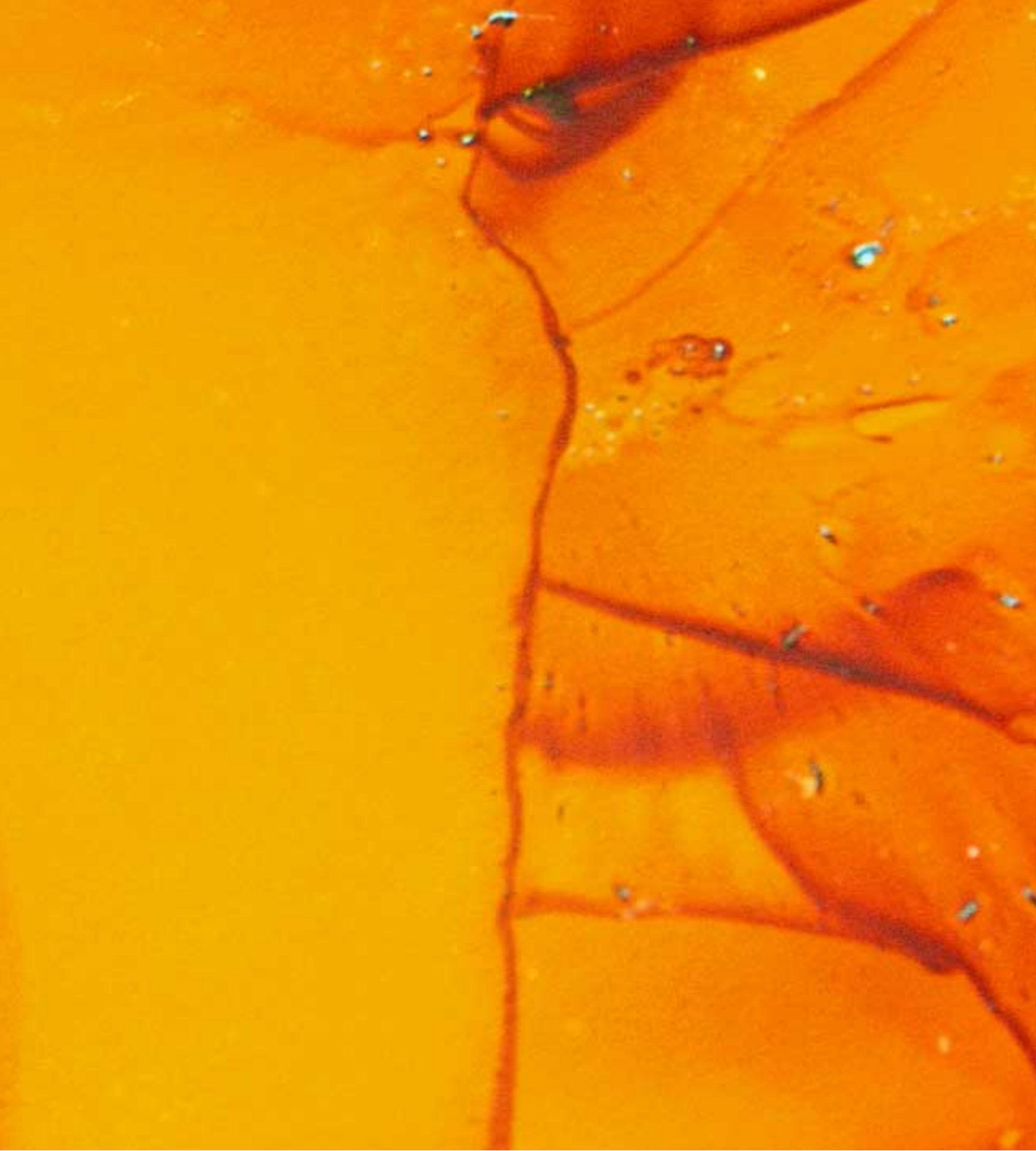
Congress established the National Science Foundation in 1950 to transform wartime research into a peacetime engine for prosperity and national security. The Foundation has succeeded masterfully, albeit quietly, in achieving these goals. Maybe that's because NSF does not operate any laboratories, conduct any experiments, or land any astronauts on the moon. Rather, NSF is the nation's single largest funder of laboratories and experiments, of the kind of exploratory research that quietly plants seeds today that make headlines tomorrow.

This book tells the stories behind those headlines—stories about the men and women who are helping us to understand the world around us. For the past fifty years, this has been the story of the National Science Foundation.

Near the end of *A Reporter's Life*, I wrote: "A career can be called a success if one can look back and say, 'I made a difference.'" After reading this book, I think you'll agree that the National Science Foundation is doing just that.



Walter Cronkite today (top) and aboard the NSF-funded expedition on *The Alvin* in 1982.



The National Science Foundation at 50

Where Discoveries Begin

At the National Science Foundation, we invest in America's future. Our support of creative people, innovative ideas, and cutting-edge technologies has led to thousands of discoveries vital to our nation's health and prosperity.

Unique among federal research agencies, the National Science Foundation's mission is to advance learning and discovery in all disciplines of science and engineering and to foster connections among them. Our job is to keep science and engineering visionaries focused on the furthest frontier, to recognize and nurture emerging fields, to prepare the next generation of scientific talent, and to ensure that all Americans gain an understanding of what science and technology have to offer.

Retired hockey star Wayne Gretzky used to say, "I skate to where the puck is going, not to where it's been." At NSF, we try to fund where the fields are going, not where they've been. In marking our fiftieth anniversary, we are celebrating this kind of vision and foresight.

For example, as chronicled in this book, NSF began funding efforts in the mid-1980s to expand what was largely a Department of Defense networked computer system into the civilian realm. NSFNET linked NSF-supported supercomputer centers at five universities and was open to all academic users. Response was so great that NSF was soon able to turn much of the burgeoning network over to the private sector. Meanwhile, a student working at one of the NSF supercomputer centers developed the first major Web browser, Mosaic. Other NSF-funded research led to the first widely used Internet routers, the gateways and switches that guide information around the globe. Besides enabling the freer flow and more sophisticated manipulation of information, the Internet has triggered a surge of new business activity, which some say will amount to \$1.3 trillion in e-commerce activity by 2003.

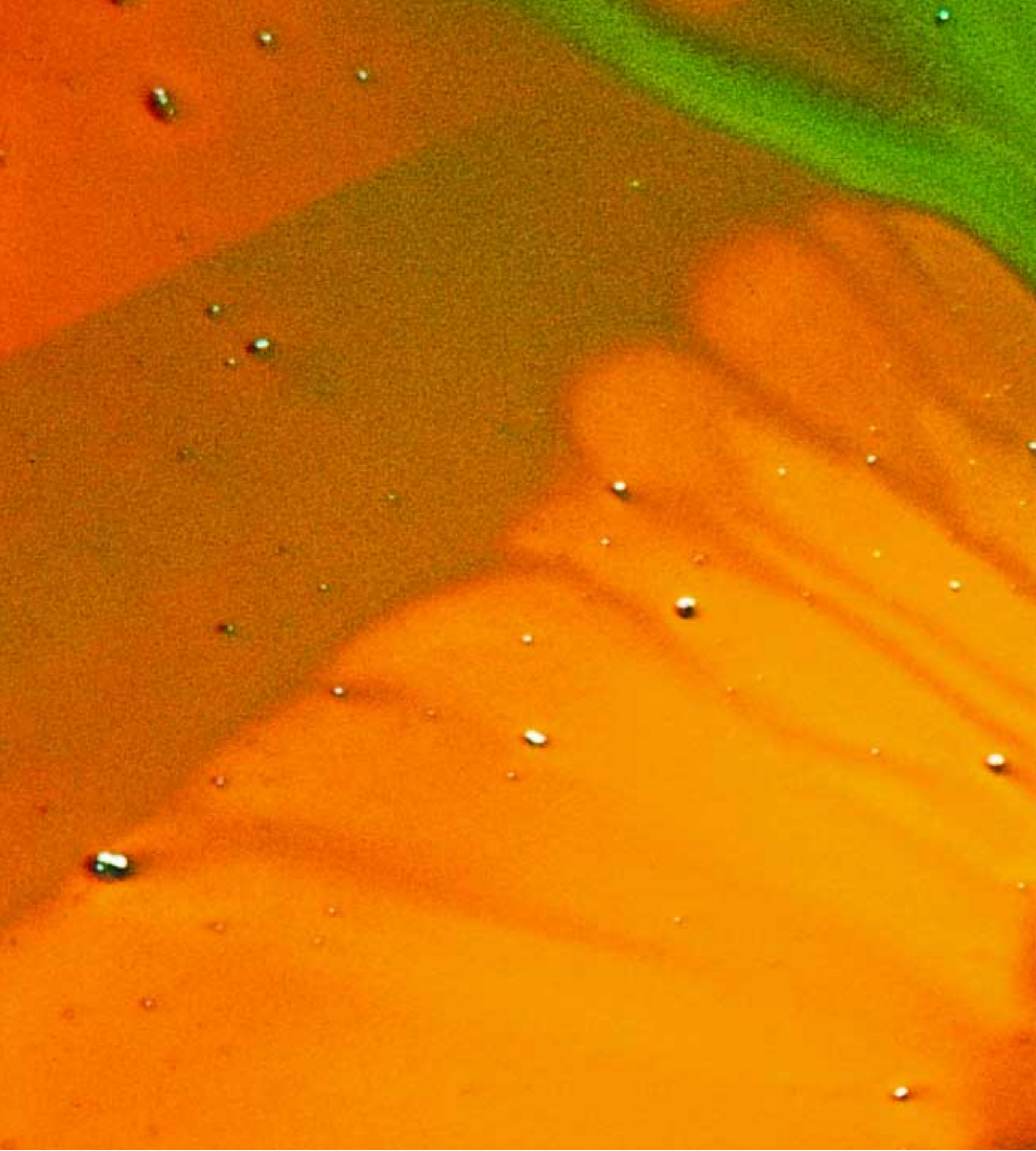
All in all, NSF's role in the birth of the Internet is a perfect example of how the right public investment can lead to huge societal pay-offs. Other stories you'll read here highlight NSF's instrumental role in such important innovations as Magnetic Resonance Imaging, or MRI, one of the most comprehensive medical diagnostic tools; the identification of the "ozone hole" over the Antarctic and chlorofluorocarbons as the probable cause; advances in the underlying mathematics of computer-aided design (CAD) and computer-aided manufacturing (CAM), two techniques that power much of U.S. industry's global competitiveness; and many other discoveries.

The point to remember is that these and other advances came only after long years of publicly funded basic research that NSF had identified as among the most promising avenues for exploration. Businesses, understandably, tend to make research investments that pay off in the short term. Other federal agencies have as their mission the oceans, energy, defense, or health, and they fund research that directly relates to those missions. In contrast, NSF's mandate is broad, deep, and long: to invest in educational programs and fundamental, multi-disciplinary research of strategic, long-term interest to the nation.

Science—The Endless Frontier, a 1945 report by Vannevar Bush, a respected engineer and President Franklin Roosevelt's science advisor, made the case for why the federal government should actively promote the progress of research and science-related education. On May 10, 1950, President Harry Truman signed the bill creating the National Science Foundation. Now, fifty years later, we are reaping the rewards of this prescient



When she assumed her post in August 1998, Dr. Rita Colwell became the Foundation's first female director. She is a nationally respected scientist and educator. Before she became NSF director, Dr. Colwell was president of the University of Maryland Biotechnology Institute and professor of microbiology at the University of Maryland where she produced the award-winning film, *Invisible Seas*. While at the University of Maryland, Dr. Colwell also served as director of the Sea Grant College and as vice president for academic affairs.



commitment. As a whole, we are a healthier, better educated, and more accomplished nation. Advances in knowledge have accounted for half of the net new growth in the U.S. economy since the end of World War II. This is a mighty return on investments made by NSF, other government agencies, and their partners in the science and engineering community. NSF's share of that investment totals nearly \$4 billion in fiscal year 2000.

We have reason to celebrate NSF's historical accomplishments, but looking back is an unusual posture for the Foundation. We are more accustomed to anticipating new frontiers so that we can enable researchers, students, and educators to get where they need to be. As we look ahead today, one of the highest priorities for NSF and its partners is information technology research. There is no area of life that has not been dramatically altered by the advent of computers. In my own work, tracking the environmental conditions that give rise to cholera outbreaks, I've gone from very early studies using an IBM 650 (a model now on display at the Smithsonian Institution) to recent, highly complex analyses of data collected from global satellites and remote sensing systems. NSF's multidisciplinary connections, its historically strong relationships with the nation's research universities, and its commitment to the public good make the agency a natural leader with regard to information technologies. That is why NSF has been asked to lead the federal government's initiative to develop faster, more powerful computers and networks.

Another priority for NSF in the next few years will be to nurture the development of an emerging area known as "biocomplexity." The NSF-led

biocomplexity initiative will lead to a better understanding of the interaction among biological, physical, and social systems. As this book illustrates, many of the most exciting discoveries occur at the intersections of multiple disciplines, where chemists help biologists see how blood vessels can be repaired with polymers and social scientists learn from mathematicians how to study the seeming chaos of human interactions. NSF is committed to joining what were once discrete disciplines into a more powerful understanding of the whole of nature.

The education of our nation's youth also remains a major concern. In an economy ever more driven by knowledge and ideas, it's paramount that we discover better ways to prepare a culturally diverse and globally competitive workforce of scientists, engineers, and other citizens. NSF has always encouraged innovation in the teaching of science, mathematics, and engineering at all grade levels and among the general public. We will continue to build the kind of synergistic partnerships among researchers, educators, policymakers, parents, and students that lay the groundwork for true reform. As NSF Deputy Director Joseph Bordogna has said, "It's not enough just to discover new knowledge; we need to train people in the use of that new knowledge if the American workforce is to prevail in the twenty-first century."

As we look to the century ahead, it is apparent that science and technology will continue to be the propelling and sustaining forces of our nation's well-being. Our quality of life will in large measure depend on the vigor of our economy, the health of our planet, and the opportunities for enlightenment. Wherever the next research challenge lies, you will find the National Science Foundation.

—Rita R. Colwell
Director

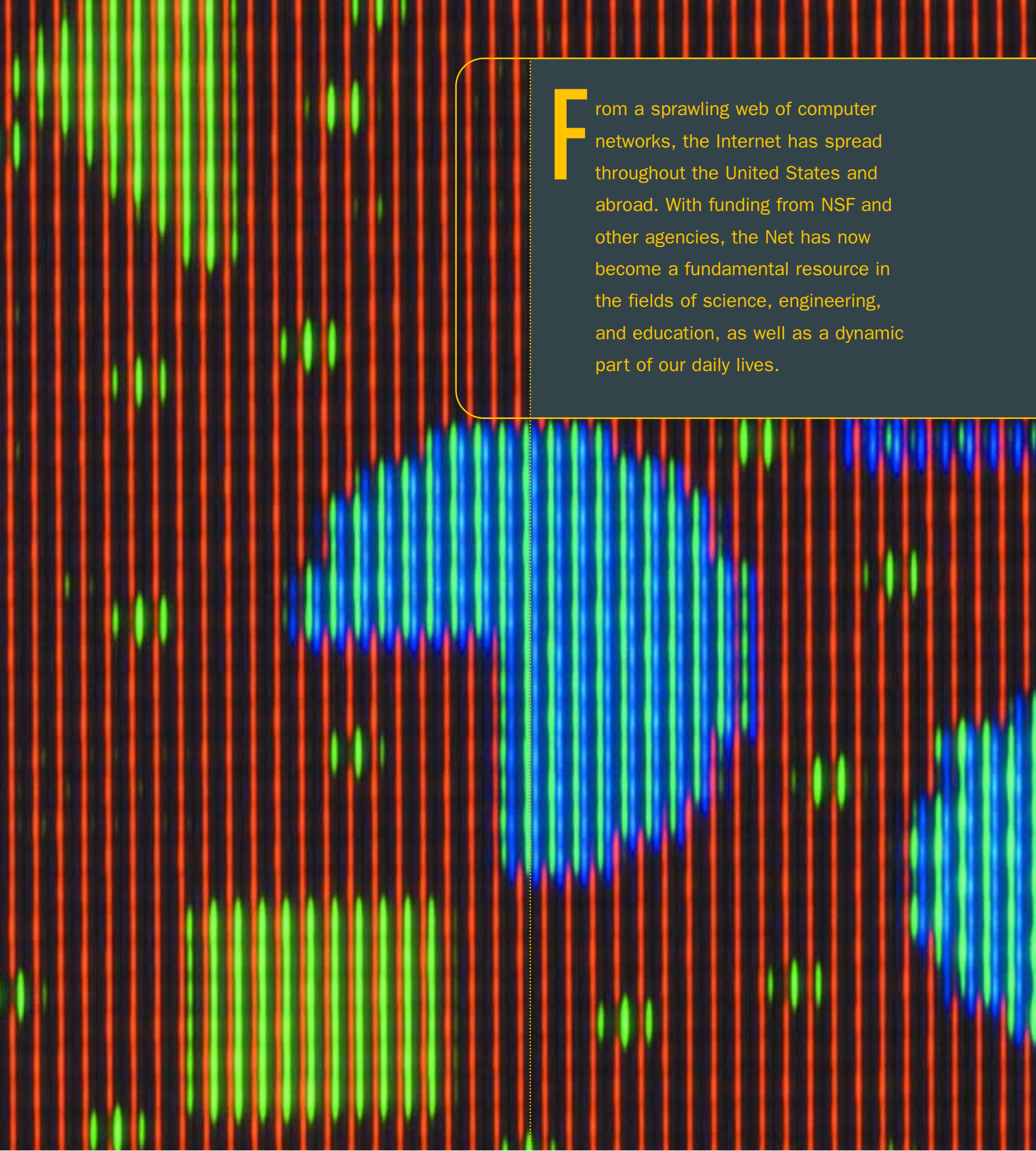


Dr. Colwell has studied the causes and cycles of the infectious cholera bacterium for more than 30 years. While working in Bangladesh recently, she demonstrated how to use sari cloth as an excellent, affordable water filter to screen out plankton associated with cholera transmission.



The Internet

**changing the way we
communicate**

The background of the entire page is an abstract digital pattern. It consists of numerous vertical lines of varying thickness and color, primarily in shades of red, green, and blue, set against a dark, almost black background. The lines are somewhat blurred and have a soft, glowing appearance, creating a sense of depth and movement. The overall effect is reminiscent of a data visualization or a digital signal waveform.

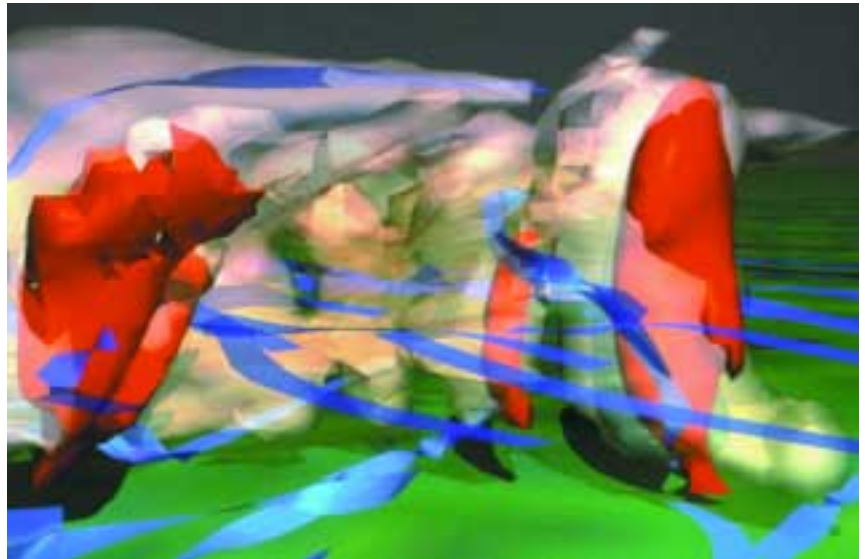
From a sprawling web of computer networks, the Internet has spread throughout the United States and abroad. With funding from NSF and other agencies, the Net has now become a fundamental resource in the fields of science, engineering, and education, as well as a dynamic part of our daily lives.



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 space-weather 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 worldwide, 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 high-end 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.

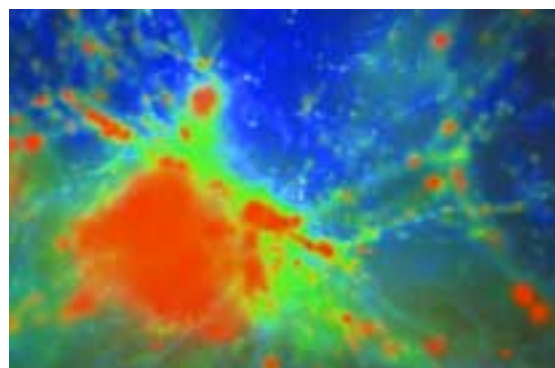
Satellites, the Hubble Space Telescope, and observatories around the world provide data to Earth-bound scientists. Once received, the data are sent, via the Internet, to researchers around the country. At the University of Illinois-based National Center for Supercomputing Applications, Frank Summers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



Mosaic: The Original Browser

By 1992, the Internet had become the most popular network linking researchers and educators at the post-secondary level throughout the world. Researchers at the European Laboratory for Particle Physics, known by its French acronym, CERN, had developed and implemented the World Wide Web, a network-based hypertext system that let users embed Internet addresses in their documents. Users could simply click on these references to connect to the reference location itself. Soon after its release, the Web came to the attention of a programming team at the National Center for Supercomputing Applications (NCSA), an NSF-supported facility at the University of Illinois.

The history of NSF's supercomputing centers overlapped greatly with the worldwide rise of the personal computer and workstation. It was, therefore, not surprising that

software developers focused on creating easy-to-use software tools for desktop machines. The NSF centers developed many tools for organizing, locating, and navigating through information, but perhaps the most spectacular success was the NCSA Mosaic, which in less than eighteen months after its introduction became the Internet "browser of choice" for over a million users, and set off an exponential growth in the number of decentralized information providers. Marc Andreessen headed the team that developed Mosaic, a graphical browser that allowed programmers to post images, sound, video clips, and multifont text within a hypertext system. Mosaic engendered a wide range of commercial developments including numerous commercial versions of Web browsers, such as Andreessen's Netscape and Microsoft's Internet Explorer.

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.



Fuzzball: The Innovative Router

Routers, sometimes referred to as gateways or switches, are combinations of hardware and software that convey packets along the right paths through the network, based on their addresses and the levels of congestion on alternative routes. As with most Internet hardware and software, routers were developed and evolved along with packet switching and inter-network protocols.

NSFNET represented a major new challenge, however, because it connected such a diverse variety of networks. The person who did more than anyone else to enable networks to talk to each other was NSF grantee David L. Mills of the

University of Delaware. Mills developed the Fuzzball software for use on NSFNET, where its success led to ever broader use throughout the Internet. The Fuzzball is actually a package comprising a fast, compact operating system, support for the DARPA/NSF Internet architecture, and an array of application programs for network protocol development, testing, and evaluation.

Why the funny name? Mills began his work using a primitive version of the software that was already known as the “fuzzball.” Nobody knows who first called it that, or why. But everyone appreciates what it does.



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 tele-manufacturing—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

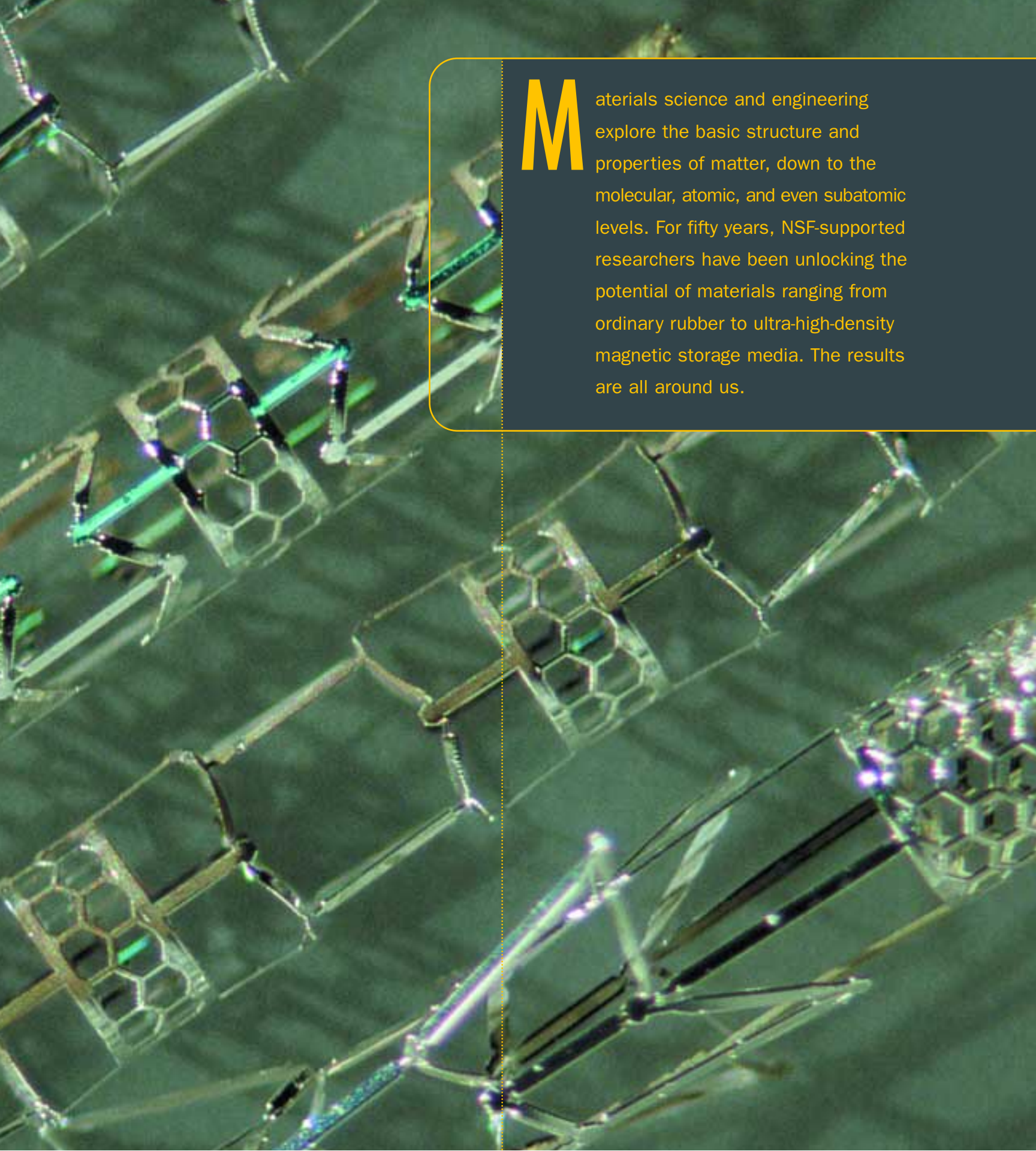
Charles Babbage Institute at University of Minnesota

www.cbi.umn.edu/darpa/darpa.htm

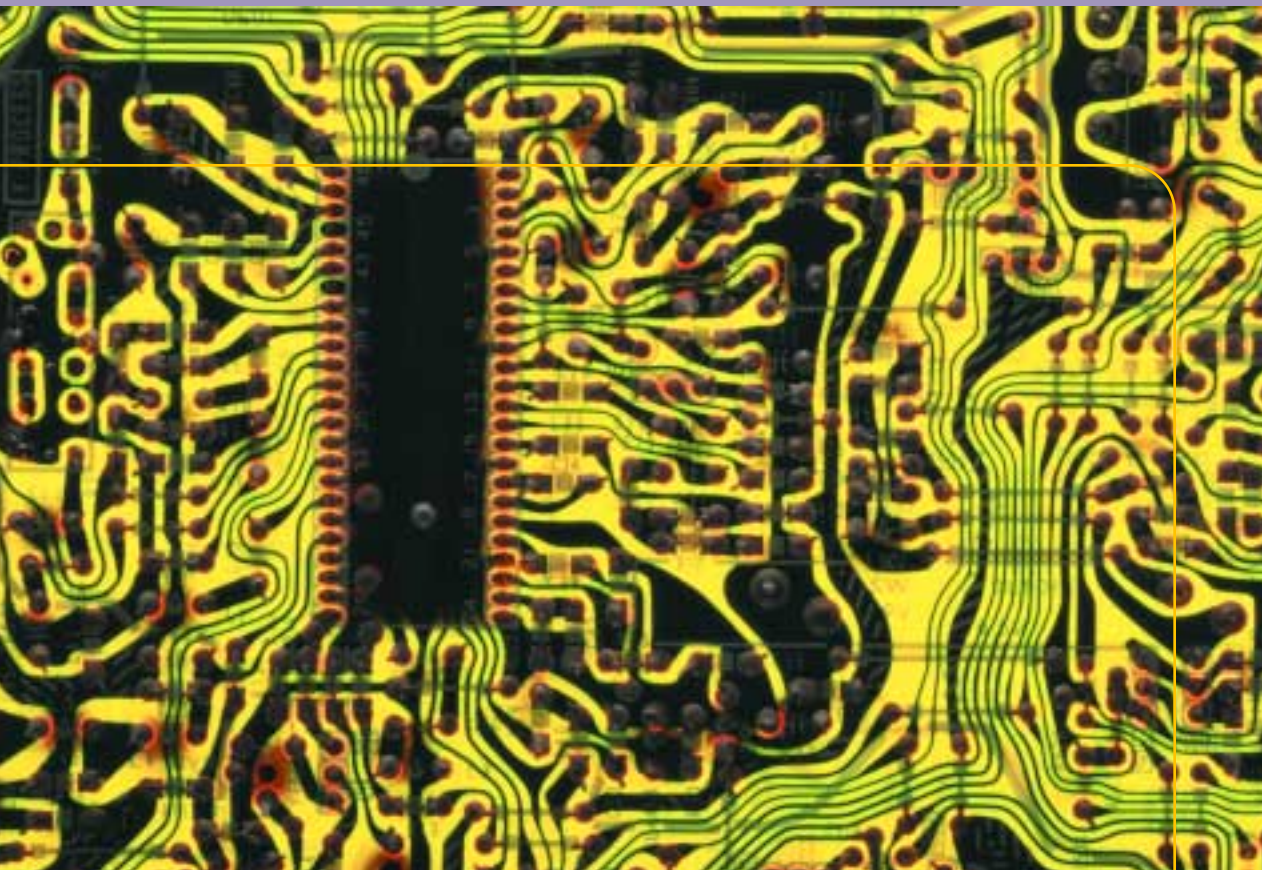
A microscopic image showing a complex lattice structure of carbon nanotubes. The structure consists of interconnected hexagonal rings of carbon atoms, forming a mesh-like pattern. The nanotubes are oriented in various directions, creating a three-dimensional network. The image is overlaid with white text.

Advanced Materials

**the stuff dreams
are made of**



Materials science and engineering explore the basic structure and properties of matter, down to the molecular, atomic, and even subatomic levels. For fifty years, NSF-supported researchers have been unlocking the potential of materials ranging from ordinary rubber to ultra-high-density magnetic storage media. The results are all around us.



NSF funds a broad array of research to discover new materials and processing methods and enhance knowledge about the structures and functions of materials. A high priority for NSF since the 1950s, materials research has led to countless innovations that now pervade everyday life. Hand-held wireless cellular telephones and oxygen-sensing anti-pollution devices in automobiles number among the breakthroughs. NSF supports both individual investigators and collaborative centers at universities, which bring together materials scientists, including engineers, chemists, physicists, biologists, metallurgists, computer scientists, and other researchers to work on projects whose commercial potential attracts significant funding from industry as well as government. Future discoveries in NSF-supported materials research laboratories will transform life in ways we cannot yet imagine. Semiconductor substrates whose storage capacity is hundreds of times greater than the current industry standard; artificial skin that the body accepts as its own; and the remarkable buckyball, a recently discovered form of carbon with unprecedented strength and hundreds of potential uses ranging from spaceships to pharmaceuticals—all these materials and more will change the way we live and work.

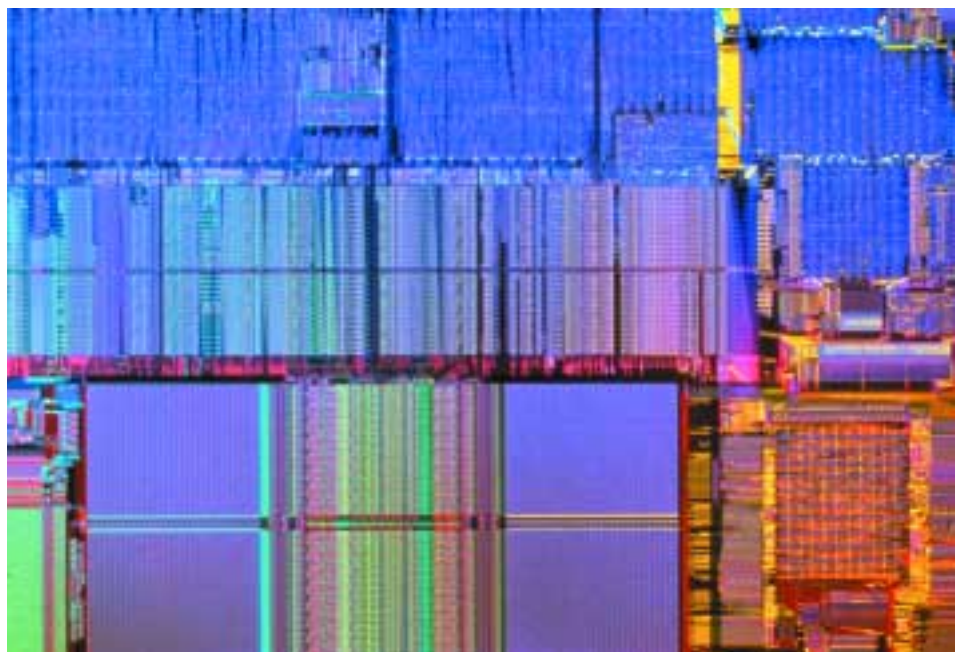
From Craft to Science in Two Centuries

What determines a civilization's ability to move forward? In large measure, it is mastery over materials. The key indicators of progress—military prowess; the ability to produce goods; advances in transportation, agriculture, and the arts—all reflect the degree to which humans have been able to work with materials and put them to productive use.

Humans have progressed from the Stone Age, the Bronze Age, and the Iron Age to the Silicon Age and the Age of Materials Science. Scientists and engineers have achieved mastery over not only silicon, but also over glass, copper, concrete, alloys or combinations of aluminum and exotic metals like titanium, plastics, and wholly new “designer materials” that are configured one atomic layer at a time.

It may seem hard to believe, but it has been only in the last 200 years that we humans have understood elemental science well enough and had the instrumentation necessary to go beyond fabrication—taking a material more or less in its raw form and making something out of it. Once we began to explore the basic structure and properties of materials, a wealth of discoveries ensued:

- Ceramics with distinctive electrical properties that make it possible to miniaturize wireless communications devices ranging from cellular telephones to global positioning technologies.



- A totally new family of materials called organic metals: conductive polymers (compounds assembled like chains, with numerous units linked together to form a whole) that are soluble, can be processed, and whose potential applications include “smart” window coatings with optical and transparency properties that can be changed electrically.

- An optic layer that fits over liquid crystal displays to maintain high contrast even when the display is viewed from an angle—now used in instrument panels of military and commercial aircraft.

- Nonlinear optical crystals of lithium niobate, a unique combination of materials that is ideal for many laser applications.

- Artificial skin that bonds to human tissue so successfully that many burn victims now heal with a fraction of the scarring that once was considered inevitable.

Microprocessors such as this one, which contains more than one million transistors, have led to advances in all areas of science and engineering. NSF support has enabled researchers to create computer chips that are incredibly tiny and can perform complex computations faster than the blink of an eye.

NSF-funded research played a pivotal role in all of these and many other innovations. Through support of individual researchers and multidisciplinary centers around the country, NSF is fueling a vast number of diverse projects in materials science and engineering. Undertaken for the purpose of advancing knowledge, many materials sciences projects also have industry co-sponsors who eagerly anticipate commercialization of the results.

With support from NSF, researchers are attempting to create materials that will improve the manufacturing of cars, furniture, and other items. Bruce Novak at the University of Massachusetts, is studying thin films such as the one below in an effort to test and produce such novel substances.

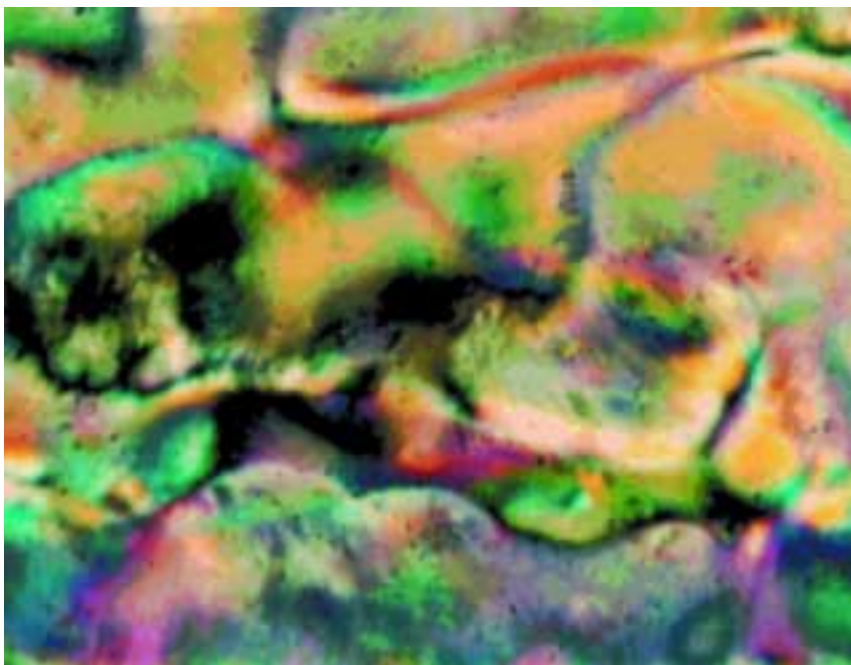
A Never-Ending Search for the New and Useful

Materials research grew out of a union among physicists, chemists, engineers, metallurgists, and other scientists, including biologists. Today, the field has a body of literature and a research agenda of its own. NSF supports both experimental and theoretical research with three primary

objectives: to synthesize novel materials with desirable properties, to advance fundamental understanding of the behavior and properties of materials, and to develop new and creative approaches to materials processing.

Materials have been high on NSF's research agenda since the earliest days. In the 1950s, NSF built on the momentum of the World War II effort by making grants to the University of Akron to help researchers with their work on durable forms of rubber that could withstand elevated temperatures and pressures. Rubber belongs to the class of materials known as polymers, gigantic molecules made up of single units, or monomers, that link together in chains of varying lengths. Other naturally occurring polymers include complex carbohydrates, cellulose, proteins, spider silk, and DNA. For the Akron researchers, it was a smooth transition from rubber to an ever-widening range of synthetic polymers, examples of which are found today in products ranging from clothing and packaging to automobile and aircraft components.

In the center of what is now called "Polymer Valley," Akron University's College of Polymer Science and Engineering houses a faculty whose names are legendary in the world of rubber and plastic. Known both for their own work—much of it funded by NSF—and for their students' contributions to industry, these faculty members include Alan Gent and Joseph P. Kennedy. Gent, an authority on deformation and fracture processes in rubbery, crystalline, and glassy polymers, served on the space shuttle redesign committee after the 1986 Challenger disaster. Kennedy conducted some of the earliest research on vulcanized rubber and has received two American Chemical Society awards for pioneering work in polymer synthesis.





The Strongest Material Ever

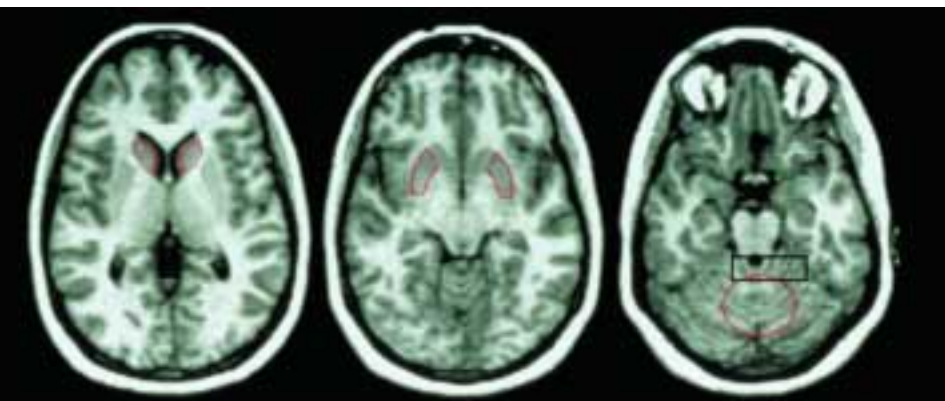
Richard E. Smalley of Rice University, a long-time NSF grant recipient, was awarded the Nobel Prize in Chemistry in 1996 for discovery of a new class of carbon structures called fullerenes. In a talk that year before the American Institute of Chemical Engineers, he discussed the discovery and where it might lead.

“When you vaporize carbon, mix it with an inert gas and then let it condense slowly . . . there is a wonderful self-assembly process where the carbon atoms hook in together to make graphene sheets that start to curl around, their incentive being to get rid of the dangling bonds on the edge. With amazingly high probability [they] will close into a geodesic dome composed of some number of hexagons and 12 pentagons.

“It turns out this graphene sheet is pretty remarkable. It has the highest tensile strength of any two-

dimensional network we know. It is . . . effectively impermeable under normal chemical conditions. Even though when we look at pictures of fullerenes we see, mostly, just a lot of hexagonal holes; if you try to throw an atom through those holes, it will generally just bounce off . . . So this graphene sheet is really a membrane, a fabric, one atom thick, made of the strongest material we expect will ever be made out of anything, which is also impenetrable. And now we realize that with pentagons and hexagons it can be wrapped continuously into nearly any shape we can imagine in three dimensions. That’s got to be good for something.”

—Richard E. Smalley, “From Balls to Tubes to Ropes: New Materials from Carbon.” Paper presented at the American Institute of Chemical Engineers, South Texas Section, January 1996.



The strong magnetic properties of superconductors made it possible for researchers to develop magnets for MRI (magnetic resonance imaging) systems. NSF-funded research into superconductivity has enabled advances in MRI technology, which, in turn, have led to more accurate diagnosis of disease.

Today's vibrant materials science community began its ascent in 1957. After the launch of Sputnik by the Soviet Union, the Department of Defense lobbied strenuously to make space-related research and technology a national priority. The effort gave birth to Interdisciplinary Laboratories (IDLs) under the Department of Defense's Advanced Research Projects Agency (DARPA). DARPA took a more integrated approach than did most universities at the time and brought together physicists, chemists, engineers, and metallurgists into collaborative research teams. They were encouraged to cross departmental boundaries and use systems approaches to attack complex problems of materials synthesis or processing. Graduate students trained in the IDLs accepted multidisciplinary research as the norm, which influenced the way they approached their own work.

In 1972, DARPA transferred the management of the IDLs—600 faculty members at twelve universities—to NSF. NSF's involvement gave even stronger emphasis to the multidisciplinary team approach in the way funding opportunities were defined. "NSF makes awards to the projects that look as if they will have the most impact on science or technology, or both," explains W. Lance Haworth, executive officer in the Division of Materials Research, which is part of NSF's Directorate for

Mathematical and Physical Sciences. "Those projects typically involve people from several disciplines. The field benefits from this approach—sparks fly at the boundaries."

One of the best places to see "sparks fly" is at the Data Storage Systems Center, an NSF-funded Engineering Research Center (ERC) at Carnegie Mellon University in Pittsburgh and the largest academic research effort in recording technology in the United States. Engineers, physicists, chemists, and materials science researchers at the Carnegie Mellon Center are working together to increase dramatically the data storage capacity of computer systems. Among their goals, Center researchers aim to demonstrate the feasibility of 100 gigabits (100 billion bits) per square inch recording density for magnetic and optical recording systems by 2003—hundreds of times higher than the current industry standard.

The Center recently made advances toward this goal by synthesizing two new materials. Each has led to the development of high-quality magneto-optic recording media for ultra-high densities. One is an artificially structured material made of very thin layers of platinum and cobalt. The other is a magnetic oxide. Both provide dramatically improved performance over current systems. In a recent breakthrough experiment, researchers achieved recording densities of forty-five gigabits per square inch with platinum and cobalt films.

Other NSF-supported centers also have taken the challenge of advancing high-density storage media. At the University of Alabama's Center for Materials for Information Technology, which is home to one of the twenty-nine Materials Research Science and Engineering Centers (MRSEC) that NSF supports. The MRSECs stress pioneering materials research, education, and outreach, and they foster multidisciplinary collaborations between academia and industry. One interdisciplinary team at University of Alabama's MRSEC is studying the

physical properties of granular films that have shown potential as a future low-noise, ultra high density magnetic media. A second interdisciplinary team at the Alabama Center is exploring the functional limits of magnetic materials in high speed switching. The work could lead to the development of hard disk drive heads and storage media that are capable of operating at frequencies approaching a gigahertz.

Other sparks at the boundaries have developed into industry standards. For example, work on semiconductor lasers made the photonics revolution of the last three decades possible. Photonics uses light for signaling and conducting information along a pathway (electronics uses electrons for the same purpose). Researchers at several NSF-funded centers, including the Center for Materials Science and Engineering at the Massachusetts Institute of Technology, are continuing research into photonics, a field that has already produced compact disk players, laser printers, bar code readers, and medical applications, as well as new systems for displaying information.

Triumphs in Everyday Life

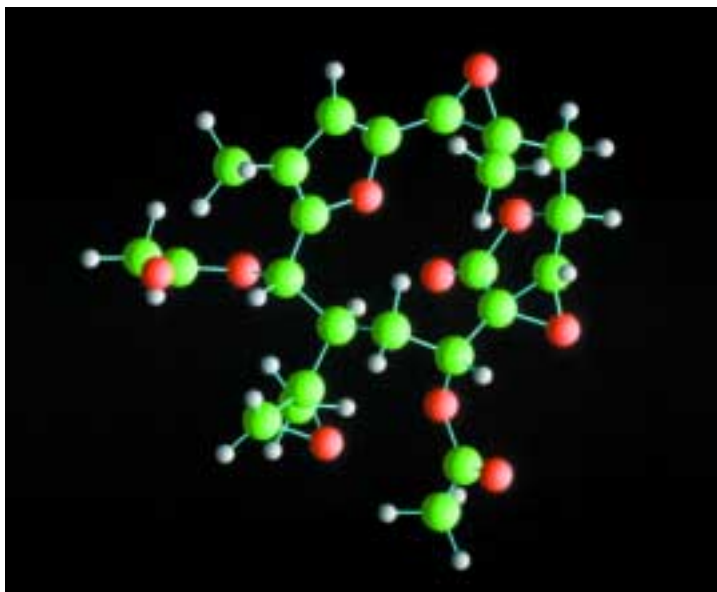
NSF supported many of the pioneers whose investigative triumphs led to innovations that are now part of everyday life. One example is Art Heuer of Case Western Reserve University, whose research on transformation toughening in ceramics led to a way of producing strong ceramics capable of operating and surviving in extremely demanding environments. As ceramics cool after firing, their tiny constituent particles expand slightly and cause occasional microcracks. To reduce the risk of cracking, the particles that make up the ceramics must be extremely small—on the order of one micron. Using zirconium dioxide-based ceramics,

Heuer and others were able to prevent cracking by using appropriate processing to control the expansion of the particles during cooling. To the delight of the automotive industry, these tough ceramics, when integrated into catalytic converters, also increased gas mileage.

Many other founders of modern-day materials science have been longtime recipients of NSF support. Alan MacDiarmid of the University of Pennsylvania and Alan Heeger of the University of California at Santa Barbara are considered the fathers of conducting polymers, or synthetic metals. MacDiarmid, a chemist, and Heeger, a physicist, were the first to demonstrate that conjugated, or paired, polymers such as polyacetylene can be “doped,” or intentionally changed to the metallic state. The process of doping involves introducing into a substance an additive or impurity that

continued on p. 28

Molecular models such as this are helping researchers discover and create the next generation of superstrong materials.



Tomorrow's Materials: Lighter, Tougher, Faster

Heavy Lifting

We are familiar with composites in recreational applications such as tennis rackets, golf clubs, and sailboat masts. These materials also bring comfort to thousands of people as prosthetic arms and legs that are much lighter than wood or metal versions. At higher performance levels, the success of satellites and stealth aircraft depends on composites.

In aircraft, weight affects every performance factor, and composites offer high load-bearing at minimal weight without deterioration at high or low temperatures. NSF-supported researchers and engineers are developing tough new materials like the resin and fiber composite used in the tail section of the Boeing 777. That composite is lighter than aluminum but far more durable and fatigue-resistant at high altitudes. Use of such advanced composites reduces the weight of an 8,000-pound tail section by 15 percent, which means designers can increase the aircraft's payload and fuel capacity.

Meanwhile, down on the ground, advanced composites are being evaluated for use in building the U.S. infrastructure for the 21st century. In one test, researchers at the Center for High-Performance Polymeric Adhesives and Composites at Virginia Polytechnic Institute and State University have partnered with the Virginia Transportation Research Council, the state Transportation Department, the town of Blacksburg, and manufacturer Strongwell to test the long-term effectiveness of composites as an alternative to steel in bridges. (The center at Virginia Tech, one of the first Science and Technology Centers

(STC) established by NSF, is transitioning to self-sufficiency after eleven years of Foundation support.) Deteriorating steel beams on the Tom's River bridge, located on a rural road near Virginia Tech, were replaced with structural beams made out of a strong composite. The new bridge was completed in 1997 and since then, Virginia Tech researchers have been closely monitoring it to determine how well the composite beams withstand the tests of time, traffic, and weather. Depending on the results of this field test and others that are planned or underway, bridges constructed of composites could become as familiar in the future as tennis rackets and aircraft made of composites are today.

Standing Up Under Stress

Designing composites is one method of fabricating novel materials with special properties. Surface engineering is another. Thermal spray processing—a group of techniques that can propel a range of materials including metals, ceramics, polymers, and composites onto substrates to form a new outer layer—has proven to be a cost-effective method for engineering surfaces that are resistant to corrosion, wear, high or low temperatures, or other stresses. Current applications include the aerospace, marine and automobile industries, power generation, paper processing and printing, and infrastructure building.

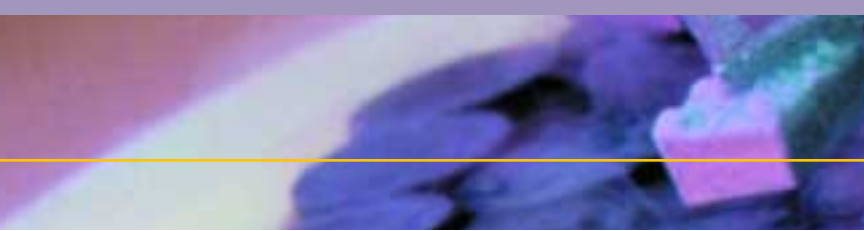
Despite this widespread use of thermal spray processing, the underlying science was little understood until recently. That's beginning to change, due in part to the work of researchers and students at the Center for Thermal Spray Research, the

NSF-supported Materials Research Science and Engineering Center (MRSEC) based at the State University of New York (SUNY) at Stony Brook, who are studying the characteristics of various spray processes, feedstock materials, and resulting spray deposits. Their goals include the development of methodology for selecting source materials and achieving a fundamental understanding of flame-particle interactions and the physical properties of spray deposits. Earlier research by Herbert Herman, the Center's director and professor of materials science at SUNY-Stony Brook, and his students advanced the use of plasma guns to apply coatings that protect against very high temperatures and corrosive environments. Plasma-sprayed coatings are commonly used on components for aircraft engines and gas turbines and in other areas where materials are required to function under extreme conditions

Superconductivity We Can Live With

A superconducting material transmits electricity with virtually no energy loss. In a world where every electrical cord steals some of the current passing through it, a room-temperature superconductor could save billions of dollars. Superconducting computers could run 100 times faster than today's fastest supercomputers.

To compare the normal electrical system with a superconductive one, imagine a ballroom filled with many dancers. In normal material, all of the dancers are moving in different directions at different times, and much of their energy is spent bumping into each other. In a superconductive material, the dancers are synchronized, moving in



unison, and therefore can spend all of their energy on the dance and none on each other. The dancers represent the electrons of each material, chaotic in the normal setting and well-ordered when the material is superconductive. While the entire theory is more complicated, the overall effect is that the electrons in superconductive material move electrically more easily through the system without wasting energy bumping into each other.

Superconductivity, which occurs in many metals and alloys, isn't yet in widespread use, however. For most of the 20th century, the phenomenon required very cold temperatures. Superconductivity was first observed by Dutch physicist Heike Kamerlingh Onnes in 1911 when he cooled mercury down to -425°F , a few degrees above absolute zero. Until the mid-1980s, commercial superconductors usually used alloys of the metal niobium and required expensive liquid helium to maintain the temperature of the material near absolute zero. The need for expensive refrigerants and thermal insulation rendered these superconductors impractical for all but a limited number of applications. That began to change in 1986 when Alex Müller and Georg Bednorz, researchers at an IBM Research Laboratory in Switzerland, discovered a new class of ceramic materials that are superconductive at higher temperatures. So far, materials have been known to reach the superconductive state at temperatures as high as -209°F , making it possible to use liquid nitrogen coolant, a less costly alternative to liquid helium. Since the mid-1980s, much of the current research has focused on so-called high temperature superconductors. The new superconducting ceramics are hard and

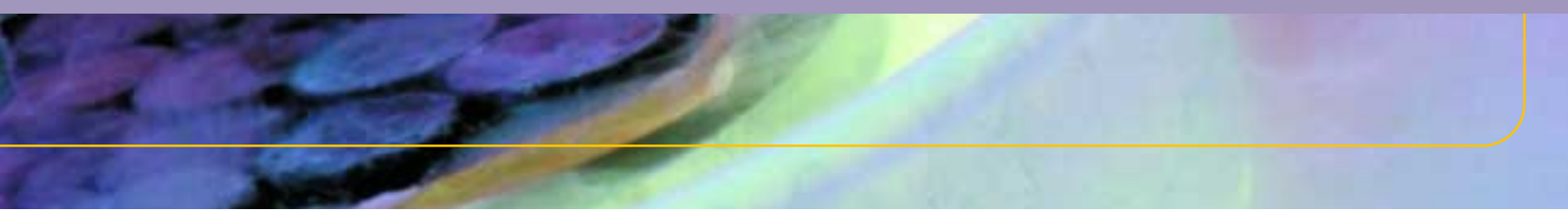
brittle, making them more difficult than metal alloys to form into wires. An interdisciplinary team at the NSF-supported MRSEC on Nanostructured Materials and Interfaces, based at the University of Wisconsin-Madison, is focusing on understanding the properties of the grain boundaries of high temperature superconductors. The center's research could lead to better materials processing and the development of a new generation of superconductors for high current and high magnetic field technology.

Even as research continues, superconductors are being used in a number of fields. One of the more visible is medicine. Superconductors have strong magnetic characteristics that have been harnessed in the creation of magnets for MRI (Magnetic Resonance Imaging) systems. An MRI takes images of a patient by recording the density of water molecules or sodium ions within the patient and analyzing the sources. When used for brain scans, this technique allows clinicians to identify the origin of focal epilepsy and to pinpoint the location of a tumor before starting surgery. Similar magnetic resonance systems are used in manufacturing to test components for cracks and other defects.

One of the preeminent facilities for researchers and engineers to test superconductivity and conduct other materials research is the National High Magnetic Field Laboratory (NHMFL), a unique laboratory funded by NSF's Division of Materials Research and the state of Florida and operated as a partnership between Florida State University, the University of Florida, and the Los Alamos National Laboratory in New Mexico. Since it was established

in 1990, the NHMFL has made its state-of-the-art magnets available to national users for research in a variety of disciplines including condensed matter physics, chemistry, engineering, geology, and biology, as well as materials science. The NHMFL features several of the world's most powerful magnets, including a hybrid magnet, developed jointly with the Massachusetts Institute of Technology, that delivers continuous magnetic fields of 45 tesla, which is about one million times the Earth's magnetic field. The 45 tesla hybrid consists of two very large magnets. A large resistive magnet (electromagnet) sits at the center of a huge superconducting magnet, which forms the outer layer and is the largest such magnet ever built and operated to such high field. The hybrid's record-setting constant magnetic field strength gives researchers a new scale of magnetic energy to create novel states of matter and probe deeper into electronic and magnetic materials than ever before.

The NHMFL's 45 tesla magnet is cooled to within a few degrees of absolute zero using a superfluid helium cryogenic system. The discovery of superfluid helium was made in 1971 by NSF-funded researchers at Cornell University who found that, at extremely low temperatures, the rare isotope helium-3 has three superfluid states, where the motion of atoms becomes less chaotic. This discovery by David Lee, Douglas Osheroff, and Robert Richardson led to greatly increased activity in low temperature physics and furthered studies of superfluidity. Lee, Osheroff and Richardson received the 1996 Nobel Prize in Physics for their contributions to the field.



continued from p. 25

produces a specific and deliberate change in the substance itself. Their work stimulated research worldwide on metallic organic polymers; applications include rechargeable batteries, electromagnetic interference shielding, and corrosion inhibition. Heeger, MacDiarmid, and Japanese researcher Hideki Shirakawa were awarded the 2000 Nobel Prize in Chemistry for the discovery and development of conductive polymers. Another longtime NSF grantee is Richard Stein, who established the highly respected Polymer Research Institute at the University of Massachusetts at Amherst and is known for developing unique methods for studying properties of plastic films, fibers, and rubbers.

One of NSF's best known principal investigators is Richard Smalley of Rice University, who in 1985 discovered a new form of carbon with astounding properties and potential for useful applications. The Buckminsterfullerene, named for the American architect R. Buckminster Fuller, is a hollow cluster of 60 carbon atoms that resembles one of Fuller's geodesic domes. It is the third known form of pure carbon, the first two being graphite and diamond, and is the most spherical and symmetrical large molecule known to exist. "Buckyballs," for which Smalley and his colleagues Harold W. Kroto and Robert F. Curl received the Nobel Prize in chemistry

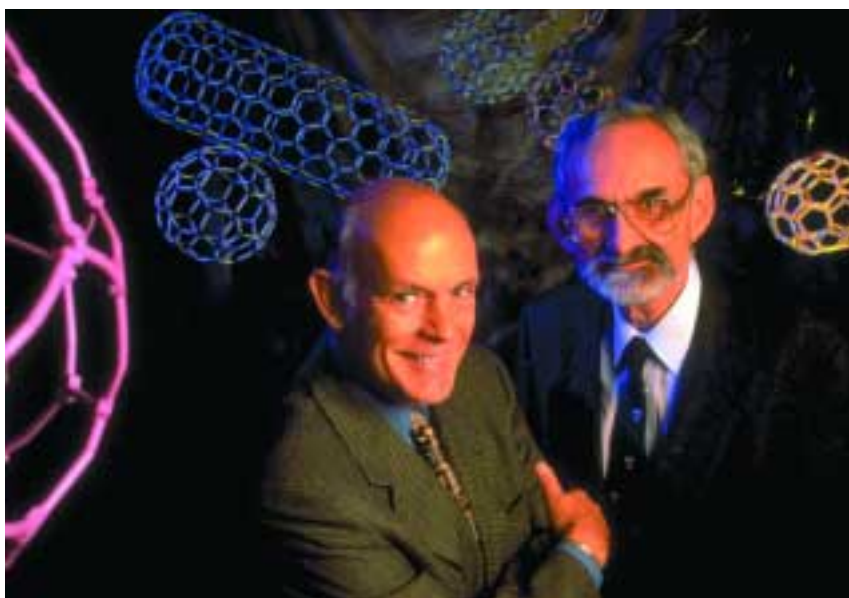
in 1996, are exceedingly rugged and very stable, capable of surviving the temperature extremes of outer space. Numerous applications have been proposed, including optical devices, chemical sensors and chemical separation devices, batteries, and other electrochemical applications such as hydrogen storage media. In addition, medical fields are testing water-soluble buckyballs, with very promising results. The soccer-ball-shaped form of carbon has been found to have the potential to shield nerve cells from many different types of damage including stroke, head trauma, Lou Gehrig's disease, and possibly Alzheimer's disease.

Designer Molecules Reach New Heights

Smalley and his colleagues discovered fullerenes serendipitously while exploring the basic structure and properties of carbon. In contrast, other NSF-supported investigators deliberately set out to create novel materials with desirable properties. An example is Samuel Stupp, currently Professor of Materials Science at Northwestern University, whose successes while he was at the University of Illinois at Champaign-Urbana were described by writer Robert Service in the April 18, 1997 issue of *Science* magazine.

"Living cells are masters of hierarchical building. For much of their molecular architecture, they first string together amino acids into proteins, then assemble proteins into more complex structures. Chemists have been working to imitate this skill, in the hope of making new materials tailored right down to the arrangement of molecules. Researchers at [the University of Illinois] report taking this assembly process to a new level of sophistication, creating molecules that assemble themselves over several size scales, first forming clusters, then sheets, and, ultimately, thick films. Because the building-block molecules are all oriented in the same direction, the films' properties mirror those

Nobel laureates Robert Curl and Richard Smalley pose with their buckyball models. This superstrong carbon molecule may have applications to chemistry, medicine, and manufacturing.



of the individual molecules, yielding a bottom surface that's sticky and a top that's slick. This property could make the films useful for everything from anti-icing coatings on airplane wings to anti-blood-clot linings for artificial blood vessels . . .” More recently, Stupp and his research team have had success using molecular self-assembly to change the properties of polymers. Their self-assembly method has potential for producing extremely strong polymers and polymers with improved optical properties, and it could impact such diverse fields as the plastics industry, medicine, and optical communications.

Other advances in new materials are coming out of NSF-supported basic research in the field of condensed-matter physics. Researchers at the NSF-funded centers at the University of Chicago and Cornell University are investigating the fundamental physical structure and properties of material when it is placed under extreme conditions—such as low temperature, high pressure, and high magnetic fields. Investigators look at the novel compositions and structures with extraordinary electrical and optical properties, including metals, insulators, semiconductors, crystals, and granular material. They also learn to control that structure—for example, moving electrons around on the surface of the material. Among other applications, this work will be important as engineers work at creating ultra-high performance computer chips. Other researchers at Michigan State University and Northwestern University are also looking at solid-state chemistry and have synthesized metals with highly efficient thermoelectric properties—that is, the ability to generate electricity when junctions between the metals are maintained at different temperatures. Thermoelectric materials already are used in space applications, but as they improve they may be useful in environmentally friendly refrigeration, thermal suits for diving, and cooling systems for electronic devices.

The Healing Arts Embrace Materials Science

Recent advances in NSF-supported biomaterials research are hastening the development of innovative healing aids. Researchers at Georgia Institute of Technology, California Institute of Technology, and Massachusetts Institute of Technology (MIT) are working with physicians and biological specialists to develop polymer composites for patching wounds, biocompatible casings for cell transplants, scaffolds that guide and encourage cells to form tissue, bioreactors for large-scale production of therapeutic cells, and experimental and theoretical models that predict behavior of these materials *in vivo*. Biomaterials have already been developed to block unwanted reactions between transplanted cells and host tissue and to help prevent scarring during healing. Closest to commercialization is a polymeric material, synthesized at MIT, to which biological cells can adhere. Because the human body accepts biological cells while it might reject the overlying synthetic material, this breakthrough makes possible the development of inexpensive multilayer materials that can promote healing, act as artificial skin, or temporarily replace connective tissue until the body can produce natural tissue to complete the healing process.

Another NSF-supported technology for skin replacement, developed by Ioannis V. Yannas of MIT and his colleagues, received FDA approval in 1996. The Yannas technology addresses the challenge of treating severe burns that result in the loss of dermis, a layer about two millimeters thick that lies beneath the epidermis and does not regenerate when damaged. Traditionally, patients with such severe burns receive skin transplants from sites elsewhere on their bodies, a method that results in scarring. The new technology



NSF-funded researcher Lynn Jelinski at Cornell University is using spiders' silk as a model for creating an incredibly strong and resilient polymer that will have a variety of practical applications.

involves collagen taken from animal tendons. Collagen is part of the structural scaffolding in mammals (analogous to cellulose in plants) that allows tissues to maintain their shape. This collagen is chemically bonded with glycosaminoglycan (GAG) molecules, from animal cartilage, to create a simple model of the extracellular matrix that provides the basis for a new dermis. The collagen-GAG combination “makes a simple chemical analog of the matrices in our own tissues,” Yannas explains. GAG cells synthesize a new dermis at the same time that the scaffold is being broken down. Epidermis then grows naturally over the new dermis, unless the wound area is especially large. Patients end up almost completely free of disfiguring scars. The new skin also grows as the patients do, an important consideration for children who have been burned.

Materials for a Small Planet

A number of NSF-supported investigators are looking for more environmentally benign substitutes for chemically synthesized materials currently in use. Dragline silk from the orb-weaving spider *Nephila clavipes* is one of the most promising new biomolecular materials, thanks to the silk's great strength and flexibility—greater even than the lightweight fiber used to reinforce bulletproof

helmets. Also attractive is the environmentally friendly process used to make the silk, which the spider spins from a water-based solution. Intrigued by this spider, which actually makes seven different types of silk, Lynn Jelinski, then at Cornell University and currently chemistry professor and Vice Chancellor for Research and Graduate Studies at Louisiana State University, had a vision that high-performance, renewable, silk-like polymers eventually can be made using the tools of biotechnology. She thinks scientists may be able to synthesize the key spider genes and insert them in plants, which then would express the protein polymers. The resultant materials might be used in products ranging from reinforced tennis rackets to automobile tires.

Discoveries of new materials lead to new questions, the answers to which create opportunities to find still more new materials. An example of this cycle is the work of Donald R. Paul of the University of Texas at Austin, an authority on the ways in which polymers interact when blended. Polymer blends are a powerful way of enhancing toughness or otherwise tailoring the performance of a given material. The information generated by Paul's research may lead to the development of high-performance polymeric alloys that could be used to replace metal components in automobiles. These lightweight and easy-to-fabricate alloys could help create vehicles that have greater fuel efficiency and produce fewer emissions.

At the same time, materials synthesis research is being used to investigate new metal alloys. To create these alloys, researchers must learn about the chemistry of the alloy, the microstructure basic to the alloy, and its macroscopic behavior. NSF-funded researchers, including those at the University of Alabama at Birmingham, are investigating how to control the alloy composition. Some of the alloys are thin films that will find their way into the electrical industry. Others may be used in newly designed vehicles. These alloys are not only stronger and lighter than their predecessors, but also more resistant to stress and fatigue, producing a more fuel-efficient, longer-lasting vehicle.

In research supported jointly by NSF and the U.S. Environmental Protection Agency, an environmentally benign method of polymer synthesis was discovered using liquid carbon dioxide in place of toxic volatile organic solvents. The work by Joseph DeSimone, professor of chemistry at the University of North Carolina at Chapel Hill and professor of chemical engineering at North Carolina University, and his graduate students received one of *Discover* magazine's 1995 Awards for Technological Innovation. The discovery led DeSimone and his colleagues to patent an environmentally friendly process for dry cleaning clothes that uses carbon dioxide instead of perchloroethylene, a highly toxic organic solvent in

wide use throughout the industry. As the lead principal investigator for the NSF-supported Science and Technology Center for Environmentally Responsible Solvents and Processes, DeSimone continues to advance research into environmentally safe solvents. Meanwhile, other work in polymers focuses on finding ways to use plastics in place of silicon as the base material of microcircuits.

"Materials research is pushing the edge of the technologies of a whole array of societal systems," said NSF Deputy Director Joseph Bordogna in an interview for NSF's publication, *Frontiers*. "It's a very powerful catalyst for innovation. As new materials become available and processable, they will make possible improvements in the quality of life. And that's the heart of the leadership issue and the competitiveness issue, isn't it? That's the future."

To Learn More

NSF's Division of Materials Research (DMR)

www.nsf.gov/mps/dmr/start.htm

NSF Materials Research Science and Engineering Centers (MRSEC)

www.nsf.gov/mps/dmr/mrsec.htm

NSF Engineering Research Centers (ERC)

www.eng.nsf.gov/eec/erc.htm

NSF Science and Technology Centers (STC)

www.nsf.gov/od/oia/programs/stc/start.htm

Department of Defense Advanced Research Projects Agency (DARPA)

www.darpa.mil

National High Magnetic Field Laboratory

www.magnet.fsu.edu

The Nobel Prize in Chemistry 1996

www.nobel.se/chemistry/laureates/1996/index.html

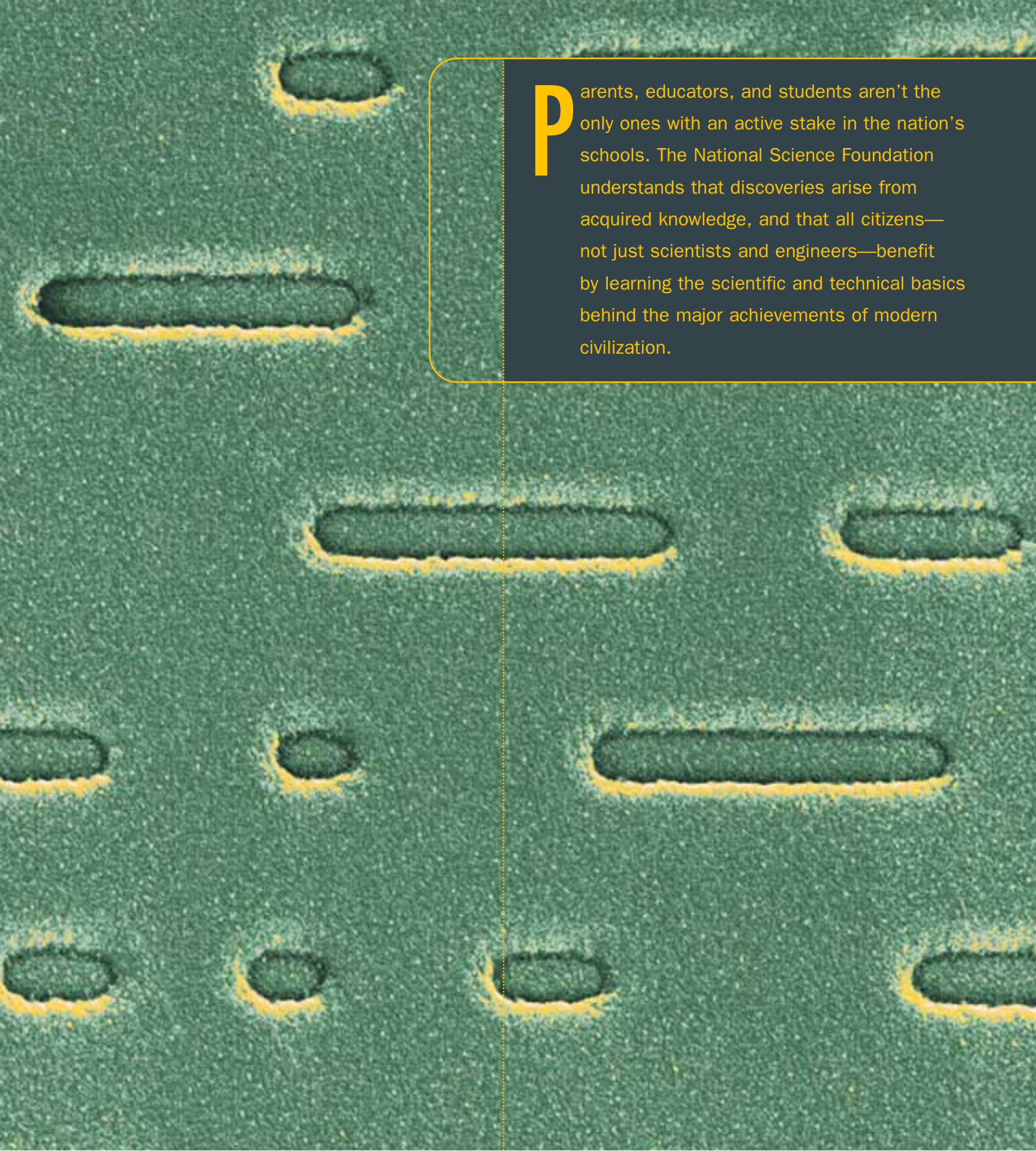
The Nobel Prize in Physics 1996

www.nobel.se/physics/laureates/1996/index.html



Education

lessons
about learning



Parents, educators, and students aren't the only ones with an active stake in the nation's schools. The National Science Foundation understands that discoveries arise from acquired knowledge, and that all citizens—not just scientists and engineers—benefit by learning the scientific and technical basics behind the major achievements of modern civilization.



Education—When it comes to scientific progress, classrooms are just as important as laboratories. That's why nearly 20 percent of NSF's budget is devoted to improving students' grasp of science, mathematics, engineering, and technology—at all levels, pre-kindergarten to postdoctoral. From the agency's Sputnik-inspired reforms of science and mathematics curricula to today's basic research into human acquisition of knowledge, NSF has devoted itself to answering two fundamental questions: How do students learn and what should they know?

The Evolution of Education

Reading, writing, and arithmetic. Rote memorization and drills. American children in the first half of the twentieth century were taught according to the philosophy that the mind was a muscle, which could best be strengthened by lectures and the mental equivalent of push-ups. By the 1950s, critics complained that schools had become little more than vocational sorting stations, sending this child into shop class, that child into family life class, and preparing relatively few for the rigors of college.

All that changed in October 1957 with the Soviet Union's launch into orbit of *Sputnik*, the first-ever artificial satellite. The Russian achievement served as a wake-up call for Americans who realized they needed to improve U.S. science and mathematics education to compete in a science- and technology-driven world. The space race was on, and only a highly educated group of homegrown scientists and engineers could get Americans to the moon ahead of the Russians. For the first time, education in the United States became a major federal imperative.

The government, perceiving a national crisis, turned to the young National Science Foundation, which had established strong ties to the country's research universities. With the National Defense Education Act of 1958, Congress called upon NSF to attend to kindergarten through twelfth-grade (K-12) education in mathematics and science. Later, Congress explicitly added social studies to the mandate.

Over the next twenty years, the Foundation spent \$500 million on elementary and secondary school curricula and teacher development. Teams of scientists, educators, and teachers worked together to develop new curricula in physics, biology, chemistry, and mathematics. At the same time, uni-

versities held hundreds of summer programs to assist teachers in understanding and using the new materials.

Two aspects of the new curricula distinguished them from their predecessors. First, there was an emphasis on basic principles. How do waves form? What keeps molecules from flying apart? What are functions? Second, there was an assumption that students would best learn basic scientific principles by actually performing experiments rather than simply memorizing facts.

In a 1977 survey, NSF found that 41 percent of the nation's secondary schools were using at least one form of the science curricula developed with NSF funds. In contrast, fewer than 10 percent of schools were using NSF-funded math materials, which many found confusing. Despite the partial success, Congress reined in much of the NSF curriculum effort by the late 1970s. Lawmakers' objections to a new social science curriculum and a general lack of enthusiasm for major changes in education were largely to blame. The decline continued in the early 1980s when the administration's goal of a smaller federal government resulted in budget cuts that hit NSF's education programs particularly hard.

But then the tide turned again. In 1983, a federally commissioned report entitled *A Nation at Risk* warned of "a rising tide of mediocrity" in the nation's schools that was serving to erode America's leadership in the world economy. The report triggered fresh calls for the setting of national or at least state-level education standards and sent NSF back into the K-12 education arena with renewed vigor.

New Approaches for New Times

Today, NSF is once again an influential player in the search for better instructional materials and methods, largely through the efforts of its Directorate for Education and Human Resources. The current programs embody what was learned from the successes and disappointments of earlier years, and also reflect the importance of science and technology to the U.S. economy—and hence, to the country’s workforce and citizenry.

A defining feature of today’s curriculum reform movement is the emphasis on all students. Regardless of whether they intend to pursue science-related careers or even to go to college, all students should receive quality mathematics and science instruction before they leave high school. And at NSF, “all students” means everyone, including girls and women, persons with disabilities, and ethnic minorities—groups that remain underrepresented in the nation’s science and engineering communities.

Of course, what constitutes a good way to learn and teach science and mathematics remains a matter of some debate, as evidenced by the current effort to develop and implement standards. State and local districts now have two sets of national standards to guide them: the 1989 standards put forth by the National Council of Teachers of Mathematics and the 1996 National Science Education Standards established by the National Research Council. Both sets of standards grew out of long processes, including in-depth consultations with the science and mathematics communities, with teachers and educational researchers, and with others concerned about the issue.

NSF-funded curriculum development teams are also drawn from a broad spectrum of the science, mathematics, and educational communities. In their standards-based approaches, these teams are moving beyond the kind of learning-by-doing that asks students to conduct experiments or

manipulate mathematical equations with the simple goal of getting an already-determined result—doing things the “right” way to get the “right” answer. In the new “inquiry-based, problem-oriented” curricula, students become participants in discovery by using fact-based knowledge to think through open-ended problems in a variety of ways.

Making Mathematical Connections

Take *Connected Mathematics*, for example, a middle-school instructional series developed in part with NSF funds. In 1999, these materials were being used in more than 2,200 school districts across the country. *Connected Mathematics* was judged the best of four—and only four—sets of middle-school mathematics materials receiving an excellent rating from Project 2061, a curriculum reform effort of the American Association for the Advancement of Science. The three other top-rated instructional materials—*Mathematics in Context*, *MathScape*, and *Middle Grades Math Thematics*—were also developed with NSF funds. None of these materials, however, are as yet in wide use.

What’s so different about *Connected Mathematics* and the other top-rated materials? Ask Linda Walker, a teacher at Cobb Middle School in Tallahassee, Florida, who participated in the development of *Connected Mathematics* and whose school district implemented the series with the help of an NSF grant.

“When I went to school,” she says, “there was one way to do a mathematics problem—the teacher’s way. He’d show you how to work the problem, repeat it, and move on. With *Connected Mathematics*, I set up a problem and then let the kids explore for answers. They gather data, share ideas, look for patterns, make conjectures, develop strategies, and write out arguments to support their reasoning. Instead of getting bored, they’re getting excited.”

Excellence in Higher Education

The longest running education program offered by the National Science Foundation is the Graduate Research Fellowship, which provides funds and national recognition to university students working toward careers in science or engineering. In 1952, NSF's first fully budgeted year, almost half of the agency's \$3.5 million appropriation—\$1.5 million—was disbursed in the form of research fellowships to 573 graduate students, 32 of them women.

From the start, awardees considered the NSF fellowships prestigious and career-making. More than one member of the class of 1952 has kept the telegram that brought the news of his or her good fortune. World-famous biologist and Pulitzer Prize-winning author Edward O. Wilson recalls that “the announcements of the first NSF pre-doctoral fellowships fell like a shower of gold on several of my fellow [Harvard] students in the spring of 1952. I was a bit let down because I wasn't amongst them.” Wilson's spirits lifted the following Monday when he got his own, albeit belated, notice.

Of the thousands of young scientists who have received fellowships over the years, many have made significant contributions in a wide variety of fields and eighteen have gone on to win Nobel Prizes. Says Donald Holcomb, professor emeritus of physics at Cornell University and a 1952 graduate research fellowship recipient, “I do think it is fair to say that the coincidence of the career spans of me and my contemporaries with the life span of the National Science Foundation created a symbiosis which has profited both us as individuals and American science at large.”

Today graduate research fellows—and, in fact, all science and engineering students—have a large number of superior colleges and universities that they can attend, almost anywhere in the United States. But it wasn't always so. NSF's science development programs—better known as the Centers of Excellence—were created in 1964 in response to

several national concerns: the growing population of college and university students, the explosion of scientific and engineering knowledge, and the fact that the country's top-notch research schools were concentrated in only a few regions of the country. Through such programs as the University Science Development Grants, the Departmental Science Development Grants, and Special Science Development Grants, NSF helped degree-granting institutions all around the United States strengthen the quality of their science-related research and education activities during the 1960s and 1970s.

“NSF provided the seed money for the development of institution-wide master plans, and also helped to fund the implementation of those plans,” says Judith Sunley, NSF interim assistant director for Education and Human Resources. “Then the universities took over, providing the funds to maintain excellence over the long haul.”

The first grants were announced by President Lyndon Johnson in 1965. By 1972, when the last science development awards were made, NSF had distributed \$233 million in 115 grants to 102 public and private institutions in forty states and the District of Columbia. Institutions used the grants primarily to recruit strong faculties, support postdoctoral scientists and graduate students, acquire sophisticated equipment and materials, and construct, modernize, and renovate laboratories, libraries, and other special facilities for research and teaching.

NSF's Centers of Excellence program resulted in stronger science and engineering departments across the United States. The program's impact continues to be felt by succeeding generations of science and engineering students.

(Information on the graduate research fellows' Class of 1952 is based on material gathered by William A. Blanpied, NSF's Division of International Programs.)

In one recent eighth-grade class, Walker asked her students to redesign a brand-name cereal box to use less cardboard while putting the same amount of cereal in the same number of boxes on a grocery shelf. There was no single right answer—the goal was just to come up with a more environmentally friendly box design and, as a result of the exercise, learn about the ratio of surface area to volume.

Walker says she could have had her students just crunch out formulas, but too much would have been lost in the process. “The importance of a student’s exploration is that you, as the teacher, can see what they’re *really* understanding,” she says. “Getting a correct answer is only one goal. Are they comfortable with fractions or do they avoid them in their calculations? What do their guesses tell you about what they know and don’t know?”

Science Instruction Changes Course

As for science courses, among the many inquiry-based curricula developed with NSF funds is *Active Physics*, a course for high school students that creatively organizes physics content. Usually, students study physics in a predictable way: mechanics during the fall term, waves in the winter, then electricity and magnetism in the spring. With *Active Physics*, students explore concepts in one of six thematic areas, such as medicine or sports.

In one classroom exercise, students draft a mock proposal to NASA under a scenario in which the space agency, as part of its plans for a moon colony, is soliciting ideas for how to encourage exercise among the colonists. The students’ challenge is to invent or modify a sport so that colonists can play it in the meager gravity of the moon’s environment. As a result, students learn about friction’s relationship to weight and discover that there is little friction on the moon. They learn why moon football might put a premium on lifting opponents out of the way rather than trying to push them, and why figure skaters would need larger ice rinks for their quintuple jumps.

“Why don’t kids like mathematics and physics but do like English and social science?” asks Arthur Eisenkraft, science coordinator for the Bedford Public Schools in New York. Eisenkraft developed *Active Physics* with NSF funds and the help of leading physicists, physics teachers, and science educators. “At least one reason is that something like *Grapes of Wrath* can spark kids to share their own experience with poverty or hopelessness. They get to contribute to the discussion, really contribute, not just . . .”—raising his hand in imitation of a student with the right answer to a math question—“. . . 4.3. With *Active Physics*, students never ask me, ‘why are we learning this?’ And my AP [Advanced Placement] kids get just as much out of it as my LD [learning disabled] kids.”

Most widely used middle and high school science textbooks do not yet reflect these new approaches, though a growing body of evidence suggests that they should. The Third International Mathematics and Science Study (TIMSS), conducted in 1995, involved forty-one countries at three grade levels and compared students’ grasp of mathematics and science. U.S. students scored above the international average in both mathematics and science at the fourth-grade level, dropped below average in mathematics at the eighth-grade level, and by twelfth grade were among

These high school scientists are engaged in a hands-on *Active Physics* exploration. The *Active Physics* curriculum, developed with the help of NSF funding, helps students to better understand and appreciate the unseen forces that shape our daily lives.



the worst performers in both science and math. In May 1999, however, a study involving NSF-funded curricula and teacher development efforts showed that they seemed to be making a difference. When given the physics portion of the TIMSS test, students who were learning physics with NSF-supported curricula or from teachers trained in NSF-funded projects posted scores significantly higher than U.S. students in the initial TIMSS assessment.

Curriculum reform is a work in progress. However, even the best reformulated instructional materials won't be enough to sustain real improvement in students' grasp of science and mathematics. Just ask their teachers.

A More Synergistic Whole

In July 1999, Gerry Wheeler, executive director of the National Science Teachers Association (NSTA) and a long-time veteran of the curriculum reform effort, stood before a crowd of teachers gathered to learn about the latest NSF-sponsored K-12 curricula.

"We've been saying the same thing since Sputnik," he exclaimed. "We need inquiry-based curricula, we need to make thinking citizens of our children. But we also need to do more than just produce good material." He pounded the lectern once or twice for emphasis, as if to mark time with the teachers' nodding heads. "What good is the best textbook if teachers aren't given the time, material, and support they need to prepare themselves to use it?"

One of the things NSF learned from its curriculum reform efforts in the 1960s and 1970s was that more needed to be done to prepare teachers to use new materials. Today that means setting up training opportunities that meet not just for a couple of weeks in the summer but also in the evenings or on the weekends, or even over the Internet—whatever best accommodates the teachers' own schedules and far-flung locations. Teachers learn not just about the content of the



new curriculum, but also the practical aspects of implementing it. This includes everything from new ways to assess student progress (for example, through students' daily journals) to suggestions for gaining support from parents, colleagues, and school boards. NSF programs also encourage school districts to free up senior teachers already trained in the new curricula to coach others.

Stronger professional development for teachers and improved materials are crucial, but by themselves won't be enough to make a major difference in the way students learn. What's needed is a larger vision that addresses all the factors affecting the success of a student's educational experience. At NSF, a key part of that vision can be summed up in two words: systemic reform.

The idea is simple even if the execution is not—in order for a better set of practices to take hold in a school, everything influencing the school system must be reevaluated, from parental involvement right on up to statewide laws and policies concerning education. NSF launched the Statewide Systemic Initiatives (SSI) program in 1991. In the program's first three years, NSF provided funds to twenty-five states and Puerto Rico to help them start on systemic reform. Today, seven states and Puerto Rico are participating in a second phase of the SSI program. In addition, modified systemic approaches form the basis of the Rural Systemic Initiatives (RSI) and Urban Systemic Initiatives (USI), and the Local Systemic Change (LSC) component of NSF's teacher enhancement programs.

These members of the Wilson High School (Rochester, New York) FAIHM team work on a robotics project. FAIHM, funded in part by NSF, is an acronym for FIRST (For Inspiration and Recognition of Science and Technology), Autodesk, Institute for Women and Technology, Hewlett Packard, and MIT. The program is designed to promote interest in science and technology that will lead high school women to careers in engineering.

In states and territories around the country, NSF's Statewide Systemic Initiatives program is successfully combining curriculum reform—including hands-on activities such as this exhibit at the San Francisco Exploratorium for students—and teacher training to improve student performance in science and mathematics.



Through these programs, NSF grants funds to local school systems with well-thought-out plans for how to reform K-12 science and mathematics education at the state, city, or regional level. So far, NSF has spent more than \$700 million on such efforts.

How well can systemic reform work? During the 1994-95 school year, the first year that NSF funded the urban systemic program, Chicago's school system saw significantly more of its students score above the national norm in mathematics on a commonly used assessment called the Iowa Tests of Basic Skills. What's more, Chicago students' performance in mathematics has increased in sixty-one out of sixty-two high schools, suggesting that improvement is occurring across the board. Similar results have been achieved in Detroit, where students from a diverse range of public schools performed significantly better on a state standards test after the Detroit Urban Systemic Program implemented sections of the *Connected Mathematics* curriculum. And in Dallas, the number of students passing science and mathematics Advanced Placement tests has tripled since the start of NSF systemic reform funding.

On the state level, Puerto Rico has raised its students' achievement in science and mathematics with an innovative pyramid system that brings systemic reform to one school at a time. The NSF-supported effort, which began in 1992, has so

far brought standards-based curricula into more than one-quarter of the island's schools.

"Everybody said it was a clumsy idea because it takes so long," Manuel Gomez, head of the Puerto Rico SSI, told a reporter in 1998. "But I said, 'Be patient. It will work if we give it time.'"

Given the complexities, time is a critical factor to the success of any systemic reform initiative—time, and local school systems willing to commit energy and resources long after NSF's initial support has kick-started reform.

"The underlying belief of systemic reform is that piecemeal attempts, limited by finite projects and inadequate funding, will not change the system, its culture, and its capacity to share what happens in the classroom," says Daryl Chubin, a senior policy officer with the National Science Board, the governing body of NSF. "Change requires conviction and staying power. Nothing happens quickly."

Infusing Education with Research

True reform at the system level requires the participation of everyone who cares about improving the way that students learn about science, mathematics, and engineering. And that includes the research community itself. Finding more ways to foster the infusion of research into education is a major NSF goal as the agency heads into the new millennium.

"If we are to succeed in making our education system truly world class," NSF Director Rita Colwell told the U.S. House of Representatives' science committee in April 1999, "we must better integrate our research portfolio with the education we support."

One way NSF has been taking on this challenge is to fund programs that link ongoing research projects with K-12 students through information technologies such as the Internet. A prime example: the Albatross Project.



Science for Everyone

The good news is that more women and minorities are earning undergraduate and graduate science and engineering degrees—their numbers rose as much as 68 percent from 1985 to 1995, according to recent data from a series of congressionally mandated reports prepared by NSF's Division of Science Resources Studies.

The bad news is that they and persons with disabilities are still underrepresented when compared with the overall U.S. population of eighteen- to thirty-year-olds.

While NSF as a whole is committed to ensuring that the nation's scientific and technical workforce is peopled by all those with gifts to contribute, this mandate is the specific mission of NSF's Division of Human Resource Development, a branch of the Directorate for Education and Human Resources. Why is the crusade for equity allied so closely (though not exclusively) with NSF's educational aims? Because schools are fulcrums on which a young life can turn.

For example, when Tanya Lewis entered Louisiana's Grambling State University (GSU) as a freshman, she signed up to participate in an NSF-funded minority scholars program whose goal was to attract undergraduates to the school's physics and chemistry departments and guide them into graduate school. She struggled with class work and with problems in her personal life; midway through, she decided to take a full semester off. Even then, the mentor who had been assigned to Lewis kept calling.

"I remember sitting in my house and thinking about what it used to be like to get up and go to school everyday and do research," Lewis says. "I realized that I had a gift, and I missed it. I knew I wanted to spend my time doing research."

The next semester, with her mentor's support, she returned to GSU and graduated in 1995. The following fall, she entered graduate school.

Blinded at the age of five in a household accident, Lawrence Scadden,

director of NSF's Program for Persons with Disabilities, knows firsthand the frustrations that confront someone bucking society's notion of who should be a scientist.

"For far too long we've been closing disabled people out of science and math," says Scadden, who received his doctorate in psychology and has spent thirty years conducting research in human perception. "These attitudes—the myths and the ignorance—have created a major barrier that must be removed."

Mentors, culturally appropriate role models, networking, quality learning materials, research fellowships, access to skilled teachers and to assistive technologies that can help students overcome impairments—these are the factors included in myriad NSF programs aimed at knocking down barriers of poverty, discrimination, and distrust.

NSF-funded research into new learning technologies, such as the virtual reality demonstration at right, gives students hands-on experience in the scientific process.

Wake Forest University biologist David Anderson is tracking albatrosses that nest on Tern Island, Hawaii, in an effort to understand (among other things) how the availability of food affects the huge seabirds' extremely slow rate of reproduction. The birds embark on searches for food that last days and even weeks. Do the albatrosses simply fly to relatively close feeding sites and, once there, take plenty of time to gather their food? Or do they travel to remote feeding areas, pick up their food, and return immediately? Supported by NSF, Anderson has worked for years to discover why the trips take so long, using satellites to keep tabs on albatrosses fitted with miniature transmitters.

But early in his research Anderson realized that his project had applications beyond the science of albatross behavior. "It's a perfect opportunity to engage school-age kids in science," he says.

So in a collaboration that continues today, Anderson arranges to feed the satellite data via daily emails to middle school classes that sign up for the experiment from all over the United States. Teachers receive software and support material that help them guide their students in making sense of the birds' movements. A related Web site provides even more information, such as weather systems that could affect flight patterns, basic facts about albatross biology, and material on the history and geography of the Northwest Hawaiian Islands. Mathematical techniques to calculate the birds' flight distances and speed are clearly explained. The students then analyze the data in terms of the hypotheses about the birds' food journeys.

"Kids need to know that scientists pose a conjecture, or hypothesis, and then collect data to try to prove or disprove the hypothesis," says Anderson. "This project emphasizes science as a process and a tool to get reliable answers to questions. At the same time, the data help us answer basic questions about declining albatross populations worldwide." So far the project has filled in many details about albatross behavior, including the fact that the birds can fly for hours, and maybe



even days, without flapping their wings, thereby conserving energy on long-distance hunts for food.

Another example of how information technologies are allowing students to perform actual research is the NSF-funded Hands On Universe Project, originally developed in 1991 by astrophysicist Carl Pennypacker of the Space Sciences Laboratory at the University of California at Berkeley. As large telescopes became automated, they began generating huge numbers of new images that needed to be analyzed. Pennypacker's idea was to get students involved by providing schools with image processing software, an archive of astronomical images, and related curriculum materials.

In 1995, a couple of astronomy teachers—Hughes Pack of Northfield Mount Hermon School in Northfield, Massachusetts, and Tim Spuck of Oil City Area High School in Oil City, Pennsylvania—teamed up with Jodi Asbell-Clarke of TERC, a nonprofit research and development organization in Cambridge, Massachusetts, to develop a Web-based project that works in conjunction with the Hands On Universe (HOU) curriculum. Their HOU Asteroid Search project allows students to download recent images via the Internet from an NSF-supported telescope in Chile with the specific aim of looking for previously unidentified asteroids. Over the years, students have found nearly two hundred asteroids that appear never to have been seen before in the main belt of asteroids circulating through the solar system.

Then, in 1998, three high school students taking Pack's astronomy class made an even more exciting discovery: a previously unknown asteroid in the Kuiper Belt, a collection of celestial objects orbiting beyond Neptune thought to be leftovers



A Lifelong Love of Science

The Informal Science Education (ISE) program, created in 1984, is one way that NSF nurtures a lifelong love of science. ISE projects include everything from film and radio to exhibits in museums and technology centers. The idea, says Hyman Field, deputy division director of the Elementary, Secondary, and Informal Education Division, is to “engage everybody from pre-kindergartners to senior citizens in activities outside the formal school system.”

About a third of ISE-supported projects involve radio, television, or film. Two particularly successful shows are aimed at young audiences. *The Magic School Bus*[®] began as a series of commercial books published by Scholastic Inc. for children of elementary school age. The series features a wacky science teacher named Ms. Frizzle who takes her class on educational field trips in her magically transformable bus. “Building on [the books],” says Field, “we supported development of a television series—one of the first animated series on the Public Broadcasting System for early elementary school kids.”

The television exposure stimulated fresh outlets for the project. A live, traveling version of *The Magic School Bus*[®] now brings fun science activities to schools, malls, and theaters. Related materials, such as videos, CD-ROMs, and teaching guides are also available.

Older children have benefited from the televised exploits of Bill Nye, the Science Guy. A mechanical engineer who moonlighted as a stand-up comic, Nye first appeared as the Science Guy in 1987 on *Almost Live!*, a local version of *Saturday Night Live* in Seattle. Six years later, Nye and two producers had expanded the concept into the outline of a popular science show featuring Nye’s zany but educational demonstrations using inexpensive, safe household items. As with *The Magic School Bus*[®], NSF provided the initial funding that has allowed the Science Guy to take off and succeed.



Programs such as Teachers Experiencing Antarctica combine research and education in an effort to improve both teacher training and student appreciation and mastery of science, math, engineering, and technology.

from the formation of the solar system. At the time of discovery, only about seventy-two such objects had been identified—none, until that point, by anyone other than a professional astronomer. The students—Heather McCurdy, Miriam Gustafson, and George Peterson—had become stargazers of the first order.

“They called me over to take a look at a couple of dots on an image they were analyzing,” recalls Pack of that October afternoon. “They suspected the dots were artifacts, and I agreed with them. But right below those dots was another pair of dots that made the hair on the back of my neck stand up. I recognized the signature of Kuiper Belt objects. But I was a good teacher and just took a deep breath and turned to walk away. Then one of the girls said, ‘Mr. Pack, what about *these*?’ They told me the dots looked like evidence of an object that was moving, and at a very great distance.”

A week later, with the help of their cohorts in Oil City, the Northfield students had done all the calculations needed to confirm their find.

Says HOU founder Carl Pennypacker, “This is a fantastic piece of science, of education, of discovery. The Northfield students’ discovery has shown that all students from a broad range of backgrounds can make solid, exciting, and inspiring scientific contributions.”

Students aren’t the only ones to benefit from direct experience with scientific research. NSF sponsors a number of programs that temporarily put K-12 teachers “in the field,” with or without their students, while also coaching the teachers on how to transfer their research experience into classroom learning. As a result, NSF-sponsored teachers are working alongside scientists in the forests of Puerto Rico and the floodplains of the Mississippi Delta, at Washington State’s Pacific National Laboratory and West Virginia’s National Radio Astronomy Observatory. Some are even going to the ends of the Earth itself.

Each year the Teachers Experiencing Antarctica and the Arctic (TEA) program sends between eight and twelve elementary and secondary teachers to research stations at or near the polar ice caps for up to eight weeks. TEA teachers have explored hydrothermal vents around the Antarctic Peninsula, pulled ice cores from the Greenland Ice Sheet, and released weather balloons at South Pole Station. Professional support abounds, both before and after the research trips. Veterans from past TEA expeditions help mentor the new recruits, who also spend time at the home institutions of their scientist-partners where they get a thorough grounding in their particular project. During their expedition or upon their return from the ice, TEA teachers receive professional help in turning their experience into classroom lessons, sharing their knowledge with other teachers back home, and even attending scientific conferences as co-presenters with other members of the polar learning community.

In 1998, as a biology teacher at Mayo High School in Rochester, Minnesota, Elissa Elliott joined a team of researchers studying microbial life at frozen Lake Bonney in the Dry Valleys region of Antarctica. She kept a daily journal, as TEA teachers are encouraged to do, and uploaded her entries along with photos to the TEA Web site maintained by Rice University. That way, her students back in Minnesota could share in her learning and excitement. Elliott was in electronic contact with more than three hundred classrooms and individuals interested in learning about Antarctic science in real time.

A New Formula for Calculus

By the 1960s, three hundred years after Gottfried Leibnitz and Isaac Newton independently developed it, calculus had become a standard freshman course for students in the physical sciences and engineering. Faculty began to use grades in those courses to screen potential majors in other scientific disciplines and to weed out the less gifted students, even in majors that scarcely required calculus. That approach drew protests, particularly from students not destined for fields that required advanced training in mathematics. The fact that several colleges took an assembly line approach to the subject, grouping students in large lecture classes taught by teaching assistants, exacerbated the situation. Indeed, a high proportion of the more than half a million students enrolled in calculus courses each semester either failed or could not apply calculus concepts in later courses.

In January 1986, mathematicians from twenty-five influential colleges and universities met at Tulane University under the auspices of the Mathematics Association of America (MAA). There, they discussed better ways to give students a conceptual grasp of calculus. NSF kept in touch with the reform movement, and in October 1987 announced its Calculus Curriculum Development Program, jointly administered by the Divisions of Undergraduate Education and Mathematical Sciences.

Over the next ten years, NSF-supported reform projects eventually led to a significant change in how calculus was taught. Changes include the use of graphing calculators and computers, open-ended projects, extensive writing, more applications, and use of cooperative learning groups. NSF-funded projects have also changed the infrastructure of calculus teaching. Virtually every traditional college-level textbook has been revised in light of the reform movement. The Advanced Placement calculus outline for high school students has been overhauled, and revisions are underway on the Graduate Record Examination's mathematics section.

"There is no question of the importance the NSF initiative has had in achieving the changes reported to date," wrote the authors of an MAA report. "The NSF program successfully directed the mathematics community to address the task of reforming the calculus curriculum and provided coherence to those efforts."

A substitute teacher was filling in for Elliott during her absence but, thanks to TEA's technical support, "essentially, I was able to hold class from Antarctica," she says. "My students and I emailed back and forth. They had a ton of questions. So much of the time, we're teaching what is already known and the sense of discovery just isn't there. But because I was able to pretty much communicate with them in real time, they could see that science is something that is happening right now. And that does so much more for kids than textbooks do."

A Revolution in University Culture

As exciting and worthwhile as such programs are, of course, they reach only a small fraction of the teacher workforce. Recognizing that not all teachers can go to the field, NSF is looking for more ways to bring the field to them. One approach is NSF's Graduate Teaching Fellows in K-12 Education program. Begun in 1999, the program aims to place graduate and advanced undergraduate science, mathematics, and engineering students into K-12 classrooms as resources for teachers and students.

A critical component of the fellowship is pedagogical training for the upper-level science students, so they will know how to transform their cutting-edge knowledge into something that younger students can understand and appreciate. Still, "the intention is not to make teachers out of scientists, although some may decide that's what they want to do," says NSF's Dorothy Stout, who headed up development of the program. Rather, NSF hopes that the teaching fellows will go on to become scientists who, in turn, will act as bridges between the research and education communities by serving as resources for their local school districts.

"We want them to be well-rounded individuals," says Stout, "who can enhance K-12 classrooms with their specialized backgrounds."

Or as NSF Director Rita Colwell says, "We cannot expect the task of science and math education to be the responsibility solely of K-12 teachers while scientists, engineers, and graduate students remain busy in their universities and laboratories."

A natural extension of NSF's commitment to bringing the research and education communities together is a greater emphasis on the conduct of research into education itself. Says Colwell, "We've spent a lot of time focused on teaching and yet we don't really know how people learn—how effectively a person's learning can be enhanced, and the differences in how people learn."

Education research emerged as a field in the 1950s and 1960s. Although it once struggled to gain the level of funding and respect afforded to other areas of scientific inquiry, the field is coming into its own as growing numbers of scientists and educators advocate research to better understand how people learn and think.

Finding out more about how children learn, and figuring out how to implement what *is* known about the acquisition of knowledge, are huge challenges. Recognizing the importance of this work, the U.S. government announced in April 1999 a unique collaboration among NSF, the National Institutes of Health, and the Department of Education. The goals of the new Interagency Education Research Initiative (IERI) are to meld different kinds of research in how children learn mathematics, science, and reading; to understand the implications of research for the education community, speeding the implementation of research-based instruction; and to expand the appropriate uses of technology in schools.

For example, one project funded by IERI will conduct a cross-cultural study comparing the early development of mathematical concepts and understanding in three- to six-year-old Chinese, Japanese, and American children. The project will also study

how different cultures support the children's early mathematical development in various settings: at home, in child care facilities, and in preschool. The idea is to gain insight into how best to support the growth of children's mathematical skills prior to elementary school.

Another project funded by IERI will expand the testing of an automated reading tutor for at-risk children. Children read aloud while a computer program "listens" and verbally corrects any mistakes. The program is not fooled by accents and is able to use other cues (thanks to a camera mounted on the computer) to see if the child is paying attention to the task. Preliminary studies have shown that seriously underperforming first- and second-graders who use the automated tutor for three to six months jump almost to their grade level in reading skill. Researchers will also compare the automated tutor to human tutors. It's expected that students will respond best to human tutors, but by how much? With schools struggling to provide at-risk students with the extra help they need, such technology could be an affordable and effective boon.

A Great Deal of Good

Since 1950, NSF has worked for stronger curricula and enhanced professional development for teachers. The agency has planted the seeds of systemic change and made it possible for researchers to work in partnership with educators to bolster the scientific basis of learning. Despite all that NSF has done over the years in these areas, some may be surprised to discover just how important education is at one of the country's primary sources of research funding. But NSF's commitment to the nation's students has been part of its mission from the very beginning.

In 1954 Daniel Lednicer, a doctoral student in chemistry, received a third year of financial support through NSF's fledgling Graduate Research Fellowship program. Full of gratitude for the life of

learning that NSF was allowing him to pursue (he went on to make important contributions as a research chemist at the National Cancer Institute), Lednicer wrote a letter of thanks to the man who had signed NSF into existence, President Harry Truman. Truman's plain-spoken reply on October 2, 1954, speaks presciently about NSF's unique role as a catalyst for scientific knowledge, in the laboratory as well as in the classroom:

Dear Mr. Lednicer:

Your good letter of September 21 was very much appreciated. I always knew that the [National] Science Foundation would do a great amount of good for the country and for the world. It took a terrific fight and three years to get it through Congress, and some smart fellows who thought they knew more than the President of the United States tried to fix it so it would not work.

It is a great pleasure to hear that it is working and I know it will grow into one of our greatest educational foundations.

*Sincerely Yours,
Harry S Truman*

To Learn More

NSF Directorate for Education and Human Resources

www.ehr.nsf.gov

American Association for the Advancement of Science Project 2061

www.project2061.org

National Academy Press

www.nap.edu

National Council of Teachers of Mathematics

www.nctm.org

National Science Teachers Association

www.nsta.org

The Albatross Project (at Wake Forest University)

www.wfu.edu/albatross

The Hands On Universe Project (at Lawrence Berkeley National Laboratory)

<http://hou.lbl.gov>

Teachers Experiencing the Antarctica and the Arctic (at Rice University)

<http://tea.rice.edu>

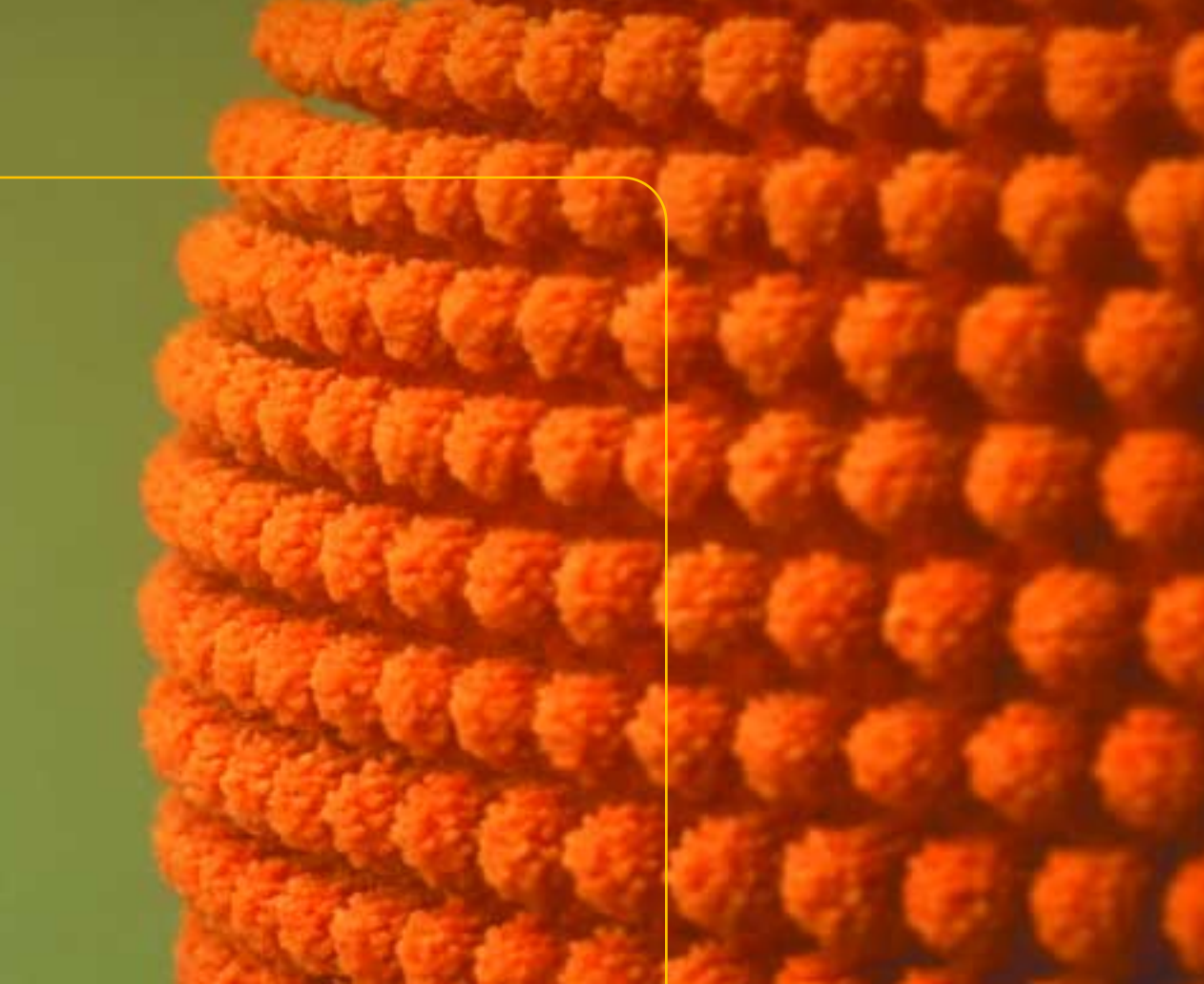


Manufacturing

**the form of
things unknown**



Contrary to its image as a fading giant, manufacturing is helping to propel the U.S. economy to new heights of wealth and reward. NSF contributes to manufacturing's success by investing in innovative research and education.



Manufacturing—the process of converting dreams into objects that enrich lives— is the poetry of the material. Traditionally, the path from an engineer’s imagination to a finished prototype was labyrinthine, involving draftsmen, model makers, rooms full of machine tools, and lots of time. But all that is changing. Over the last two decades, NSF grants have helped to create new processes and systems as well as innovative educational programs that have transformed manufacturing from a venture dominated by smoke-belching factories to the clean and agile enterprises of today and tomorrow.

The Myth of Manufacturing's Demise

Here at the close of the twentieth century, manufacturing accounts for one-fifth of the nation's gross domestic product and employs 17 percent of the U. S. workforce, according to the National Science and Technology Council. More significantly to the nation's economic well-being throughout the 1990s, productivity in manufacturing—the ability to produce more goods using less labor—far outstripped productivity in all other sectors of society, including the service sector. As the nation's productivity leader, manufacturing has helped the nation to achieve low unemployment with only modest inflation.

“Other sectors generate the economy's employment,” says National Association of Manufacturers economist Gordon Richards. “Manufacturing generates its productivity.”

This record of success seems remarkable when compared to the state of manufacturing just twenty-five years ago.

“There was a lot of literature in the mid-seventies that argued quite strongly that the United States was basically going to a service economy,” says Louis Martin-Vega, NSF's acting assistant director for Engineering and former director of the Directorate's Division of Design, Manufacture, and Industrial Innovation (DMII). Back then, Americans worried while clean, efficient Japanese factories rolled out streams of products—cars, televisions, VCRs—that were of higher quality and lower cost than those produced in the United States.

Still based on the classical mass-production model pioneered by early automaker Henry Ford, American manufacturing was proving no match for the leaner, more flexible manufacturing techniques that, although first conceived by American thinkers, were being improved upon elsewhere. In order to modernize manufacturing processes and systems, however, U.S. businesses needed to do the kind

of research and development (R&D) that was becoming too expensive for any one business to undertake by itself. Government help was required, but in the early 1980s, help was hard to come by: The push was on to beef up defense and shrink the rest of the federal government, all while rampant inflation eroded existing research budgets. The result at NSF, according to Dian Olson Belanger, author of *Enabling American Innovation: Engineering and the National Science Foundation*, was that “in real purchasing power, 1982 [research] grantees were living with dollars adequate for 1974.”

By the mid-1980s, the United States was no longer “the unquestioned technological hub of the world,” according to Harvard physicist and Nobel Laureate Sheldon Glashow, but was instead passing “the torch of scientific endeavor” to other nations. “Steel, ships, sewing machines, stereos, and shoes” were “lost industries,” he said. Unless something was done soon, Glashow exclaimed, Americans would be left with “their Big Macs . . . and perhaps, [their] federally subsidized weapons industries.”

The NSF-supported Integrated Manufacturing Systems Laboratory (IMSL) at the University of Michigan is developing next-generation manufacturing systems that can be quickly reconfigured to adapt to changing market realities. Research focuses on open architecture controls, reconfigurable machining systems, and sensor-based monitoring systems. Here, graduate students demonstrate their work in the lab during a visit by NSF officials.



Says Martin-Vega of that troubling time, “There was a realization that, well, we’ve lost the electronics business, the automotive industry was hurting, the machine-tool industry was all Germany and Japan, and then it seemed like we were going to have the same fate in the semiconductor industry.”

The potential loss of an industry so crucial in the burgeoning Computer Age frightened public officials and turned federal attention to manufacturing-related research in a new way. In 1987, the government worked with industry to start a research consortium of semiconductor companies known as SEMATECH. The group continues to operate today (having weaned itself from government support) with member companies sharing expenses and risk in key areas of semiconductor technology research.

Within NSF, says Martin-Vega, “The argument for supporting work in manufacturing was made less difficult when you had a situation that could almost be considered a national threat.” Engineering research seeds planted in the early 1970s began to bear fruit. By the mid-1980s, some pivotal scientific foundations for design and manufacturing were in place. To build on them, in 1985 NSF established a separate design and manufacturing division.

NSF helped to move manufacturing from the obituaries to the headlines, which now are more likely to celebrate the “new manufacturing,” with its reliance on information technologies and more malleable, quick-response organizational structures. As the following highlights demonstrate, with some critical assistance from NSF, U.S. manufacturing isn’t dying after all—it’s just changing.

Rapid Prototyping

In the late 1960s, Herbert Voelcker—then an engineering professor at the University of Rochester, now at Cornell University—went on sabbatical and asked himself how to do “interesting things” with the automatic, computer-controlled machine tools that were just beginning to appear on factory floors. In particular, Voelcker wanted to find a way to take the output from a computer design program and use it to program the automatic machine tools.

With funding from NSF, Voelcker tackled the problem first by developing the basic mathematical tools needed to unambiguously describe three-dimensional parts (see the chapter on “Visualization,” p. 88). The result was the early mathematical theory and algorithms of solid modeling that today form the basis of computer programs used to design almost everything mechanical, from toy cars to skyscrapers.

During the 1970s, Voelcker’s work transformed the way products were designed, but for the most part they were still made the same old way. That is, either a machinist or a computer-controlled machine tool would cut away at a hunk of metal until what remained was the required part, in much the same way as Michelangelo removed chips of marble from a block until all that remained was a statue of David. But then in 1987, University of Texas researcher Carl Deckard came up with a better idea.

Next-Generation Manufacturing

Since 1976, various U. S. presidents have formed interagency councils—with gradually increasing participation from industry—to try to build consensus and identify strategies in certain key areas of the economy, including manufacturing. NSF's leadership has been critical to these efforts, which most recently took the form of the Next-Generation Manufacturing (NGM) project.

NGM was funded by NSF and other federal agencies but headed by a coordinating council drawn from the manufacturing industries. Starting in 1995, more than 500 industry experts worked together to produce a final 1997 report offering a detailed vision for the future of manufacturing. Today the NGM report forms the basis of a follow-up effort called the Integrated Manufacturing Technology Roadmap (IMTR) project, also funded by NSF and other federal agencies.

"The question that guided us," says NSF's Deputy Director Joseph Bordogna, former head of NSF's Directorate for Engineering and a primary architect of NGM and other efforts to rejuvenate manufacturing in America, "is 'what principles underlie the ability of a company to continuously change itself in response to the changing marketplace?' That means figuring out adaptive, decision-making processes and software, as well as manipulating materials and coming up with new machines for the factory floor."

According to the NGM report, a "next-generation" manufacturer will need to transform itself from a twentieth century-style company—one that functions as a sovereign, profit-making entity—into a twenty-first century company that is more of an extended enterprise with multiple and ever-shifting business partners. As Stephen R. Rosenthal, direc-

tor of the Center for Enterprise Leadership, describes it, next-generation manufacturers should be companies that stretch from "the supplier's supplier to the customer's customer."

Successful next-generation manufacturers, the NGM report concludes, will have to possess an integrated set of attributes. The company will need to respond quickly to customer needs by rapidly producing customized, inexpensive, and high-quality products. This will require factories that can be quickly reconfigured to adapt to changing production and that can be operated by highly motivated and skilled knowledge workers. Workers organized into teams—both within and outside a company—will become a vital aspect of manufacturing. As participants in extended enterprises, next-generation companies will only undertake that part of the manufacturing process that they can do better than others, something industry calls "adding value."

Inherent in these requirements are what the NGM project report calls "dilemmas." These arise from the conflict between the individual company's needs and those of the extended enterprise. How can knowledge be shared if knowledge is itself a basis for competition? What security can companies offer their skilled employees when the rapidly changing nature of new manufacturing means that firms can't guarantee lifetime employment? How can the gaining of new knowledge be rewarded in a reward-for-doing environment?

Resolving these dilemmas is an important part of NSF's vision of the work to be done in the twenty-first century, work in which NSF will play a leading role.



NSF helped launch rapid prototyping technologies, which can build new products from a computer-aided design (CAD) model without any carving or machining. Here, a student works with rapid prototyping equipment in the NSF-supported Advanced Design and Manufacturing Laboratory at the University of Maryland. One goal of the lab is to create graphical materials for visually impaired students.

Instead of making a part by cutting away at a larger chunk of material, why not build it up layer by layer? Deckard imagined “printing” three-dimensional models by using laser light to fuse metallic powder into solid prototypes, one layer at a time.

Deckard took his idea—considered too speculative by industry—to NSF, which awarded him a \$50,000 Small Grant for Exploratory Research (SGER) to pursue what he called “selective laser sintering.” Deckard’s initial results were promising and in the late 1980s his team was awarded one of NSF’s first Strategic Manufacturing (STRATMAN) Initiative grants, given to the kind of interdisciplinary groups often necessary for innovation in the realm of manufacturing.

The result of Voelcker’s and Deckard’s efforts has been an important new industry called “free form fabrication” or “rapid prototyping” that has revolutionized how products are designed and manufactured.

An engineer sits down at a computer and sketches her ideas on screen with a computer-aided design program that allows her to make changes almost as easily as a writer can change a paragraph. When it’s done, the design can then be “printed” on command, almost as easily as a writer can print a draft—except this draft is a precise, three-dimensional object made of metal or plastic.

“To take a computer model and turn it into a physical model without any carving or machining is incredible,” says an analyst who tracks this new industry. “It’s almost like magic when you see that part appear.”

The method can be used to make things that are more than prototypes. “Because you can control it in this incredible way, you can make objects that you just couldn’t think of machining before,” says George Hazelrigg, group leader of DMII’s research programs. “For example, you can make a ship in a bottle.”

More practically, the method has been used to make a surface with lots of tiny hooks that resembles Velcro. These new surfaces are proving to be ideal substrates for growing human tissue. NSF-funded researchers have already grown human skin on these substrates and are looking to grow replacements of other organs as well.

“So these are pretty fundamental things,” Hazelrigg says. “I think it’s fair to say that we played a major role in it.”

Bruce Kramer, acting division director of NSF’s Engineering and Education Centers, is even more definite: “For a majority of successful rapid prototyping technologies, the first dollar into the technology was an NSF dollar.”

Getting Control

Rapid prototyping may be the wave of the future but most manufacturing is still done by traditional machine tools—the drills, lathes, mills, and other devices used to carve metal into useful shapes. Machine tools have been around for more than two centuries, only recently changing to keep time with the revolution in computer technology. Through most of the 1980s, computer-controlled machine tools were capable of only a narrow range of pre-programmed tasks, such as drilling holes or cutting metal according to a few basic patterns. For simple designs these controllers were pretty good,

but by 1986, when University of California engineering professor Paul Wright applied to NSF for a grant to improve machine tools, the limitations of these so-called closed architecture controllers were becoming apparent.

“Our goal was to build a machine tool that could do two things,” Wright explains. “Number one, be more connected to computer-aided design images so that if you did some fantastic graphics you could actually make the thing later on. Number two, once you started making things on the machine tool, you wanted to be able to measure them *in situ* with little probes and then maybe change the machine tool paths” to correct any errors.

The idea was to devise a controller that was flexible both in hardware and software, allowing the use of advanced monitoring and control techniques based on the use of sensors. Wright also wanted to standardize the basic system so others could more easily develop new hardware and software options over time.

At first, Wright asked machine tool manufacturers to support his research, but “they thought I was a complete idiot,” he recalls. Wright wanted to use the relatively new Unix operating system, which the machine tool companies thought was daring and unsafe. So Wright and his colleagues turned to NSF. The agency responded, says Wright, with a grant “to open up the machine tool controller box, which was very crude and inaccessible back then. And, in my humble opinion, that has led to a lot of good results.”

Today, Wright’s open architecture controllers are the industry norm and have quite literally changed the shape of manufactured products. That NSF was there when even the ultimate beneficiary—industry—was not, is “why I’m so enthusiastic about NSF,” Wright says.

Supply Chain Management

Rapid prototyping and open architecture controllers are examples of advances in manufacturing processes, but NSF has also been instrumental in helping to modernize manufacturing systems.

In 1927, Henry Ford’s Rouge complex near Detroit began churning out a ceaseless stream of Model A cars. The Rouge facility was perhaps the ultimate expression of mass production and “vertical integration,” in which a company tries to cushion itself from the vagaries of the market by owning or controlling virtually every aspect of its business, from the mines that provide the ore to the factories that make the glass. Raw materials—iron ore, coal, and rubber, all from Ford-owned mines and plantations—came in through one set of gates at the plant while finished cars rolled out the other.

Ford’s vision informed how manufacturing was done for most of the twentieth century, but by the late 1970s the limitations of this approach had started to become obvious, at least to the Japanese. Why make steel if what you do best is make cars? Why be responsible for your own suppliers—and pay to maintain all that inventory—when it’s cheaper to buy from someone else? Bloated, vertically integrated American companies faced a serious challenge from Japanese carmakers who organized their factories along a different, leaner model resulting in cheaper, better cars. Japanese factories—in which each car was built by a small team of workers rather than being pieced together along a rigidly formulated assembly line—were far more efficient when it came time to shift to a new model. An American car plant was like a machine dedicated to building a single type of vehicle. Workers were interchangeable parts of that machine, whose “intelligence” was vested in the machine’s overall design rather than in the

workforce. In contrast, Japanese plants depended on the intelligence of their workers, who were encouraged to make any improvements to the manufacturing process that they saw fit.

It took some time, but by the 1980s American manufacturers such as General Motors (GM) had absorbed the Japanese lessons of “lean” manufacturing and were looking to make some improvements of their own. For help, GM turned to Wharton Business School professor Morris Cohen who, with support from NSF, analyzed a critical part of its production system: The process by which GM distributed 600,000 repair parts to more than a thousand dealers.

Cohen’s approach was to see this process as one of many “supply chains” that kept GM up and running. Supply chains form a network of resources, raw materials, components, and finished products that flow in and out of a factory. Using empirical data and mathematical models, Cohen and his colleagues proposed a complete reorganization of GM’s repair parts supply chain.

“We suggested that a high degree of coordination be put in place to connect decisions across the supply chain,” says Cohen. “Today that’s commonplace, but back then the idea was considered radical.”

In fact, the idea was considered so sweeping that GM executives rejected it—not because they disagreed with Cohen’s analysis but rather because the scale of the reorganization was too much for them to contemplate at the time. However, GM was soon to embark on building a new car company called the Saturn. GM’s management decided to apply a number of Cohen’s recommendations to the new venture, including the main proposition: centralized communications and coordinated planning among the Saturn dealerships and the

company distribution center. Rather than operating in the traditional fashion, as separate entities, the dealerships would be hooked up via satellite to a central computer. By consolidating information and making it available to everyone, management could make optimal parts-ordering decisions, neighboring dealerships could pool resources, and dealers could focus on maximizing customer service without worrying about what inventory they should be stocking. All of these improvements let management accommodate difficult-to-predict parts service demands without holding excessive inventory, while still ensuring that dealers got the parts they needed to repair cars in a timely manner.

Cohen’s approach to supply chain management quickly proved a success: Saturns, which are relatively low-cost cars, are routinely ranked among the top ten cars with respect to service. “The other top ten are high-priced imports,” Cohen says.

Only the Agile Survive

Supply chain management may make for leaner manufacturing, but there is also a premium on agility. Agile manufacturers recognize that information technology and globalization have dramatically quickened the rate at which new products must be innovated and brought to market. In such a rapidly shifting marketplace, it’s best to operate not as a vertically integrated giant but rather as part of a loose confederation of affiliates that form and reform relationships depending on changing customer needs. In the 1990s, NSF set up three institutes—at the University of Illinois, Rensselaer Polytechnic Institute (RPI), and the University of Texas at Arlington—to study issues raised by agile manufacturing.



A Brief History

Manufacturing, because it is a multi-faceted endeavor depending on the integration of many ideas, techniques, and processes, draws largely on the skills of engineers, a group that has not always felt entirely welcome at NSF. Vannevar Bush, head of the wartime Office of Scientific Research and Development, wrote a major report for President Harry Truman that led to the establishment of NSF in 1950. In that report, Bush warned that while America was already preeminent in applied research and technology, “with respect to pure science—the discovery of fundamental new knowledge and basic scientific principles—America has occupied a secondary place.”

As a result of this view many came to see engineering, rightly or wrongly, as a quasi-applied science that, says historian Dian Olson Belanger, “was always alien to some degree” within the historically basic science culture of NSF.

This attitude began to change during the post-Sputnik years and continuing through the Apollo moon landing, when engineering gradually assumed a more prominent role at NSF. President Lyndon Johnson amended the NSF charter in 1968 specifically to expand the agency’s mission to include problems directly affecting society. Now “relevance” became the new by-word, embodied in the 1969 launch of a new, engineering-dominant program called Interdisciplinary Research Relevant to Problems of Our Society (IRRPOS), which funded projects mostly in the areas of the environment, urban problems, and energy.

IRRPOS gave way in 1971 to a similar but much expanded program called Research Applied to National Needs (RANN). And within RANN, an NSF program officer named Bernard Chern began to fund pioneering research in computer-based modeling, design, and manufacturing and assembly processes.

“It is fair to say that Chern’s early grantees . . . set the character of much of American automation and modeling research for almost a decade,” says Herbert Voelcker, former deputy director of DMII and now an engineering professor at Cornell University. But despite its successes, RANN remained controversial among those concerned that NSF not lose sight of the importance of curiosity-driven research. Still, by the time RANN was abolished in 1977, it had built a substantial beachhead within NSF for problem-oriented and integrative R&D.

In 1981, NSF was reorganized to establish a separate Directorate for Engineering. As part of its mandate to invest in research fundamental to the engineering process, the directorate includes specific programs devoted to design and manufacturing issues. Today such issues are the province of the Division of Design, Manufacture, and Industrial Innovation, whose mission is to develop a science base for design and manufacturing, help make the country’s manufacturing base more competitive, and facilitate research and education with systems relevance.

NSF-funded researchers at the University of California at Berkeley, have created an experimental system called CyberCut that allows users to quickly design and manufacture prototypes for mechanical parts via the Internet. An online computer modeling tool links to a computer-controlled milling machine. Here, Cybercut renders art—a human face scanned by lasers.



“Agile manufacturing takes on a slightly different definition depending on whom you talk to,” says Robert Graves, who is a professor in the Decision Sciences and Engineering Systems department at RPI as well as director of the Electronics Agile Manufacturing Research Institute, which studies issues of agile manufacturing as they apply to the electronics industry. “Here in electronics we look at the idea of distributed manufacturing.”

In the distributed manufacturing model, an enterprise consists of a core equipment manufacturer that produces the product and is supported by supply chains of materials manufacturers and services. As an exercise, Graves and his colleagues at RPI set up their own agile “company” to redesign a circuit board used in an Army walkie-talkie. While team members finished the product’s design, companies were found that could potentially supply the parts and assembly services required. But parts listed in the companies’ catalogs weren’t always available or, if they were, might not have been available quickly.

So the team redesigned their circuit board to include other, more readily available parts. This, and the search for new suppliers, took excessive time and required extra resources—circumstances that emulated the realities of traditional design and manufacturing. But the time wasn’t wasted, since the whole point was to identify common manufacturing obstacles and devise ways for the system to become more agile.

In the end, the RPI researchers saw that they could streamline the system by using computers and networks to handle the negotiations between suppliers and designers. The researchers developed software that takes a circuit board design, works out all possible, functionally equivalent variants, and sends out “agents”—self-sufficient computer programs—to the computers of the various parts suppliers. These automated agents carry a “shopping” list of the physical characteristics of some sub-system of the board. List in hand, each automated agent essentially roots around in the suppliers’ computers, making note of such things as how much each supplier would charge for the components on the list and how quickly the supplier can deliver. The agents then carry the information about pricing and availability back to the designer’s computer, which may use the new data to further modify the design and send out yet more agents.

RPI researchers using this new system cut the circuit board design process from a typical nine months to a matter of weeks. In 1999, the group spun off a company called ve-design.com to market their newly developed agile system.

Education that Works

The success of supply chain management and agile manufacturing shows that manufacturing cannot be considered primarily in terms of transforming raw materials into finished goods, says Eugene Wong, former director of NSF's Directorate for Engineering and currently professor emeritus at the University of California at Berkeley. Rather, manufacturing should be thought of as a "system function" that serves as the core of a modern production enterprise.

"In a larger sense," says Wong, "the distinction between manufacturing and service is not useful. Modern manufacturing encompasses inventory management, logistics, and distribution—activities that are inherently service-oriented." Wong suggests that this blurring of the manufacturing and service sectors of the economy constitutes a paradigm shift with profound implications for the future. That is why NSF continues to invest not only in the development of new manufacturing processes and systems, but also in new approaches to engineering education. As NSF Deputy Director Joseph Bordogna says, "It's not just the discovery of new knowledge, but the education of workers in that new knowledge that is the fundamental—and maybe unique—mission of NSF."

The education of both scientists and engineers has been a goal of NSF since 1950. During the economic turbulence of the 1970s and 1980s, however, it became clear that industry and academia had become estranged from each other in the critical area of manufacturing. Manufacturing-related scientific research at the universities wasn't making it out into the real world quickly enough, if at all, and companies were complaining that their young engineering hires, while capable of scientifically analyzing a problem, couldn't produce actual solutions in a timely fashion. So NSF began looking for ways to nurture mutually beneficial partnerships between companies seeking access to cutting-edge research and students and professors looking for practical experience in putting their ideas to work.

In the early 1980s, NSF spearheaded what was then known as the Engineering Faculty Internship Program. The program provided seed grants—to be matched by industry—for faculty members interested in spending time in an industrial environment. A decade later, the internship model was included as part of a broader program aimed at creating opportunities for universities and industries to collaborate on long-term, fundamental research. Eventually the expanded program, called Grant Opportunities for Academic Liaison with Industry (GOALI), spread throughout the whole of NSF.

Research funded through the GOALI program has led to such advances as more efficient chip processing and improvements in hydrocarbon processing, which allow previously unusable heavy oils to be transformed into gasoline and chemical products.

"GOALI enhances research," says NSF's GOALI coordinator, Mihail C. Roco. "The program has unlocked a real resource in academic and industrial research. GOALI promotes basic research that can provide enormous economic benefits for the country."

Another effort by NSF to bridge the gap between industry and academia is the Engineering Research Centers (ERC) program, launched in 1984. The ERC program supports university-based research centers where industry scientists can collaborate with faculty and students on the kind of knotty, systems-level engineering problems that tend to hobble innovation in the long run. Companies get a chance to conduct cutting-edge research with a long-term focus while faculty and students (both graduate and undergraduate) become more market-savvy in their approach to problem-solving. In the end,



A student at the NSF-supported Microelectronics Lab at the University of Arizona adjusts the water flow to an apparatus used to study wafer rinsing, a critical step in the manufacture of semiconductor chips. Current methods use huge amounts of water, an environmental concern. Through the fundamental study of wafer rinsing, NSF-funded researchers have discovered bottlenecks in the process and have created optimal flow cycles to reduce waste.

ERCs shorten the path between technical discovery and the discovery's application.

"The basic goal of the ERC program is to form partnerships within industry to advance next-generation technology and to develop a cadre of students who are much more effective in practice," explains NSF's Lynn Preston, ERC program leader. "Because of the sustained support that we can give them, the centers focus and function with a strategic plan."

ERCs focus on relatively risky, long-term research—the kind that industry, coping with an increasingly competitive marketplace, is often reluctant to chance. "It's about really big, tough challenges that industries can't take on their own," says Preston.

A prime example with regard to manufacturing is the Center for Reconfigurable Machining Systems (RMS) at the University of Michigan in Ann Arbor. Since its establishment as an ERC in 1996, the RMS center has aimed to create a new generation of manufacturing systems that can be quickly designed and reconfigured in response to shifting market realities. Working with about twenty-five industry partners, the students and faculty of the RMS center seek to develop manufacturing systems and machines with changeable structures.

"Most manufacturing systems today have a rigid structure," says Yoram Koren, the RMS center's director. "Neither the machines themselves or the systems they're a part of can be changed very easily. But with the globalization of trade, product demand is no longer fixed and product changeover becomes faster. Companies need to be able to adjust their product lines, often incrementally, to changing market realities."

Koren points to the automotive industry as an example. "When gas prices were low, everybody wanted to buy a V-8 [engine]," he says. "Car companies couldn't make enough V-8 engines to supply demand. Now gas prices are going up and companies are facing the opposite problem."

One common barrier to change is what's known as "ramp-up." Usually, it takes anywhere from several months to three years to ramp up; that is, to begin marketing an optimum volume of flaw-free new products once a new manufacturing system is put into place. A key contributor to the delay is the inherent difficulty in calibrating changes throughout the existing system; a single machine error can propagate and cause serious product quality problems. To address this issue, the students, faculty, and staff at the RMS center have come up with a mathematically based "stream-of-variation" method that Koren says significantly reduces ramp-up time. The center's industry partners are excited about the prospects for this and other RMS-generated innovations.

"We, and our suppliers, have already benefited from working with University of Michigan researchers to implement scientific methods in our plants," says Jim Duffy, manager of manufacturing engineering at Chrysler Corporation.

Mark Tomlinson, vice president for engineering at Lamb Technicon (a major machine tool builder), agrees about the potential pay-off for industry. "The ERC for Reconfigurable Machining Systems is providing the vision and inspiration for our next-generation machines," he says, "as well as supplying the qualified engineers that support our needs."

Manufacturing the Future

The ERC program is a particularly good example of how NSF brings together the discovery-driven culture of science and the innovation-driven culture of engineering. Manufacturers applaud NSF's efforts because they recognize that coming up with new systems and products is a much more complex and expensive venture than ever before, and they need the help of university-based researchers in order to build the science base for future advancements.

For example, it takes about a billion dollars to develop a new semiconductor chip capable of the kind of performance required in, say, high-definition television. That level of investment—that level of risk—deters even the most ambitious American companies from doing the kind of pioneering research necessary to keep them globally competitive. NSF's role as a catalyst for government-industry-academia collaboration is vital for the nation's economic well-being.

"You need a partnership," says NSF Deputy Director Joseph Bordogna. "You need new knowledge out of universities and labs, new processes from industry, and a government willing to enable it all through appropriate R&D policy and frontier research and education investment, by and for the citizenry."

NSF's efforts to bridge the worlds of industry and academe reflect another truth about modern manufacturing: Knowledge and ideas are the most important raw materials.

"It's no longer profitable just to ship a piece of metal out the front door," industry analyst Graham Vickery told *Industry Week*. "What you're doing now is shipping some sort of component that requires things like support services, or advice, or design skills, or engineering know-how" in order for the component to be of actual use at the other end.

Finding innovative ways to handle information is now manufacturing's chief concern. "If you understand that today manufacturing is an enterprise-wide production process," says Eugene Wong, "you see that information management will assume an increasingly important role, one that may already have transcended the importance of transforming materials into products."

With NSF's help, American manufacturers are making the changes necessary to stay competitive in a marketplace increasingly dominated by e-commerce, while at the same time honoring the traditional core of manufacturing's purpose: the innovation of new technologies and products for an expectant public.

To Learn More

NSF Directorate for Engineering

www.eng.nsf.gov

NSF Division of Design, Manufacture, and Industrial Innovation

www.eng.nsf.gov/dmii

Engineering Research Centers

www.eng.nsf.gov/eec/erc.htm

Engineering Research Center for Reconfigurable Machining Systems (University of Michigan)

<http://erc.engin.umich.edu>


Electronics Agile Manufacturing Research Institute (Rensselaer Polytechnic Institute)

www.eamri.rpi.edu

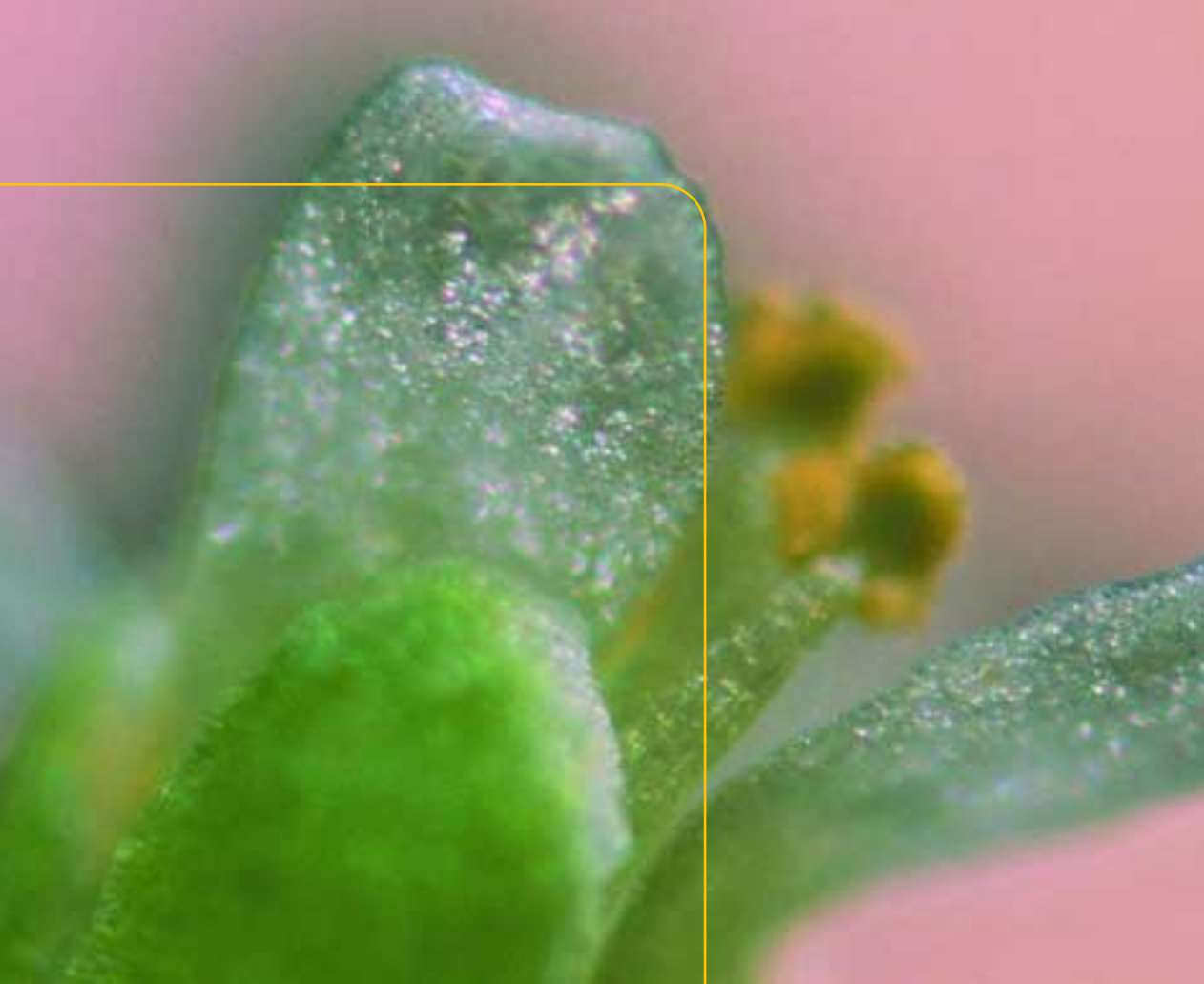
A close-up photograph of a green Arabidopsis stem. The stem is the central focus, showing several small, yellowish, fuzzy flower buds or developing structures. The background is a solid, vibrant purple color. The lighting is bright, highlighting the texture of the stem and the color of the buds.

Arabidopsis

map makers
of the plant kingdom

A microscopic view of plant tissue, showing green and purple structures. A dark grey text box with a thin yellow border is positioned in the upper right quadrant. The text inside the box is yellow and describes NSF-funded gene mapping research.

With NSF support, biologists today are mapping all of the genes of a model organism—identifying the location and function of each gene. They have already made fundamental discoveries that may lead to the development of more beneficial crops and forest products.



Arabidopsis thaliana is a small, flowering mustard plant that has become the subject of intense study by scientists around the world. It has many characteristics of an ideal experimental system—a model organism for elucidating the biology of flowering plants. Recognizing the promise of *Arabidopsis*, NSF began working with leaders in plant biology in the 1980s to cultivate a spirit of cooperation and to encourage the use of the model plant in research. In 1990, NSF launched a multi-agency, multinational project to identify all of the genes in *Arabidopsis* by location and function—in other words, to create a genetic road map to flowering plants. The collegial *Arabidopsis* research community now expects to complete the sequencing of the plant's genome by the end of 2000—several years ahead of schedule. By August 1999, nearly 70 percent of the genome sequences for *Arabidopsis* had been deposited in the public database, GenBank. Six months later, scientists reported the complete DNA sequences of two of the five chromosomes of *Arabidopsis*. Major discoveries have been made about the mechanisms by which genes regulate flower development, disease resistance, response to adverse conditions in the environment, and numerous other aspects of plant biochemistry and physiology. Commercial applications under development include trees with accelerated blooming, biodegradable plastics grown in crops, and genetically engineered vegetable oil with reduced polyunsaturated fat.

A Rose Is a Rose Is a Mustard Weed

There are approximately 250,000 different species of flowering plants, all believed to derive from a common ancestor. While plants have adapted to a multitude of terrains, climate conditions, and selective breeding efforts over the millennia, the process of evolution ensures that they remain related in fundamental ways. At the molecular level, for example, what causes a rose bush to flower is not terribly different from what occurs in a radish plant. Other characteristics also appear to be similar across species, such as the fruit-ripening process and the internal clock that tells plants when to open their pores in anticipation of daylight. In fact, the physiology and biochemistry of plants display such uniformity across species that one can say, without too much exaggeration: When you've seen one flowering plant (at the molecular level), you've seen them all.

This essential truth has altered the course of study in plant biology, a field once dominated by research into individual crops, such as corn or wheat. Today, plant biology has its own model organism, the flowering mustard plant *Arabidopsis thaliana*; consequently, research in the field now resembles other types of broad basic research, such as that done on bacteria or animals.

Considered a weed because it is uncultivated and grows in profusion, *Arabidopsis* nonetheless engages the attention of a global research community. The researchers, and agencies such as



NSF that support them, expect that by analyzing the structure and functions of *Arabidopsis*, they are laying the groundwork for analyzing most other plant species.

The project has greatly accelerated the practical application of basic discoveries in agriculture and forestry. Genetically engineered species are beginning to appear, and many believe they signal the beginning of a revolution in plant breeding.

In one such area of discovery, scientists have identified genes involved with the regulation and structural forms of flowers. Knowledge of these genes has made possible the genetic engineering of plants other than *Arabidopsis*. For example, aspens normally flower only after they have attained a height of 30 feet, which can take up to twenty years. A genetically transformed aspen, however, flowered in only six months, when it was just 2 inches tall. Commercial tree growers have

Researchers are studying the inherited characteristics of *Arabidopsis*. The NSF-funded genome research project to map *Arabidopsis* will yield important information about how flowering plants interact with their environments.



This scanning electron micrograph shows an *Arabidopsis* plant in bloom, highlighting the emergence of the plant's flower. The image provides details about the flowering process that help researchers follow the earliest events in the development of an *Arabidopsis* flower.

always wanted to control the timing of floral and fruit production, as well as the closely related reproductive cycle. The technology is also being tested in fruit and timber trees.

In another research initiative, health concerns over saturated fat and hydrogenated vegetable oils are motivating a search for edible oils that pose no threat to human health. The pathways by which plants produce edible unsaturated oils have been elucidated and the responsible desaturase genes cloned from *Arabidopsis*. The *Arabidopsis* genes were used to identify the corresponding genes in soybeans and other crop plants, whose oils account for approximately one-third of the calories in the American diet. At present, most plant oils are chemically hydrogenated to keep them from turning rancid. The availability of the

desaturase genes raises the possibility that nutritionally desirable edible oils can be produced from plants without the need for chemical modification. Agrichemical producers have begun field trials with modified soybeans and other plant species.

Inside the Little Green Factories

Plant breeding became a science around the turn of the twentieth century, thanks to Austrian scientist and mathematician Gregor Mendel. His studies of heredity in peas enabled him to draw conclusions about gene functioning by observing how the characteristics of parents showed up in generations of offspring. While adopting increasingly sophisticated techniques, plant breeders continued to improve crops in traditional ways, crossing the current stock with germplasm containing useful new characteristics. The success of the outcomes depended on the skill and judgment of the breeder in selecting plants to cross.

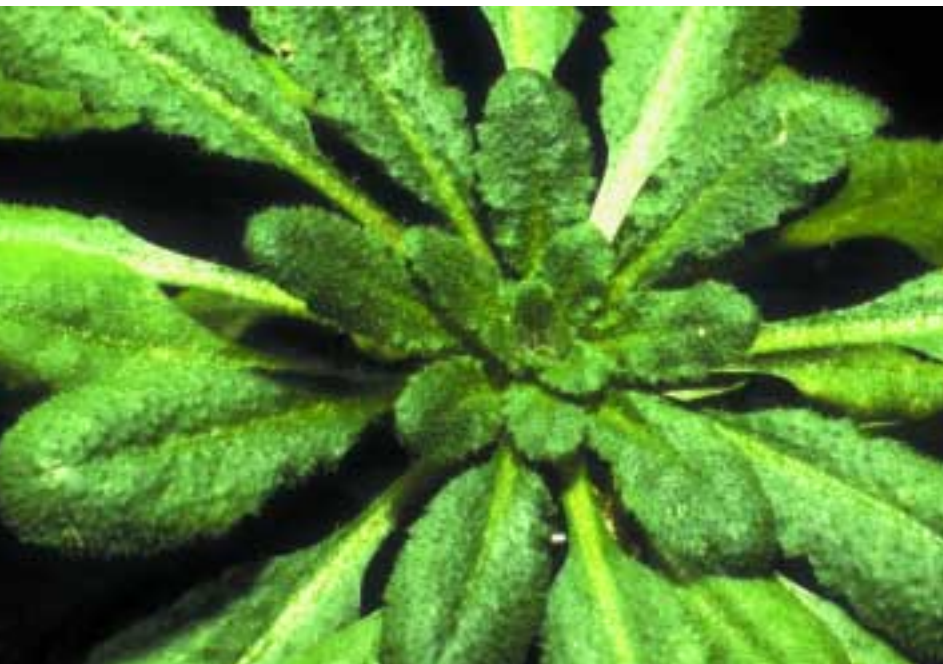
Scientists, meanwhile, sought to understand the underlying genetic mechanisms that induced plants to express inherited characteristics in certain ways. With advances in plant tissue culture techniques, biologists were able to produce novel hybrids and study them under controlled laboratory conditions. Of particular interest were plant characteristics that might potentially be modified in ways advantageous to humans. One scientist described plants as the “little green factories” that produce food, fibers, housing materials, and many pharmaceuticals, as well as the oxygen necessary for terrestrial life.

How to Make a Flower

Elliot M. Meyerowitz of the California Institute of Technology in Pasadena was one of the first molecular biologists to receive an NSF grant to study *Arabidopsis* genetics. His work on the development of flowers illustrates how the methods of scientific inquiry employed in molecular biology can unlock the secrets of plant life.

Flowers are made up of four concentric whorls. Surrounded by tough, protective structures called sepals, the petals themselves surround the male and female sex organs, respectively called stamens and carpels. Three types of genes control how the whorls develop, and by looking at flowers that lacked some genes, Meyerowitz's lab discovered that if only type A genes are active, a cell knows to become part of a sepal. With A and B genes switched on, the cell turns into part of a petal. Together, genes B and C direct a cell into a stamen, and C alone, into a carpel.

Meyerowitz's work has broad applicability. Fully 80 percent of the world's food supply is made up of flowers or flower parts: fruit, grains, or seeds. While genetically engineered flowers may have limited commercial value, the same formulas may one day be used to tailor food crops to the requirements of humankind.



This *Arabidopsis* plant, grown under short-day conditions (eight hours of light/sixteen hours of dark), shows how many leaves are produced during the vegetative phase of the plant's approximately five-week life cycle. After the transition from the vegetative to reproductive phase, the plant produces flowers.

Knowledge about genetics grew rapidly during the 1960s and 1970s, and certain characteristics became recognized as central to all organisms: bacteria, animals, plants, and humans. For example:

- Organs develop and function as they do because of the way different combinations of genes express themselves in the form of proteins produced within cells. The instructions that tell proteins to form a blood cell, a brain cell, or a flower petal are all contained within the genome, and insofar as is now known, in the chemical composition of the deoxyribonucleic acid, or DNA, in a particular gene sequence along a chromosome.
- When a gene or its constituent nucleotides undergoes a sudden random change, known as mutation, the result is an abnormality in the affected cells. Mutations that render an organism better able to cope with its environment are the raw material that natural selection acts on. Many of the successful mutations of an organism's ancestors, and possibly a mutation or two of its own, are reflected in the organism's genetic composition, or genome.

- The genome responds to environmental forces, such as the supply of essential nutrients, to produce an organism's observable characteristics, or phenotype.
- Through recombinant DNA technology, or genetic engineering, it is possible to create new strains of organisms with DNA containing the exact genes desired from different sources.

Barbara McClintock's work identifying mobile genes in corn, for which she received a Nobel Prize in 1983, provided molecular biologists with the tools necessary for the development of plant transformation. Despite the essential role that plants play in human existence, much less time and energy had gone into studying the genetic functioning of plants than of bacteria or animals—or humans. A major obstacle was the large and unwieldy mass of genetic material found in most crop plants, which were the primary subjects of scientific research.

This obstacle was a big one. A scientist who wants to find the genetic source of a mutation, such as resistance to a particular disease, has to examine the cells where the mutation was expressed and connect the genetic information there back to the DNA. The technologies for identifying and isolating genes, sequencing them, cloning them (making large numbers of exact reproductions), and determining their functions are complex, labor-intensive, and expensive. To apply these techniques to plants, molecular biologists needed a plant whose genome was of manageable size.

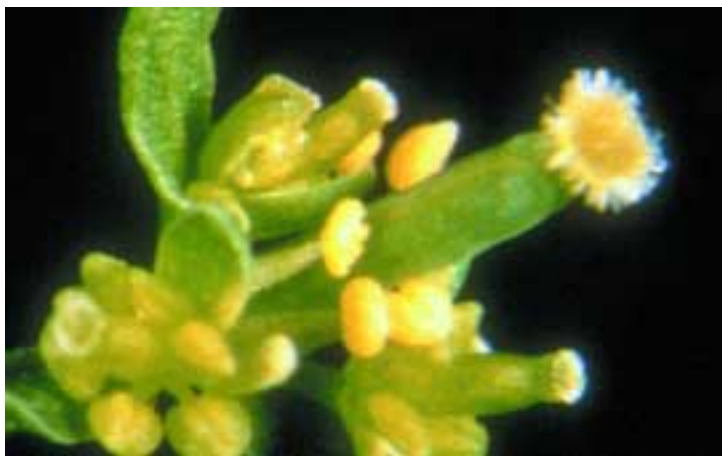
Golden Age of Discovery

“We are now in a ‘golden age’ of discovery in plant biology. Problems that have been intractable for decades are yielding to the application of modern methods in molecular and cellular biology. The formula for much of this success is conceptually simple: Isolate a mutation that affects the process or structure of interest, clone the gene, find out where and when it is expressed, where the gene product is located, what it does, and what it interacts with, directly or indirectly . . . Although it is not necessarily easy, any gene that can be marked by a mutation can be cloned. This is a qualitatively different situation from anything that has ever before existed in plant biology.”

—From *Arabidopsis*, E. Meyerowitz and C. Somerville, eds., Cold Spring Harbor Press, 1994.

Researchers around the world are using the unassuming mustard weed to unlock the secrets of the plant world—secrets with many potential benefits.

Increasingly, they converged on *Arabidopsis thaliana*, a weed of the mustard family that has one of the smallest genomes of any flowering plant. It is estimated that 20,000 to 25,000 genes are arrayed on only five chromosomes, with little of the puzzling, interminably repetitious DNA that frustrates efforts to study most plants. *Arabidopsis* is compact, seldom exceeding about a foot in height, and it flourishes under fluorescent lights. All of these characteristics enable scientists to raise it inexpensively in laboratories. During its short life cycle, this mustard weed produces seeds and mutants prodigiously. It can be transformed through the insertion of foreign genes and regenerated from protoplasts, plant cells stripped of their cell walls. For all of its superior properties, *Arabidopsis* is typical of flowering plants in its morphology, anatomy, growth, development, and environmental responses, a kind of “everyman” of the plant world. In short, *Arabidopsis thaliana* is a biologist’s dream: a model plant.

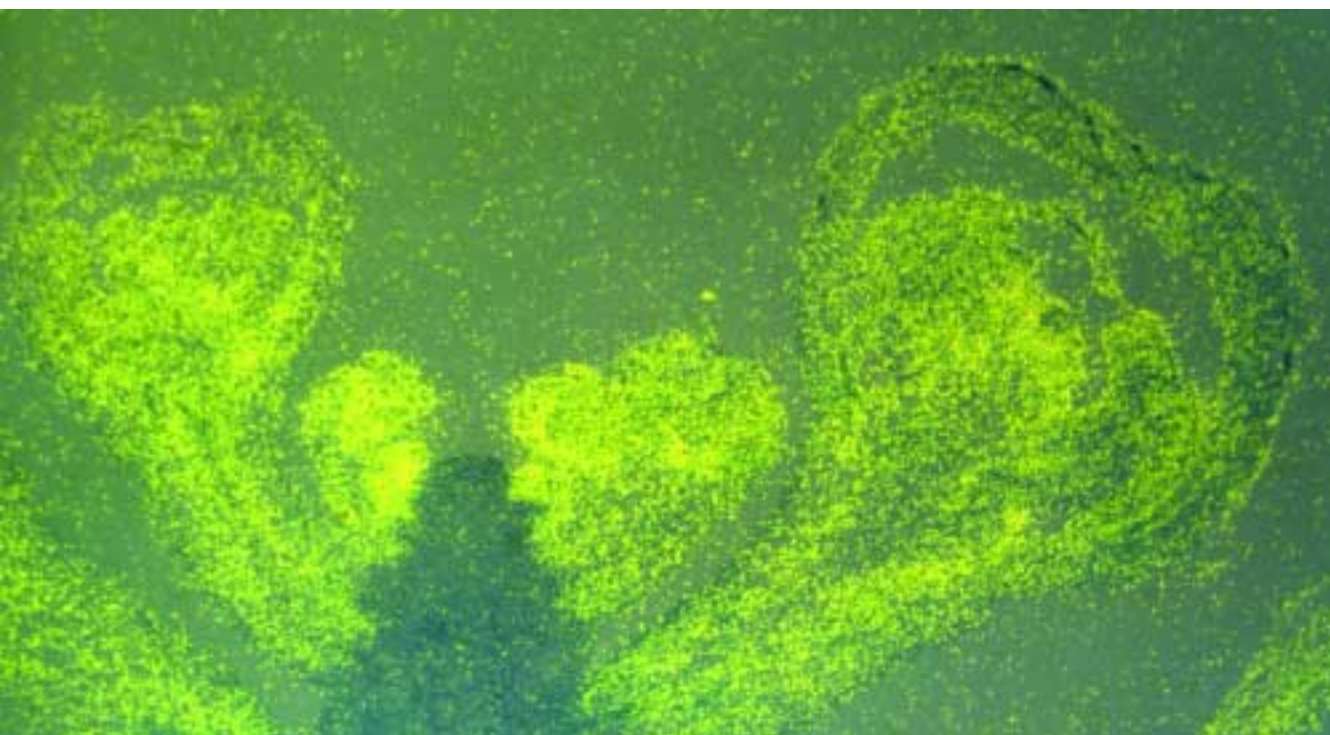


NSF Helps Launch the New Biology

Arabidopsis began to intrigue not only plant biologists, but also scientists who formerly specialized in bacteria or fruit flies. As laboratories around the world undertook *Arabidopsis* projects, the stock of available mutants grew and new techniques were developed for gene cloning. Scientists began making breakthrough discoveries. And NSF undertook to advance *Arabidopsis* research even more rapidly—first through a series of workshops and then by launching a long-range plan in 1990 for the Multinational Coordinated *Arabidopsis thaliana* Genome Research Project. The project’s steering committee, made up of scientists from eight countries, announced a collaborative agreement within the international community to pursue the goal of understanding the physiology, biochemistry, and growth and developmental processes of the flowering plant at the molecular level.

“I see the NSF program people as scientific collaborators,” said Chris Somerville, director of the Plant Biology Department at Carnegie Institution of Washington in Stanford, California, and with Elliot Meyerowitz, co-author of the leading research compendium on *Arabidopsis*. “[NSF] sensed something happening in the community that the individual scientist didn’t necessarily appreciate fully. By bringing a few of us together, they helped us develop our vision. They played a catalytic role. They observed what was going on and made a good judgment about what it meant. Once we began discussing it, we began to see what we could do collectively.”

In the years since the launch of the multinational project, the *Arabidopsis* research community has become a worldwide network of organizations and individuals. Their continued willingness to share information helps keep the project energized and



An *in situ* hybridization process reveals the accumulation of a specific type of RNA—*Apetala 1*—in a mutant *Arabidopsis* flower. Looking at the flower in this state provides scientists with details about the development of the flower's sepals, petals, stamens, and carpels.

the path cleared for new discoveries. With funding from NSF and other federal agencies, as well as governments in other countries, biological resource centers have been established around the world to make seeds of mutant strains—one scientist called them “starter kits”—available to laboratories that want to study them. Between 1992 and the summer of 2000, the *Arabidopsis* Biological Resource Center at Ohio State University, which shares responsibility with a British center for requests throughout the world, shipped 299,000 seed samples and 94,000 DNA samples. In the spirit of openness and collaboration encouraged by a multinational steering committee, hundreds of *Arabidopsis* researchers worldwide regularly make deposits of new seed lines and DNA libraries into the centers.

Accelerating the Pace

The U.S. component of the multinational effort to sequence the *Arabidopsis* genome started as a joint program by NSF, the U.S. Department of Agriculture (USDA), and the Department of Energy (DOE). Building on this effort, in May 1997 the White House Office of Science and Technology Policy (OSTP) established the National Plant Genome Initiative (NPGI) program with the long-term objective to understand the genetic structure and functions in plants important to agriculture, the environment, energy, and health. In the NPGI's first year, NSF, USDA, and DOE provided additional funds to accelerate completion of *Arabidopsis* sequencing. The international *Arabidopsis* community now expects to publish the complete sequence of the plant's genome by the end of 2000, four years ahead of the original schedule.

In 1999 U.S. and European scientists completed mapping the DNA sequences of two of the five chromosomes of *Arabidopsis* and published their findings in the December 16, 1999 issue of *Nature*. The results—the first complete DNA sequence of a plant chromosome—provided new information about chromosome structure, evolution, intracellular signaling, and disease resistance in plants.

Through the NPGI program, NSF, USDA, and DOE also began jointly funding research to sequence the rice genome, enabling U.S. participation in an international collaboration whose goals are set by the International Rice Genome Sequencing Working Group. Most of the world's major food crops (including rice) are grasses, and they share common sets of genes. The relatively small size of the rice genome—430 million base pairs of DNA divided into 12 chromosomes—makes it a model system for understanding the genomic sequences of other major grass crops including corn, wheat, rye, barley, sorghum, sugar cane, and millet. The working group estimates that researchers could complete the sequencing of the rice genome by 2008.

With rice and other plant sequencing efforts underway and with the completion of the *Arabidopsis* genome sequence tantalizingly close, plant researchers have begun to shift their focus from gene identification to functional genomics—a multidisciplinary approach to develop an understanding of the functions of the plant's genes and how they work together under different conditions. A systematic effort to effectively use the massive amounts of genome data becoming available to determine the functions of all of the genes of *Arabidopsis* is seen as the next frontier in plant research. Such an effort could be accomplished by 2010, according to a recent estimate, and would lead to an integrated database that would be a blueprint of *Arabidopsis* through its entire life cycle.

Research to understand the functions of *Arabidopsis*'s gene sequences are still in the early stages but breakthroughs with considerable practical applications could come in the areas of:

DISEASE RESISTANCE. Plant breeders have long known that certain varieties of crops are more resistant than others to particular viral, bacterial, or fungal pathogens. Disease resistance is a major goal of most plant-breeding programs, but it has typically been a long process involving crop plants found in natural wild populations. The process has been impeded by the “species barrier,” which, until recently, prevented desirable genes from being passed around—from corn to cauliflower, for example. *Arabidopsis* researchers have determined the molecular sequences of genes that code for disease resistance and, in addition, the processes by which *Arabidopsis* and perhaps other plants marshal their defenses against pathogens. This discovery may be particularly useful in triggering resistance to disease in species other than *Arabidopsis*. In one enticing example, a bacterial pathogen of mammals was also discovered to be an *Arabidopsis* pathogen. Some of the same factors are required for infection, leading researchers to speculate that evolutionary susceptibility to disease may be accompanied by factors that confer resistance.

CIRCADIAN RHYTHMS. A vast array of processes in plants are regulated in a circadian manner, including daily leaf movements and pore openings, flower-blooming schedules, and photosynthesis cycles. The term “circadian” comes from the Latin words *circa*, meaning about, and *diem*, meaning day. It refers to processes that occur approximately once every twenty-four hours, in response to an organism's internal clock. Plants gain a strong adaptive advantage by being able to anticipate oncoming dawn or dusk, rather than merely responding to the presence or absence of light. They display this ability even as

Communication . . . Fused with the Ideas and Results of Others

NSF's support of genetics dates back to the earliest days of the agency. One of NSF's first five grants in the field of genetic biology, as it was originally called, was made in 1952 to Max Delbrück, who came to the United States from Germany in 1937. Trained as a quantum physicist, he gravitated to biology. While working at the California Institute of Technology and at Vanderbilt University, Delbrück organized and inspired a distinguished group of biologists. One member of the group was James Watson, who, along with Francis Crick and Maurice Wilkins, received the Nobel Prize in 1962 for discovering the structure of deoxyribonucleic acid, or DNA.

Delbrück's contributions to the history of genetics were numerous and evolved from his early interest in bacteriophages, viruses that infect bacteria. A phage can attach itself to a bacterial cell, shuck off its own protein coat, and infiltrate the host cell the way the contents of a syringe enter a vein. Once the phage is inside a cell, its genetic material combines with that of the bacteria, and the phage reproduces itself exactly. These characteristics make phages ideal for the study of biological self-replication and the transfer of bacterial genes between

host organisms. Through experiments with phages, Delbrück and a collaborator demonstrated, for the first time, that bacteria undergo mutation. Their work validated the revolutionary idea that genetic principles apply to microorganisms. It also opened the door to genetic analysis of recombination within bacteria.

Delbrück won the Nobel Prize in 1969, as "the man who transformed bacteriophage research from vague empiricism to an exact science." In his acceptance speech, Delbrück remarked upon the ways in which one scientific discovery leads to another, and he contrasted progress in art with progress in science.

"The books of the great scientists are gathering dust on the shelves of learned libraries. And rightly so. The scientist addresses an infinitesimal audience of fellow composers. His message is not devoid of universality but its universality is disembodied and anonymous. While the artist's communication is linked forever with its original form, that of the scientist is modified, amplified, fused with the ideas and results of others, and melts into the stream of knowledge and ideas which forms our culture."



The major multinational effort to understand the intricacies of *Arabidopsis* has already led to major breakthroughs in engineering disease-resistant plants.

days grow shorter in the fall or longer in the spring. By fusing *Arabidopsis* genetic material with bioluminescent material from fireflies, researchers have been able to observe a glowing pattern of response that reflects the plants' internal clocks. This enabled them to find mutants with aberrant responses, which in turn led to identification of a biological clock gene named "toc." Although influenced by sunlight, "toc" also operates independently, even when the plant is in constant darkness.

ENVIRONMENTAL RESPONSE. Plants respond to a great deal of information from the type of daylight they receive. For example, the changing light throughout the year provides clues about whether it is time to sprout or time to make seeds. When an object blocks the light, plants respond by growing around the object to reach the light. Much of our current information about how plants perceive and respond to light is derived from studies with *Arabidopsis*. These studies have identified the basic genetic framework of light perception and the complex communications system, called a signal transduction network, through which plants act upon information from their photoreceptors. There has also been significant progress in understanding how plants respond genetically when exposed to stresses in the environment, such as ozone, UV-irradiation, touch, cold, and oxygen deprivation.

PLANT HORMONE RESPONSE. Hormones play a central role in the regulation of plant growth and development. Of particular interest is the fruit-ripening hormone ethylene; growers have long searched for a way to minimize crop spoilage by preventing or delaying ripening in a reversible manner. Studies of *Arabidopsis* have demonstrated for the first time the mechanisms through which the tissues and cells of plants respond to ethylene. A gene that prevents response to the growth substance ethylene turns out to be comparable to a "never-ripe" gene in tomatoes, a finding that further supports *Arabidopsis*'s ability to serve as a model for other plants, including crop species.

COMMERCIAL APPLICATIONS. Genetic comparisons between *Arabidopsis* and crop species are increasing constantly. For example, even though the flowers of *Arabidopsis* are very different from those of snapdragons, the same genes control flower development in both. This discovery brings scientists closer to understanding and being able to manipulate the development of grains, fruits, and other flower products to one day create more productive crops. The genes that guide the synthesis of oils in *Arabidopsis* are closely related to those that produce oils in commercial oil crops, a relationship that is already being exploited commercially to produce plants with oils lower in polyunsaturated fats. *Arabidopsis* has also been the test organism for efforts to produce biodegradable plastics in crop plants. Several large chemical companies have started active research programs based on *Arabidopsis* research to develop transgenic crops that produce polyhydroxybutyrate (PHB), a biodegradable plastic.

Why Learn about *Arabidopsis*?

The Multinational Coordinated *Arabidopsis thaliana* Genome Research Project began as an effort by NSF and leading academic researchers to advance fundamental knowledge about how plants function. When NSF published the multinational committee's long-range plan in 1990, U.S. government expenditures on *Arabidopsis* research totaled \$7.5 million. In 1993, total expenditures on *Arabidopsis* research by NSF, USDA, DOE, and the National Institutes of Health (NIH) were \$22 million. In 1998, NSF, USDA, and DOE awarded an additional \$28.3 million over a three-year period to accelerate the pace of *Arabidopsis* research. The global effort to understand *Arabidopsis* involves scientists in more than thirty countries.

From the beginning, NSF saw the *Arabidopsis* effort as an opportunity to foster a collegial, highly motivated, scientific community that would advance fundamental knowledge in an effective way. Both within NSF and in other agencies, officials also recognized that the research has important practical applications. Despite the vast productivity of the agricultural sector, most crops grown in the United States produce less than 50 percent of their genetic potential. Plants succumb to disturbances in their environment; in some years, floods, drought, disease, and parasitic attacks cost billions of dollars. Unlike humans, plants cannot be moved to high ground or inoculated against illnesses. The only protection is to grow resistant strains, and many feel that conventional plant breeding cannot accomplish this fast enough. In the developing world in particular, the problem is exacerbated by growing populations that put extraordinary pressures on the ecosystem. Many see biotechnology as the only feasible solution.

Bioengineered plants also figure prominently in the ideal world envisioned by NIH and the health care community, who see potential in plants as a source of improved, less costly pharmaceuticals. The Department of Energy, for its part, envisions a future in which biotechnology improves the quality and quantity of biomass products, such as alternative fuels and chemical feedstocks, and provides a way to engineer plants to clean up contaminated soil at former nuclear weapons production sites.

Presciently summing up the major applications of biotechnology, a 1995 report from the National Science and Technology Council called *Biotechnology for the 21st Century* stated: “Through the use of advanced tools such as genetic engineering, biotechnology is expected to have a dramatic effect on the world economy over the next decade. Innovations emerging in the food and pharmaceutical sectors offer only a hint of the enormous potential of biotechnology to provide diverse new products, including disease-resistant plants, ‘natural’ pesticides, environmental remediation technologies, biodegradable plastics, novel therapeutic agents, and chemicals and enzymes that will reduce the cost and improve the efficiency of industrial processes. . . [B]iotechnology. . . may well play as pivotal a role in social and industrial advancement over the next ten to twenty years as did physics and chemistry in the post-World War II period.”

To Learn More

NSF Directorate for Biological Sciences

www.nsf.gov/bio

The Multinational Coordinated *Arabidopsis thaliana* Genome Research Project Progress Reports (published by NSF)

www.nsf.gov:80/bio/reports.htm#progress

Gregor Mendel's work in plant heredity

www.netspace.org/MendelWeb/

***Arabidopsis* Biological Resource Center at Ohio State University**

<http://aims.cps.msu.edu/aims/>

Nottingham *Arabidopsis* Stock Centre

<http://nasc.life.nott.ac.uk/>

The *Arabidopsis* Information Resource (TAIR)

www.arabidopsis.org

National Institutes of Health

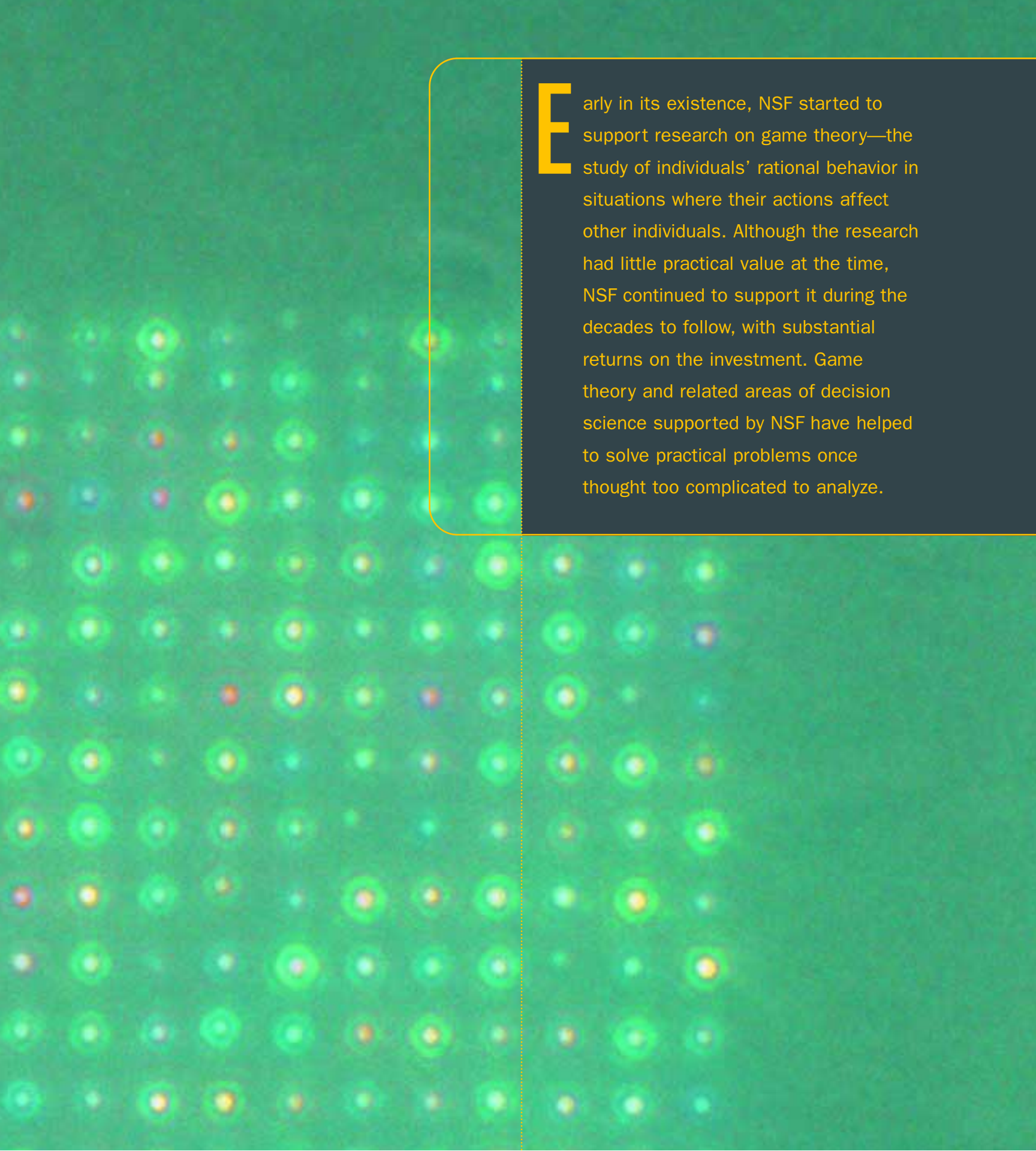
www.nih.gov/

National Science and Technology Council

www.whitehouse.gov/WH/EOP/OSTP/NSTC/html/NSTC_Home.html

Decision Sciences

how the game
is played



Early in its existence, NSF started to support research on game theory—the study of individuals’ rational behavior in situations where their actions affect other individuals. Although the research had little practical value at the time, NSF continued to support it during the decades to follow, with substantial returns on the investment. Game theory and related areas of decision science supported by NSF have helped to solve practical problems once thought too complicated to analyze.



Game theory deals with the interactions of small numbers of individuals, such as buyers and sellers. For almost thirty years after its development during World War II, the theory remained an academic exercise, its dense mathematical proofs defying practical applications. Yet NSF stood by leading economists who painstakingly demonstrated how to use game theory to identify winning strategies in virtually any competitive situation. NSF also supported experimental economists who tested theoretical approaches under controlled laboratory conditions, and psychologists whose studies of individual decision making extended understanding of how economically rational individuals behave.

Persistence paid off. In 1994, John F. Nash, Reinhard Selten, and John C. Harsanyi, who first received NSF support in the 1960s, won the Nobel Prize in Economics for “their pioneering analysis of equilibria in non-cooperative games.” The following year, game theory gave the Federal Communications Commission the logical structure for innovative auctions of the airwaves for new telecommunications services. The auctions raised over \$7 billion for the U.S. Treasury, and marked a coming of age for this important analytic branch of economics.

In supporting this field, NSF’s goal was to build the power of economics to elucidate and predict events in the real world. The support not only advanced the discipline, but also benefited all individuals in many aspects of daily life.

Decisions, Decisions

We all find ourselves in situations that call for strategic thinking. Business executives plan strategies to gain market share, to respond to their competitors' actions, to handle relations with employees, and to make career moves. Managers in government think strategically about the likely effects of regulations at home and of diplomatic initiatives abroad. Generals at war develop strategies to deploy troops and weaponry to defeat the enemy while minimizing their own losses. At a more individual level, buyers and sellers at flea markets apply strategies to their bargaining. And parents use strategy on their children, who—of course—behave strategically with their parents.

What is strategy? Essentially, it is anticipating the actions of another individual and acting in ways that advance one's self-interest. Since the other person also behaves strategically, strategy includes making assumptions about what that individual believes your strategy to be. We usually associate strategy with adversarial situations such as war, but that is much too narrow. In love, we use strategy, often unthinkingly, to win our loved one's heart without sacrificing our self-esteem or our bank account. Some strategists have objectives, such as racial harmony, that they feel serve everyone's interest. Probably the most common use of strategy occurs in basic economic transactions, such as buying and selling. However it is applied, the ultimate point of strategy is to achieve objectives.

That is precisely what players of games try to do. Similarities between games and strategic behavior in the economy formed the framework for *Theory of Games and Economic Behavior*, a book published in 1944 by mathematicians John von Neumann and Oskar Morgenstern. Their landmark work begins where classical economics leaves off.

The starting point for traditional economics is the equilibrium price, the point at which a seller's asking price equals the buyer's bid price. Classical economic theory goes on to analyze the price in terms of outside influences. Von Neumann and Morgenstern, however, went in another direction: They looked at the relationship between the participants.

Exactly how, they asked, do buyers and sellers get to the equilibrium price? In a world of perfect competition, containing so many buyers and sellers that any one individual's acts are insignificant, marketplace dynamics suffice. But what about economic transactions that involve only a few buyers and sellers? What happens when, for example, MCI offers potential customers a deal on long-distance service, and AT&T responds by offering the public its own new deal? The strategic moves in such economic decision making struck Morgenstern and von Neumann as mathematically indistinguishable from moves in chess, poker, and other games in which some strategies consistently win over others. Their book, a compendium of mathematical theorems embodying many different strategies for winning, was the first rigorously scientific approach to decision making.

Significant as it was, game theory took a long time to catch on. A small group of academics recognized its significance as a research tool. And some military applications appeared in the 1950s, when the Rand Corporation used game theory to anticipate responses of potential enemies to weaponry of various kinds. The world of business, however, regarded game theory as an arcane specialty with little practical potential.

NSF Lends Support

NSF took a different view, and began to support game theory mathematics in the 1950s. “The appeal of game theory always was the beauty of the mathematics and the elegance of the theorems,” explains Daniel H. Newlon, senior program director for economics at NSF. “That was part of the appeal to a science agency.”

A few years later, when NSF began to fund research in the social sciences, leading scholars urged the agency to continue its support for game theory. John Harsanyi of the University of California at Berkeley began receiving NSF grants in the 1960s, as did other major game theorists. “What kept NSF interested in game theory,” says Newlon, “was the drive of people working in this field to understand how people interact, bargain, and make decisions, and to do it in a more rigorous, systematic fashion. For years, the problems were so difficult, given the state of computers and the mathematical tools at people’s disposal, that you didn’t see significant results. Yet NSF hung in there.”

NSF went beyond supporting individual game theorists. It also sponsored conferences that gave game theorists the opportunity to gain visibility for their work. One such event was the annual Stanford Institute Conference in Theoretical Economics—run by game theorist Mordecai Kurtz—which NSF began to fund in the mid-1960s. Another NSF-funded meeting at the State University of New York had two goals: to use game theory to advance the frontiers of economic research and to improve the skills of graduate students and junior faculty in economics departments. From time to time, NSF invited proposals for workshops and awarded grants for computers and other needed equipment.

Into the Laboratory

Original work in game theory consisted entirely of models—simplified representations of the underlying logic in economic decision-making situations—which may have contributed to the business world’s reluctance to accept its usefulness. A theory in physics or biochemistry can be tested in a controlled laboratory situation. In real-world decision making, however, conditions are constantly altered as a result of changes in technology, government interventions, organizational restructuring, and other factors. The business world and most economists found it hard to see how reading *Theory of Games and Economic Behavior* could actually help them win games or make money.

In the early 1960s, Charles R. Plott and his colleagues at the California Institute of Technology started to make game theory into an experimental pursuit. Supported by NSF, his group conducted a series of experiments that helped to answer questions about one facet of game theory: the ideal number of stages in an auction and their overall length. Experimentation, which Plott referred to as “debugging,” became increasingly popular in economics as a complement to field research and theory.

The general idea was to study the operation of rules, such as auction rules, by creating a simple prototype of a process to be employed in a complex environment. To obtain reliable information about how test subjects would choose among various economic alternatives, researchers made the monetary rewards large enough to induce serious, purposeful behavior. Experiments with prototypes alerted planners to behavior that could cause a system to go awry. Having advance warning made it possible to change the rules, or the system for implementing the rules, while it was relatively inexpensive to do so.

Other economists refined and expanded game theory over the years to encompass more of the complex situations that exist in the real world. Finally, in the early 1980s, business schools and



The Fruits of Economic Research Are Everywhere

Starting in the 1960s, with support from NSF, Charles R. Plott of the California Institute of Technology made advances in game theory that paved the way for practical applications three decades later. Here, he outlines the practical relevance of NSF-supported economics research:

“The fruits of economic research are everywhere. Because NSF is the only dedicated source of funding in the United States for basic research in the economic sciences, its impact has been large. We see it in the successful application of game theory to the design of the FCC auctions of licenses for new telecommunications services.

“More broadly, we see the impact of NSF-supported work in some of the most important economic trends of our lifetimes, such as deregulation of airlines and other industries, nongovernmental approaches to environmental protection, and the liberalization of worldwide trade. The recent reexamination of the Consumer Price Index and how it should be measured relies heavily on NSF-sponsored basic research on price indices.

“In economics it is easy to find problems that are not solved, and perhaps are not solvable in any scientific sense. Yet measured in a cost-benefit sense, the achievements of economic research stand against those of any science.”

—Charles R. Plott

Ph.D. programs in economics began to appreciate the power of game theory. By the 1990s, it had all but revolutionized the training of economists and was a standard analytical tool in business schools. In 1994, game theory received the ultimate recognition with the award of Nobel prizes to Nash, Selten, and Harsanyi—three pioneering researchers in the field.

Practical Payoffs

From a financial standpoint, the big payoff for NSF's long-standing support came in 1995. The Federal Communications Commission (FCC) established a system for using auctions to allocate bands of the electromagnetic spectrum for a new generation of wireless devices that included cellular phones, pagers, and hand-held computers with email capabilities.

Instead of the standard sealed-bid auction, Stanford University game theorist Paul Milgrom, an NSF grantee, recommended open bidding, which allows each bidder to see what the others are offering. Participants could also bid simultaneously on licenses in the fifty-one zones established by the FCC. Game theory's models of move and countermove predicted that open bidding would reassure bidders who, in trying to avoid the so-called winner's curse of overpaying, might be excessively cautious. Open bidding would also enable bidders to carry out economically advantageous strategies to consolidate holdings in adjacent territories, although FCC rules guaranteed that no one could obtain a monopoly in any zone. The intended outcome was an optimal solution for all parties. The bidders would get as many licenses as they were willing to pay for, while the U.S. Treasury would earn the maximum possible.

In the final accounting, the FCC's 1995 simultaneous multiple-round auctions raised over \$7 billion, setting a new record for the sale of public property. Not only was the decision a

landmark in the recovery of private compensation for use of a public resource, it also represented a victory for the field of game theory, whose leading scholars had applied what they knew about strategic decision making in recommending an auction design to the FCC.

Game theory has proved its worth in many other practical areas, among them management planning. Alvin E. Roth of the University of Pittsburgh applied game theory to analyze and recommend matching mechanisms for allocating thousands of medical interns among hundreds of hospitals in such a way as to give both the hospitals and the interns the matches they favor the most. He had the broader research aim of understanding how market institutions evolved to determine the distribution of doctors and lawyers.

Polls, Markets, and Allocations

Game theory represents one important facet of decision science. In fact, decision science deals with the entire subject of markets—for goods, services, and ideas, as well as labor. NSF-funded researcher Bob Forsythe, at the University of Iowa, provides one example of efforts in this area: His innovative Iowa Electronic Market, started in 1988, offered speculators a “real-money futures market.” This type of market deals with abstract, but measurable, items. Participants bet on what the price of an abstract item, such as pork bellies, will be days, weeks, or months into the future. Between the time the bet is placed and the point at which it is paid off, the price of pork bellies will be influenced by a succession of economic and political events, including elections and the stock prices of firms in the pork industry.

Forsythe's “market” actually represented an effort to elicit more accurate information from voters than opinion polls provided. Instead of pork bellies, it focused on the electoral prospects of political candidates. “Market prices” summed up what

players knew, or thought they knew, about a candidate's true chances of success in an election. Participants would win if the candidates on whom they bet were elected, and would lose if the candidates lost. Plainly, market participants could influence the result by their own votes; they would slightly improve the chances of the candidates they bet on by voting for those candidates, and slightly diminish those chances by voting for the opponents. Nevertheless, in its first ten years, the Iowa Electronic Market predicted election outcomes more accurately than did pollsters.

Recently, Forsythe and his colleagues received NSF funding to develop instructional materials that use the electronic market as a laboratory exercise to help undergraduates studying economics better understand market concepts

In another innovative area, called "smart markets," computers have become partners in the process of making allocation decisions, such as assignments of airport landing rights and management of gas pipelines and electric distribution systems. Computers process information, coordinate activi-

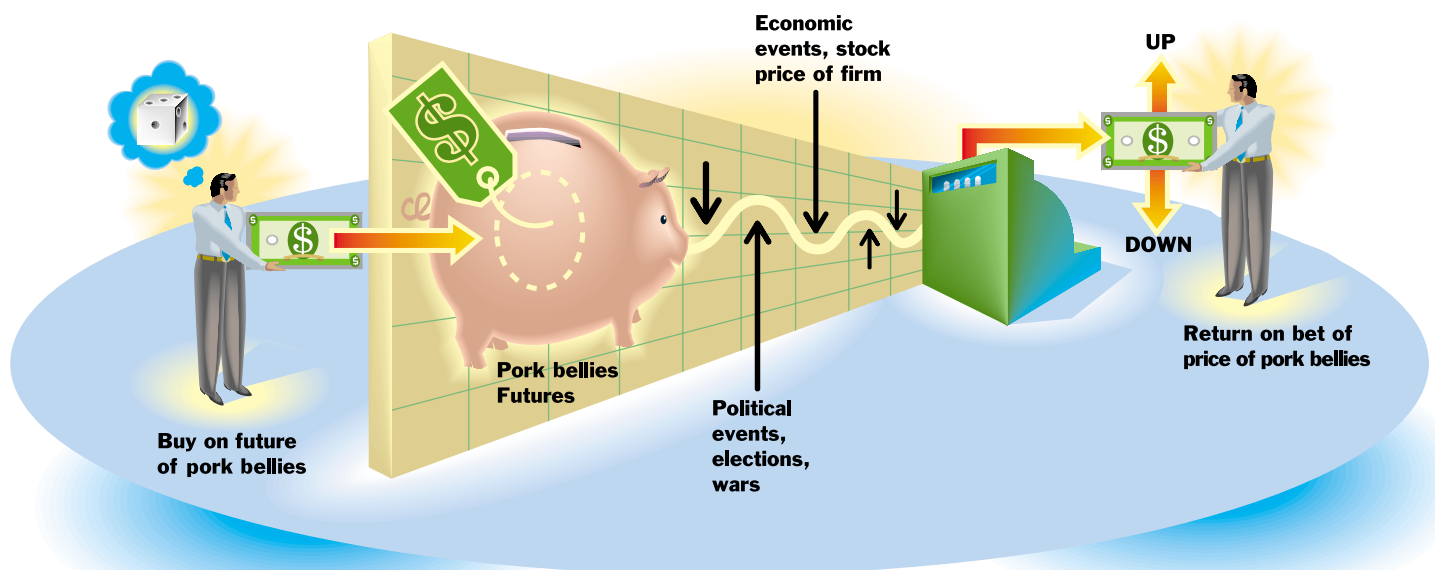
ties, and monitor allocation situations historically thought to be impossible to manage with anything other than a heavily bureaucratic administrative process. For example, the results of NSF-sponsored research have been used to shape a particular type of market that sets pollution limits and allows facilities that generate pollution to trade 'pollution permits' among themselves, so long as the overall limit is not exceeded.

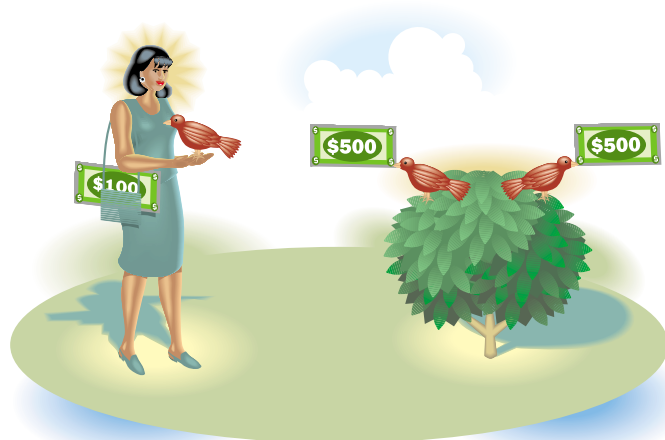
Real-World Decision Making

These examples illustrate the common thread among the diverse projects of economists who build and test models: All of the projects are designed to explain more of what occurs in the real world.

Economic models work well when applied to markets and other institutions, in part because people gathered together in large numbers seem to behave as "rational" decision makers. But individual behaviors, and the behavior of small groups of individuals like the bidders in the FCC

Decision science has broad implications for all sectors of our society. It plays a role in understanding outcomes in financial markets and assessing the role of a centralized matching system in ensuring a stable supply of medical school graduates to hospital residency programs. Among the many questions that NSF-funded decision science researchers are attempting to answer: how people behave in economic environments, how information is distributed within economic institutions, and the influence of expectations and beliefs on decision making.





Gain Only



Gain and Loss

“A bird in hand is worth two in the bush” describes one action a person might take to minimize risk and maximize utility—the real or perceived ability of a product or service to satisfy a need or desire. Utility theory attempts to define the many factors that influence how people make decisions and to predict how an individual will behave when faced with difficult choices.

auctions, often seem inconsistent with rationality. NSF’s Decision, Risk, and Management Science Program, within the Directorate for Social, Behavioral, and Economic Sciences, supports leading scholars in the decision sciences who look at these inconsistencies from another point of view. They try to determine the nature and origins of systematic errors in individual decision making, and use game theory to provide sets of strategies for anticipating and dealing with them.

Systematic errors abound in decisions that involve probability. Most people are not good at estimating the statistical likelihood of events, and their mistakes fall into distinct patterns. Reporting

on these tendencies, Paul Slovic, Baruch Fischhoff, and Sarah Lichtenstein of Decision Research in Eugene, Oregon, wrote:

“People greatly overestimate the frequency of deaths from such dramatic, sensational causes as accidents, homicides, cancer, botulism, and tornadoes, and underestimate the frequency of death from unspectacular causes that claim one victim at a time and are common in nonfatal form—diabetes, stroke, tuberculosis, asthma, and emphysema . . . The errors of estimation we found seemed to reflect the working of a mental shortcut or ‘heuristic’ that people commonly use when they judge the likelihood of risky events.”

The authors explain that people judge an event as likely or frequent if instances of it are easy to imagine or recall. On the other hand, individuals often don’t bother to consider information that is unavailable or incomplete. Every time we make decisions that involve probabilities, we confirm the reality of the phrase “out of sight, out of mind.”

Another area where humans are systematically error-prone involves what economists call utility. We frequently face choices between doing the safe thing and taking a risk. One example is the choice between driving to work on secondary roads or taking the interstate, which usually saves several minutes but can occasionally take an extra half-hour or more because of back-ups. Another is the decision between investing in a safe money market account and taking a flier on a volatile stock.

No two people feel exactly the same about which risks are worth taking. The concept of utility combines several factors in decision making: the range of possible outcomes for a particular choice, the probability associated with each outcome, and an individual’s subjective method of ranking the choices.

Imagine choosing between two tempting opportunities. One is a coin toss—heads you win \$1,000, tails you win nothing. The other is a sure thing—an envelope with \$500 inside. Do you choose the safe and sure \$500 or the 50/50

All in a Day's Work

Imagine you are a cab driver. What you earn in a given day varies according to the weather, time of year, conventions in town, and other factors. As a rational person, you want to maximize both your income and your leisure time. To achieve that, you should work more hours when wages are high and fewer hours when wages are low.

What that means is that cab drivers should work more hours on busy days and fewer hours on slow days. Do they? Not at all; they do the opposite.

Colin Camerer of the California Institute of Technology made this discovery when he and his colleagues interviewed a large sample of cab drivers. They found that the cabbies decide how many hours to work by setting a target amount of money they want to make each day. When they reach their target, they stop working. So on busy days, they work fewer hours than on slow days.

Why? Camerer suggested that working an extra hour simply may

not be worth an hour of leisure time; in the language of economics, the marginal utility is too low. On the other hand, it may not be the money as much as cab drivers' feelings about the money—or, more precisely, how they think they may feel if they depart from their usual working habits. Will a cab driver who works an extra hour or two on a busy day feel later that it wasn't worth the effort? Will one who knocks off early on a slow day feel guilty about it? Setting a target may be a way to avoid regrets.

NSF has supported Camerer and others in their efforts to explain this and other paradoxes that characterize human economic behavior. From the beginning, decision science research has had the goal of a better fix on people's feelings about wages, leisure, and tradeoffs between them, with implications for labor relations, productivity, and competitiveness across a wide spectrum of industries.



chance to win \$1,000? An economically rational person makes the choice that reflects the highest personal utility. The wealthier that individual is, for instance, and the more he or she likes to gamble, the higher is the utility of the risky 50/50 choice versus the sure thing.

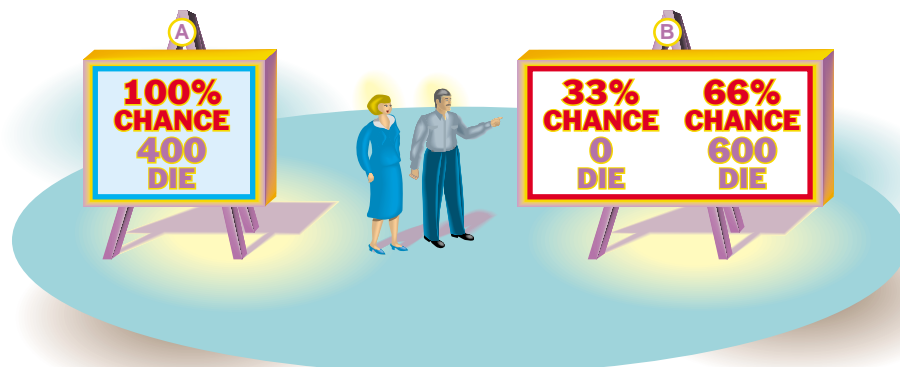
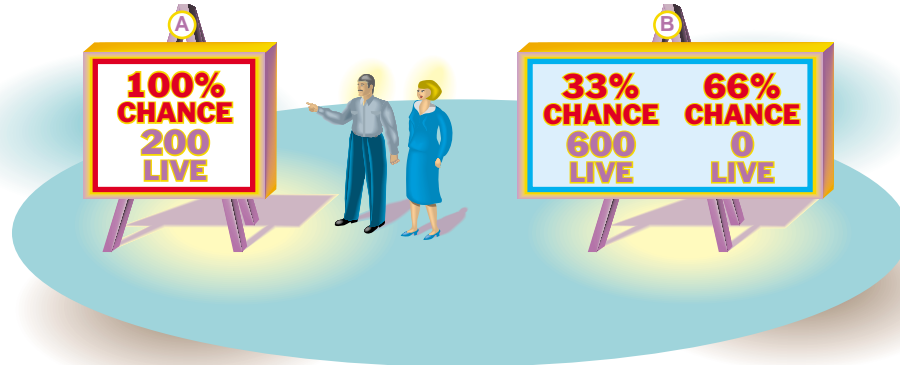
Questioning Utility Theory

Utility theory postulates that it should not matter how alternatives are presented. Once we know what's at stake, and the risks involved, we should have enough awareness of ourselves to make the choice that serves us best.

In fact, psychologists Daniel Kahneman of Princeton and the late Amos Tversky of Stanford demonstrated that the way alternatives are framed can make quite a difference in our choices. In one of their most famous studies, they presented people with a choice between two programs that addressed a public health threat to the lives of

600 people. When the outcomes of the programs were described as (a) saving 200 lives for sure, or (b) a one-third chance to save 600 lives and a two-thirds chance to save no one, most respondents preferred the first option. But when the outcomes were presented as (a) 400 people dying for sure, or (b) a two-thirds chance of 600 people dying and a one-third chance that no one would die, most respondents preferred the second option. Of course, the two versions of the problem are the same, because the people who will be saved in one version are the same people who will not die in the other. What happens here is that people are generally risk-averse in choices between sure gains and favorable gambles, and generally risk-seeking in choices between sure losses and unfavorable gambles. "Some propensities," points out former NSF Program Director Jonathan Leland, "are so ingrained that the trick is to help people understand why their decisions are bad." No one, it seems, is immune to the power of the well-chosen word.

NSF-funded researchers Daniel Kahneman and the late Amos Tversky were instrumental in the development of rational choice theory. First used to explain and predict human behavior in the market, advocates of rational choice theory believe that it helps integrate and explain the widest range of human behavior—including who people vote for, what they buy at the grocery store, and how they will react when faced with a difficult decision about medical treatment.



Why We Make Foolish Decisions

Individuals frequently ensure poor decision making by failing to obtain even the most basic information necessary to make intelligent choices. Take, for example, the NSF-supported research of Howard Kunreuther of the University of Pennsylvania's Wharton School. He and his colleagues observed that most people living in areas subject to such natural disasters as floods, earthquakes, and hurricanes take no steps to protect themselves. Not only do they not take precautions proven to be cost-effective, such as strapping down their water heaters or bolting their houses to foundations; they also neglect to buy insurance, even when the federal government provides substantial subsidies.

What accounts for such apparently foolish decision making? Financial constraints play a role. But Kunreuther found the main reason to be a belief that the disaster "will not happen here." His research suggested "that people refuse to attend to or worry about events whose probability is below some threshold." The expected utility model, he added, "is an inadequate description of the choice process regarding insurance purchases."

Kunreuther next applied decision science to devising an alternative hypothesis for the behavior. First, he posited, individuals must perceive that a hazard poses a problem for them. Then they search for ways, including the purchase of insurance, to mitigate future losses. Finally, they decide whether to buy coverage. They usually base that decision on simple criteria, such as whether they know anyone with coverage. The research showed that, since people do not base their purchasing decisions on a cost-benefit analysis, premium subsidies alone did not provide the necessary impetus to persuade individuals to buy flood insurance.

Decision making within organizations is also riddled with systematic bias. One example is the familiar phenomenon of throwing good money after bad. Corporations frequently become trapped in a situation where, instead of abandoning a failing project, they continue to invest money and/or emotion in it, at the expense of alternative projects

with higher expected payoffs. With NSF support, M.H. Bazerman of Northwestern University documented these stubborn tendencies in a variety of settings, and proposed corrective measures that organizations can take to counteract them.

Just as it supported game theory from the very early stages, NSF has funded research on the application of psychology to economic decision making from the field's infancy. That support yielded even faster dividends: Within a few years, the research had given rise to popular books advising managers and others on how to correct for error-prone tendencies and make better decisions. "We know that people bargain and interact, that information is imperfect, that there are coordination problems," NSF's Daniel Newlon explains. "NSF's long-term agenda is to understand these things. Even if they're too difficult to understand at a given time, you keep plugging away. That's science."

To Learn More

NSF Division of Social and Economic Sciences

Economics Program
www.nsf.gov/sbe/ses/econ/start.htm

NSF Decision, Risk, and Management Sciences Program

www.nsf.gov/sbe/ses/drms/start.htm

Consumer Price Index

<http://stats.bls.gov/cpihome.htm>

Decision Research

www.decisionresearch.org

Iowa Electronic Market

www.biz.uiowa.edu/iem/index.html

The Nobel Foundation

Nobel Prize in Economic Sciences
www.nobel.se/economics/laureates/1994/index.html

Stanford Encyclopedia of Philosophy

Game Theory
<http://plato.stanford.edu/entries/game-theory/>

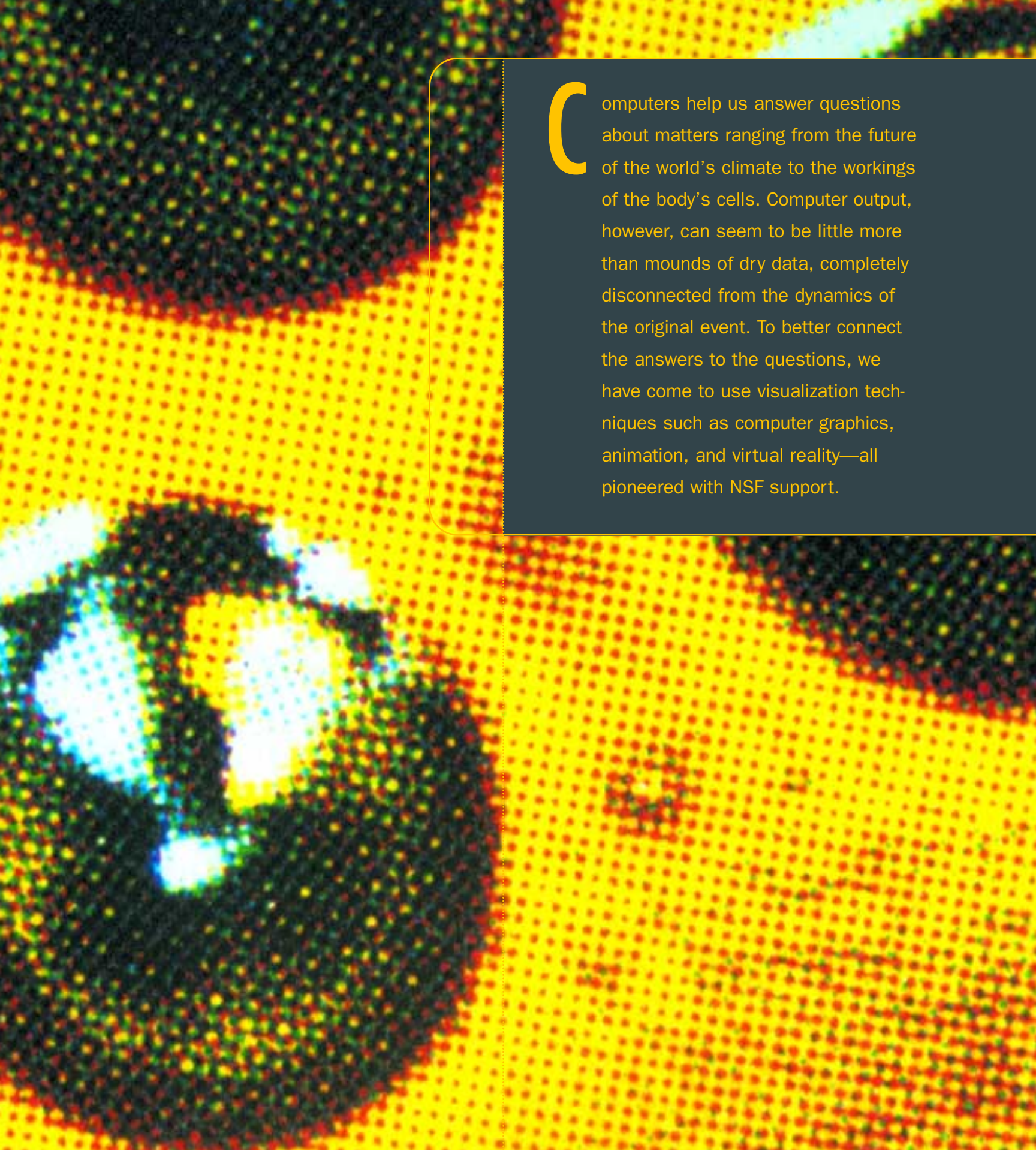
Stanford Institute for Theoretical Economics

www.stanford.edu/group/SITE/siteprog.html



Visualization

a way to see
the unseen



Computers help us answer questions about matters ranging from the future of the world's climate to the workings of the body's cells. Computer output, however, can seem to be little more than mounds of dry data, completely disconnected from the dynamics of the original event. To better connect the answers to the questions, we have come to use visualization techniques such as computer graphics, animation, and virtual reality—all pioneered with NSF support.



Scientists in many disciplines use sophisticated computer techniques to model complex events and visualize phenomena that cannot be observed directly, such as weather patterns, medical conditions, and mathematical relationships. Virtual reality laboratories give scientists the opportunity to immerse themselves in three-dimensional simulations, often with spectacular results such as those in the acclaimed IMAX film *Cosmic Voyage*. The field of computer visualization has developed rapidly over the past twenty-five years, largely because of NSF support. NSF has encouraged pioneering individual research, the development of supercomputing centers, wider-range applications being explored at science and technology centers, and far-reaching programs such as the Partnerships for Advanced Computational Infrastructure. NSF's commitment has helped computer visualization grow from its infancy in the 1950s and 1960s to the important scientific and commercial field it is today.

Visualizing Science in Action

A surgeon can repair a human heart, but like all living organs, the heart presents a host of problems to scientists who want to understand it in detail. X-rays, probes, and scans show only a partial picture—a snapshot—while often what is needed is a motion picture of how all the parts interact. In 1993, scientists at New York University came up with a solution. Working at the NSF-funded Pittsburgh Supercomputing Center, they created the first three-dimensional, animated model of a beating heart.

That first successful “heartbeat” required nearly a week of computing time and represented fifteen years of work by mathematicians Charles Peskin and David McQueen. Subsequently, the work has had broad influence in studies of biological and anatomical fluid flow.

Other simulations demonstrate the dynamics of much larger events, such as tornadoes. Scientists at the University of Illinois have traced air motion within and around tornadoes by introducing thousands of weightless particles into the flow. With that information, and with the computing power at the NSF-supported National Center for Supercomputing Applications (NCSA), also at the University of Illinois, they created a model that provides a closer look at updrafts, downdrafts, and strong horizontal changes in wind speed.

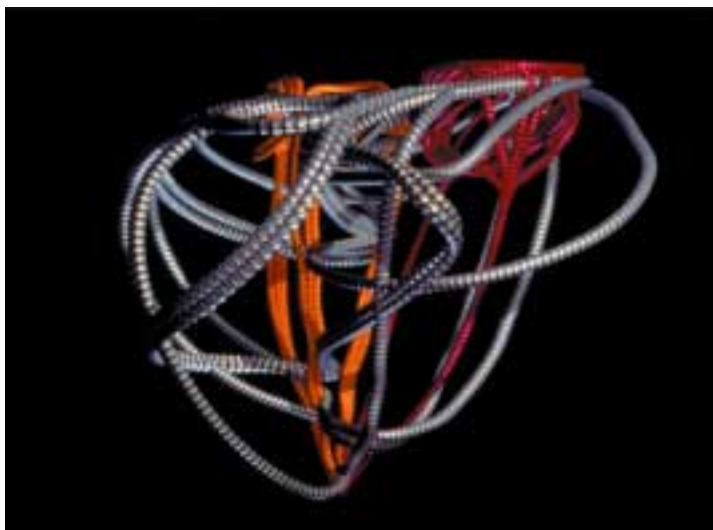
Robert Wilhelmson, an atmospheric computer scientist, began modeling storms almost thirty years ago in hopes of better predicting severe occurrences. One of the founders of NCSA, he wanted from the beginning to model how storms evolve. Wilhelmson and his research group have pushed storm visualizations from static two-dimensional images to three-dimensional animations at ever-greater resolution and over longer time spans.

All the sciences use the visual arts in some form or another, depicting everything from molecules to galaxies. Engineering, too, relies on detailed renderings. Over the years, NSF has funded the development of computer visualizations in many fields, while at the same time challenging computer specialists to go back to the basics and learn how to make these visualizations more accurate and more useful as scientific predictors.

Ensuring this accuracy, according to Cornell University’s Don Greenberg, a long-time NSF grantee, entails making sure that computer-generated visualizations obey the laws of physics. Researchers at Cornell, one of five institutions in the NSF Science and Technology Center for Computer Graphics and Visualization, address this issue by developing ways to incorporate the physics of how light behaves and how our eyes perceive it. Their renderings look like architectural photos—studies of light and space. And their research has been used by General Electric Aircraft Engines, Battelle Avionics, Eastman Kodak, and others.

Moving computer visualizations from what is acceptable to what is most useful from a scientific standpoint has taken a lot of work, says Greenberg. “It’s easy to make visualizations believable; *Jurassic Park* and *Star Wars* did a fine job of that,” he says. “But they weren’t very accurate. It’s much harder to make them accurate.”

Mathematicians Charles Peskin and David McQueen laid the groundwork for visualizations that will allow physicians to better understand the inner workings of the human heart. The model may lead to more effective diagnosis and treatment of heart defects and diseases.



Worth at Least a Thousand Data Points

The increased ability of scientists and engineers to model complex events is a direct result of NSF's investment in supercomputing centers. These university-based research facilities, started in the 1980s, gave researchers around the country access to the computational power they needed to tackle important—and difficult—problems. Visualization, while not an explicit goal of the supercomputing centers, quickly emerged as a way to cope with the massive amounts of scientific data that had been pouring out of computers since the 1960s. “We became very good at flipping through stacks of computer printouts,” recalls Richard Hirsh, a specialist in fluid dynamics who is now NSF's deputy division director for Advanced Computational Infrastructure and Research. “But we realized that, at some point, people needed to see their solutions in order to make sense of them.”

Humans are adept at recognizing patterns, Hirsh says, especially patterns involving motion. One of the early visualization success stories was a model of smog spreading over Southern California, a model so informative and realistic that it helped to influence antipollution legislation in the state. As the cost of computer memory dropped and computer scientists began finding more applications for visualization techniques, the scientific community began to take notice.

The NSF Panel on Graphics, Image Processing, and Workstations published its landmark report *Visualization in Scientific Computing* in 1987. “ViSC [visualization in scientific computing] is emerging as a major computer-based field,” the panel wrote. “As a tool for applying computers to science, it offers a way to see the unseen . . . [it] promises radical improvements in the human/computer interface.” The NSF report was accompanied by two hours of videotape demonstrating the potential of the new tool.

“Before the publication of the report, the opinions and observations of many well-known and respected computer graphics experts were of little concern to the scientific and computing

establishments,” recalls Tom DeFanti, director of the Electronic Visualization Laboratory at the University of Illinois at Chicago and co-editor of the ViSC report. Today, he says, “their comments are sought after—to educate the public, to influence industry research, and to identify new scientific markets.”


NSF earmarked funds for visualization at the supercomputing centers from 1990 to 1994. During that time, application of visualization techniques spread. Since 1997, NSF's Partnerships for Advanced Computational Infrastructure (PACI) program has stimulated further advances in areas ranging from sophisticated tools for managing, analyzing, and interacting with very large data sets to collaborative visualization tools to enable researchers from far-flung areas to work interactively on a real-time basis. Applications now span the whole of contemporary science. For example:

- Molecular biologists use modeling to depict molecular interaction.
- Astronomers visualize objects that are so far away they cannot be seen clearly with most instruments.
- Medical researchers use computer visualization in many diagnostic techniques, including the Magnetic Resonance Imaging (MRI) system that produces three-dimensional images of the body.

Art and Science: An Alternative to Numbers

DeFanti and his colleague Maxine Brown summarized reasons for the booming popularity of visualization in *Advances in Computers* (1991):

“Much of modern science can no longer be communicated in print; DNA sequences, molecular models, medical imaging scans, brain maps, simulated flights through a terrain, simulations of fluid flow, and so on all need to be expressed and taught visually . . . Scientists need an alternative to numbers. A technical reality today and a cognitive imperative tomorrow is the use of images. The ability of scientists to visualize



Computer Graphics: A Competitive Edge

“Advances in computer graphics have transformed how we use computers . . . While everyone is familiar with the mouse, multiple ‘windows’ on computer screens, and stunningly realistic images of everything from animated logos in television advertisements to NASA animations of spacecraft flying past Saturn, few people realize that these innovations were spawned by federally sponsored university research.

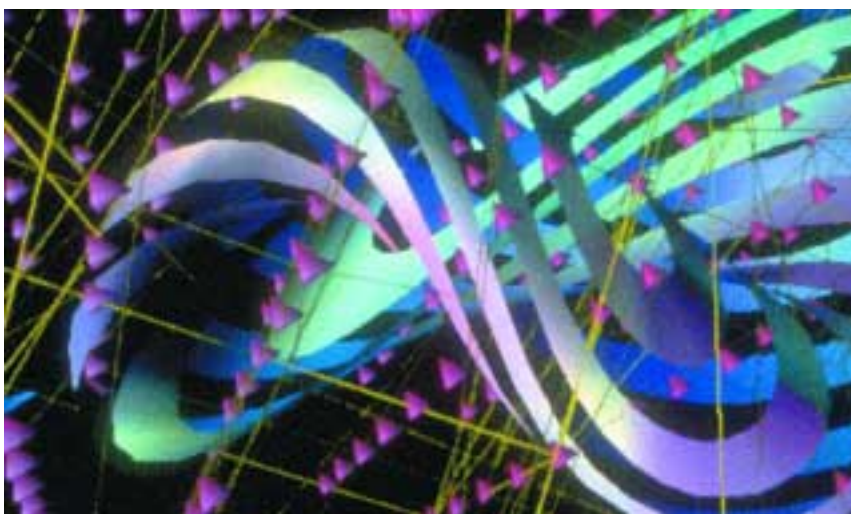
“[For example] [h]ypertext and hypermedia have their roots in Vannevar Bush’s famous 1945 *Atlantic Monthly* article ‘As We May Think.’ Bush described how documents might be interlinked in the fashion of human associative memory. These ideas inspired Doug Engelbart at SRI (funded by DARPA) and Andries van Dam of Brown University (funded by NSF) to develop the first hypertext systems in the 1960s. These systems were the forerunners of today’s

word-processing programs, including simple what-you-see-is-what-you-get capabilities . . .

“High-quality rendering has caught the public’s eye and is having a vast impact on the entertainment and advertising industries. From *Jurassic Park* to simulator rides at Disney World and dancing soda cans in TV commercials, the world has been seduced by computer animation, special effects, and photorealistic imagery of virtual environments . . .

“One could continue with many more examples, but the message is clear: federal sponsorship of university research in computer graphics stimulated a major segment of the computing industry, allowing the United States to establish and maintain a competitive edge.”

—Excerpted from *Computer Graphics: Ideas and People from America’s Universities Fuel a Multi-billion Dollar Industry* by Edward R. McCracken, Former chairman and Chief Executive Officer, Silicon Graphics, Inc.
© 1995-1997.



Through computer mapping of topographical surfaces, mathematicians can test theories of how materials will change when stressed. The imaging is part of the work at the NSF-funded Electronic Visualization Laboratory at the University of Illinois at Chicago.

complex computations and simulations is absolutely essential to ensure the integrity of analyses, to provoke insights, and to communicate those insights with others.”

Over the years, two basic types of drawing systems have vied for the attention of both developers and users—vector graphics and raster graphics. Vector graphics systems are based on specifying the location of points on an X and Y coordinate system and connecting the points with lines. The basic drawing element of vector graphics is the line, created by an electron beam in the monitor as it moves directly from one set of coordinates to another, lighting up all the points in between. By contrast, the electron beam in the monitor of a raster graphics system scans across the screen, turning on specific picture elements (which came to be called pixels) in a predefined grid format.

While the precision of vector graphics was well suited to mechanical drawing, computer-aided design and manufacturing, and architectural computer graphics, raster graphics opened up possibilities in other areas and brought many more types of people into the world of computer graphics. It was perhaps the use of raster graphics in television advertising, including titles for network

specials, that brought the public’s attention to the potential of computer graphics. The low resolution of the television screen and the short viewing time—measured in seconds—called for relatively few calculations and was therefore less expensive in terms of power, speed, and memory. However, there was initial disappointment in the precision of raster graphics; the disappointment was largely offset with anti-aliasing techniques that minimized the disturbing effect of jagged lines and stair-stepped edges. Compression in the number of pixels in the predefined grid also improved the quality of raster images.

But high resolution has a price. A typical full-color computer screen with 1,000 rows and 1,000 columns of pixels requires 24 million bits of memory. That number multiplied by at least 60 is the amount of memory required for the rapid-fire sequencing of frames in a smooth, professional-looking animation. While not as costly as it once was, animation remains an exercise in allocating the supercomputers’ massive resources to achieve the most effective results.

Today, scientific visualization embodies the results that NSF hoped to achieve in funding the supercomputing centers: to find answers to important scientific questions while advancing both the science of computing and the art of using computer resources economically.

In 1992, the four supercomputer centers then supported by NSF (National Center for Supercomputing Applications in Chicago and Urbana-Champaign, Illinois; Pittsburgh Supercomputing Center; Cornell Theory Center; and San Diego Supercomputer Center) formed a collaboration based on the concept of a national MetaCenter for computational science and engineering. The center was envisioned as a growing collection of intellectual and physical resources unlimited by geographical or institutional constraints.

In 1994, the scientific computing division of the National Center for Atmospheric Research in Boulder, Colorado, joined the MetaCenter. The five partners, working with companies of all sizes, sought to speed commercialization of technology

developed at the supercomputer centers, including visualization routines. An early success was *Sculpt*, a molecular modeling system developed at the San Diego Supercomputer Center. It earned a place on the cover of *Science* magazine and has now been commercialized by a start-up company.

The concept of a national, high-end computational infrastructure for the U.S. science and engineering community has been greatly expanded since 1997, when the National Science Board, NSF's governing body, announced PACI as successor to the NSF supercomputing program. PACI supports two partnerships: the National Computational Science Alliance ("the Alliance") and the National Partnership for Advanced Computational Infrastructure (NPACI). Each partnership consists of a leading edge site—for the Alliance it is the National Center for Supercomputing Applications in Urbana-Champaign, while the San Diego Supercomputer Center is the leading edge site for NPACI—and a large number of other partners. More than sixty institutions from twenty-seven states and the District of Columbia belong to one or both of the partnerships. With access to an interconnected grid of high-performance computing resources, many researchers at these participating institutions are developing state-of-the-art visualization tools and techniques to address multidisciplinary challenges that range from creating roadmaps of the structures and connections within the human brain to producing astronomically accurate, high-resolution animations of distant galaxies.

Staking the Pioneers: The 1960s to the 1990s

The richness of computer visualization today can be traced back to pioneering work, such as Ivan Sutherland's landmark doctoral dissertation from the early 1960s. As an NSF-supported graduate student at the Massachusetts Institute of Technology (MIT), Sutherland developed a real-time line-drawing system that allowed a per-

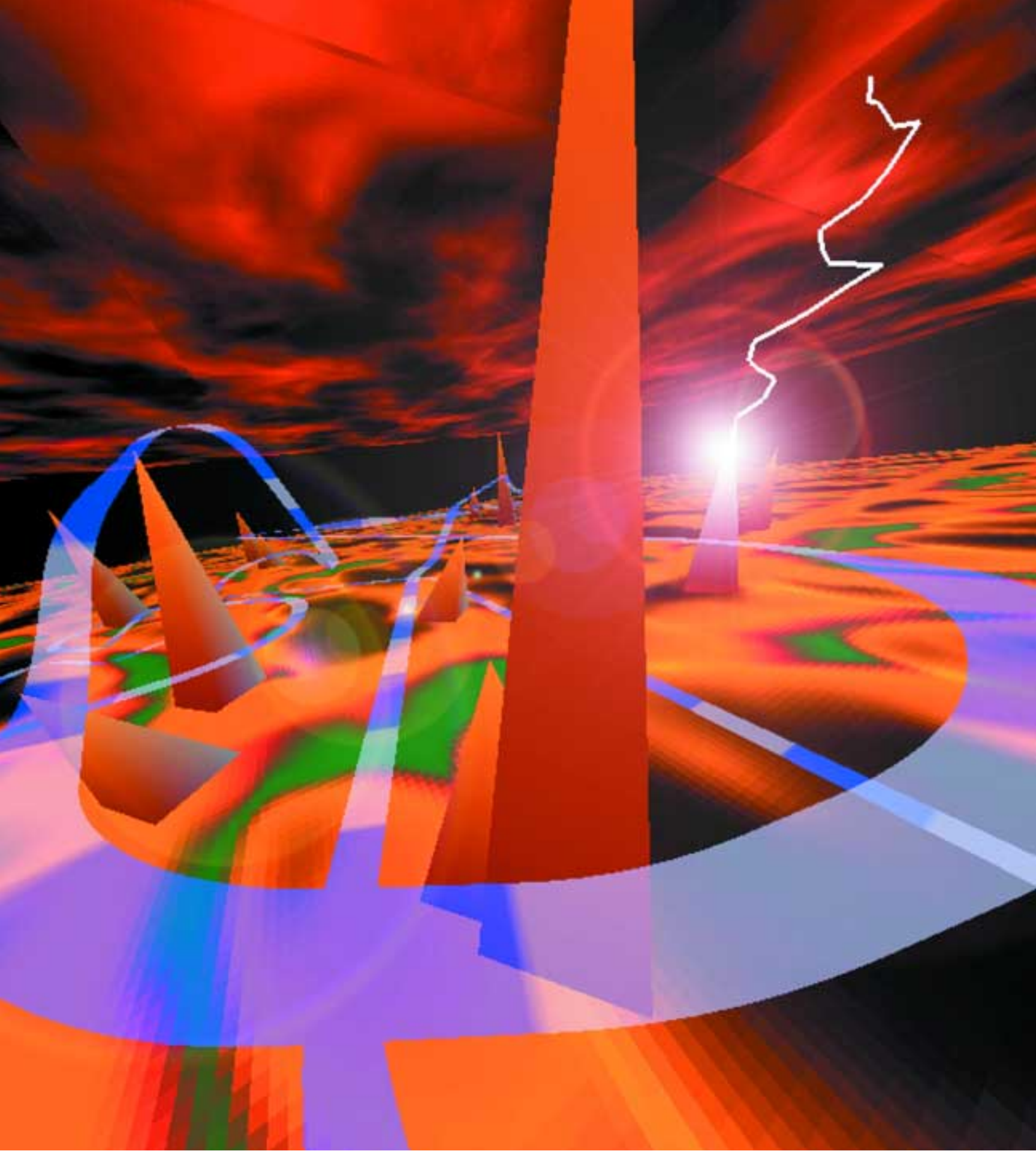
son to interact with the computer using a prototype light pen. While the research itself was supported in terms of both funds and computing resources by the Air Force through the MIT Lincoln Laboratory, the NSF fellowship helped make this graduate study possible. Sutherland credits NSF for the support it provided: "I feel good about NSF taking well-deserved credit for supporting my graduate education. Having independent NSF support was crucial to my ability to transfer to MIT from Caltech. MIT had seemed eager to have me in 1959, but was all the more willing to admit me in 1960 as a post-master's student because I brought NSF support with me."

Sutherland's Sketchpad introduced new concepts such as dynamic graphics, visual simulation, and pen tracking in a virtually unlimited coordinate system. The first computer drawing system, DAC-1 (Design Augmented by Computers), had been created in 1959 by General Motors and IBM. With it, the user could input various definitions of the three-dimensional characteristics of an automobile and view the computer-generated model from several perspectives. DAC-1 was unveiled publicly at the 1964 Joint Computer Conference, the same forum Sutherland had used in 1963 to unveil Sketchpad, which had the distinguishing feature of enabling the user to create a design interactively, right on the screen. His achievement was so significant that it took close to a decade for the field to realize all of its contributions.

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The NSF-funded National Center for Supercomputing Applications at the University of Illinois at Urbana-Champaign has long been a source of innovation in the field of visualization. One product of NCSA-based research is *Virtual Director*, created by Robert Patterson and Donna Cox. This application provides an easy-to-use method to control camera action for playback or animation recording.



A Panoply of Applications

Computer graphics has entered just about every aspect of modern life. The information age has become an age of images—a new hieroglyphics containing more content and promising greater understanding than ever before. Among the key areas of modern business, industrial, and academic activity that have been revolutionized in the last forty years are those listed here.

ARCHITECTURE & ENGINEERING Building design, space planning, real estate analyses, interior architecture and design, construction management, cost-estimating integrated with design and drafting, procurement, facilities management, furniture and equipment management, and needs forecasting.

BIOMEDICAL APPLICATIONS Surgical and radiation therapy planning, diagnostic aids, prostheses manufacturing, studies of morphology and physiology, molecular modeling, computerized tomography (CT scans), nuclear magnetic resonance (NMR, MRI), and teaching of surgical techniques.

BUSINESS & MANAGEMENT GRAPHICS Decision-making systems, graphical data displays, presentation graphics systems, visual information systems, C³I (command, control, communication, and information systems), financial graphics systems, and business and scientific charts and graphs.

EDUCATION & LEARNING Techniques for developing visual thinking skills and creative abilities in both children and adults; science and mathematics instruction; architecture, engineering, and design instruction; arts instruction; and development of the electronic classroom based on research findings on the cognitive, motivational, and pedagogic effects of computer graphics.

ELECTRIC CAD/CAM Printed wiring board and integrated circuit design, symbol construction, schematic generation, knowledge-based systems in electronic design and simulation, advanced systems for chip and circuit design, circuit analysis, logic simulation, electronic fabrication and assembly, and test set design.

HUMAN FACTORS & USER INTERFACES Advances in the visual presentation of information; graphical software development tools and visible language programming; improvements in screen layout, windows, icons, typography, and animation; and alternative input devices, iconographic menus, improvements in color graphics displays, and graphical user interfaces (GUIs).

MANUFACTURING Computer-aided design (CAD), manufacturing (CAM), and engineering (CAE); computer-integrated manufacturing (CIM), numerical control (NC) in CAD/CAM, robotics, and managing the flow of manufacturing information from design to field services; manufactured parts, buildings, and structures; and integrating CIM with CAD.

MAPPING & CARTOGRAPHY Geographic information systems (GIS) and graphical databases; computer-assisted cartography; engineering mapping applications in transportation and utility fields; computer-assisted map analysis; 3-D mapping techniques; management systems for industrial, office, and utility sites and cross-country facilities such as transmission lines; military and civilian government facilities management; natural and man-made resource mapping; and land planning, land development, and transportation engineering.

PATTERN RECOGNITION & IMAGE

PROCESSING Feature selection and extraction; scene matching; video inspection; cartographic identifications; radar-to-optical scene matching; industrial and defense applications; analysis and problem solving in medicine, geology, robotics, and manufacturing; computer vision for automated inspection; and image restoration and enhancement.

PRINTING & PUBLISHING Integration of text and graphics in printed documents, technical documentation created from engineering drawings, technical publishing systems, online documentation systems, page layout software, scanning systems, direct-to-plate printing capabilities, and computer-assisted design systems for publication design and layout.

STATISTICAL GRAPHICS Graphical techniques for rendering large masses of data to increase understanding, graphical techniques for data analysis, graphical display techniques, graphical interaction techniques, and multivariable data analysis.

VIDEO & MULTIMEDIA TECHNOLOGY

High-definition television; computer-generated video for entertainment and educational applications; electronic video-conferencing; broadcast applications for news, weather, and sports; and CD-ROM and Web graphics.

VISUAL ARTS & DESIGN Computer graphics applications for graphic design, industrial design, advertising, and interior design; standards based on design principles relating to color, proportion, placement, and orientation of visual elements; image manipulation and distortion for special effects; systems for computer artists involved in drawing, painting, environmental installations, performance, and interactive multi-image systems; computer animation in film, television, advertising, entertainment, education, and research; and digital design of typography.

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Computer graphics was still too obscure a field to be a cover story in 1972 when Bernard Chern, who later retired as director of NSF's Division of Microelectronic Information Processing Systems, began a program to support the development of computer systems for representing objects in three dimensions. Chern assembled a stable of grantees, including many of the country's leading researchers in automation and modeling.

Among them was Herbert Voelcker, who recalls the state of the technology when he launched the computer modeling program at the University of Rochester: "Major advances in mechanical computer-assisted design were not possible because there were no mathematical and computational means for describing mechanical parts unambiguously . . . There were no accepted scientific foundations, almost no literature, and no acknowledged community of scholars and researchers . . . These early explorations were unsettling, but also challenging because they led us to try to build foundations for an emerging field."

Voelcker and his team were among the pioneers in computer-assisted design (CAD), which, for most of its history, had relied primarily on wireframe systems. Mimicking manual drafting, these computer programs build either two- or three-dimensional models of objects based on data supplied by users. While useful, the programs frequently result in ambiguous renderings—a rectangle might represent either a flat side or an open space—and are fully capable of producing images that resemble the drawings of M.C. Escher, where continuous edges are a physical impossibility. Solid modeling, on the other hand, is based on the principles of solid geometry and uses unambiguous representations of solids.

In 1976, Voelcker's group unveiled one of the earliest prototype systems, called PADL, for Part and Assembly Description Language. For the next two decades, PADL and other solid modeling systems were constrained by heavy computational

requirements, but as faster computers have come into their own, PADL descendants are now displacing wireframe modeling and drafting in the mechanical industries.

NSF-funded researchers at the University of Utah are taking computer drafting techniques even further, all the way to what is known as "from art to part." That is, they are creating a system that generates a finished metal product from a sketch of a mechanical object, bypassing the prototyping stage all together.

Visualization: Back to the Future

By 1991, the field of computer visualization was exploding. "The field had gotten so big, with so many specialties, that no one could know it all. No single research lab could do it all. Graphics hadn't just become broad—it was increasingly interdisciplinary," explains Andries van Dam of Brown University. Van Dam is the current director of NSF's Science and Technology Center for Computer Graphics and Scientific Visualization, which was established both to help deal with the interdisciplinary needs of the scientists and to expand the basics of computer graphics.

The center is a consortium of research groups from five institutions—Brown University, the California Institute of Technology (Caltech), Cornell University, the University of North Carolina at Chapel Hill, and the University of Utah—all of which have a history of cutting-edge research in computer graphics and visualization.

In addition to collaborating, each university focuses on a different part of graphics and visualization research, studying such fields as novel user interfaces, hardware design for visualization and graphics, the physics of the interaction of light with its environment, and geometric modeling for mechanical design.



Computer Graphics: Into the Marketplace

The advances that built on Ivan Sutherland's ground-breaking Sketchpad work at MIT would bring computer graphics out of the laboratory, off the military base, and into the commercial marketplace, creating a steadily growing demand for computer-generated images in a variety of fields.

Continuing technical developments and the widespread commercial adoption of the personal computer—both the IBM PC and the Apple computer—helped spur a demand so strong that computer graphics ceased to be an add-on to a computer's capability and became an integral feature of the computer itself. Today, entire generations are growing up with an exclusively graphics-based experience of computing.

Some of the advancing techniques along this route to the future were:

WIREFRAME DRAWING PROGRAMS AND BOUNDARY REPRESENTATION SYSTEMS depict structures in three dimensions showing all the outlines simultaneously from various perspectives. These programs can recognize surfaces, erase hidden lines, and add shading.

SOLID MODELING SYSTEMS define the interiors, edges, and surfaces of an object.

CONSTRUCTIVE SOLID GEOMETRY SYSTEMS provide a library of preformed shapes that can be combined in additive and subtractive ways to create solid objects.

FRACTAL GEOMETRY uses self-similar forms—where the structure of a small section resembles the structure of the whole—to geometrically simulate the intricacies of nature, such as patterns in tree bark, cracks in the mud of a dry riverbed, or the edges of leaves.

RAY-TRACING ALGORITHMS simulate the effect of light rays bouncing around a scene—illuminating objects, creating reflections, and defining areas of shadow. Ray-tracing often produces strikingly realistic images.

IMAGE MAPPING, also known as texture mapping, is a technique for wrapping two-dimensional patterns and images around three-dimensional models.

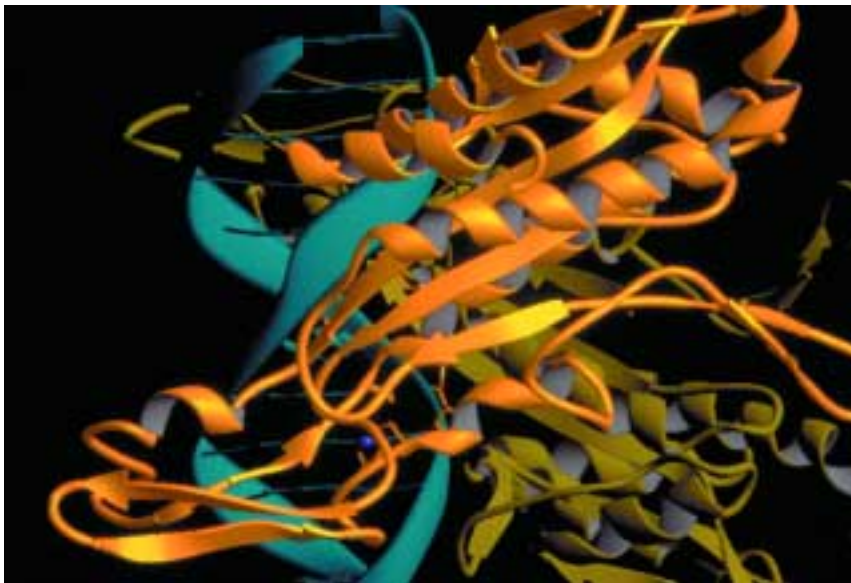
SPATIAL TEXTURING uses an automatically created three-dimensional pattern that is defined for a three-dimensional volume rather than a two-dimensional plan. With spatial texturing, also known as solid textures, you can cut a model of a block of wood in half and see the wood grain inside.

ELECTRONIC PAINT SYSTEMS include tools that imitate the use of brush, oil, and canvas and provide a menu of choices for type of paint brush, color hue and intensity, and type of stroke.

IMAGE PROCESSING PROGRAMS enable users to edit and manipulate photographs and other images to create different effects.

ANIMATION introduces the dimension of time and creates the illusion of motion.

VIRTUAL REALITY SYSTEMS create the illusion of real three-dimensional space through the use of three-dimensional graphics and head or body tracking that changes the view when a user moves.



For more than fifteen years, University of Pittsburgh researcher John Rosenberg and his colleagues have studied how protein-DNA recognition works in the case of a particular protein, Eco RI endonuclease. This detailed model shows that the DNA-Eco RI interaction creates a kink in the DNA's structure.

Another of the center's focuses, explains van Dam, is tele-collaboration. "We are building tools that will make it seem like you're looking through a glass window and seeing your colleagues in the next room working on objects you're designing. We want to create an immersive environment. In my lifetime it won't be quite real, but it will be close enough."

Visualizing a Virtual Reality

While van Dam and his colleagues are moving people into a virtual design shop, other researchers outside the center are creating virtual realities—computer-driven worlds where everything is interconnected, allowing exploration on a level so extraordinary it approaches science fiction.

In previous studies of the Chesapeake Bay, scientists had to measure the wind, current, salinity, temperature, and fish populations separately. But with a virtual reality model, all the elements come together. Glen Wheless, a physical oceanographer at Old Dominion University, worked with William Sherman, a computer scientist at the National Center for Supercomputing Applications, to create a dynamic model of the Atlantic Ocean's saline waters converging with fresh water from more than 150 creeks and rivers that flow into the bay.

The model has given scientists new insights into the ways in which fish larvae are transported

around the estuary; scientists are learning, for example, that they had previously underestimated the influence of wind, tides, and runoff.

The Chesapeake Bay virtual reality model is different from a computer animation in that it is interactive. Researchers can continually update the data and re-run the model. Computer animations, for all their explanatory power, cannot accommodate this demand; once completed, they are not easily changed.

Virtual environments are presented to the viewer through wide-field displays. Sensors track the viewer's movements through the data and update the sights and sounds accordingly. The result is a powerful mechanism for gaining insight into large, multidimensional phenomena. The Chesapeake Bay simulation was designed in one of the country's leading virtual environments for science, CAVE, which was pioneered with NSF support by the Electronic Visualization Lab at the University of Illinois at Chicago. CAVE is an acronym for Cave Automatic Virtual Environment, as well as a reference to "The Simile of the Cave" in Plato's *Republic*, which explores the ideas of perception, reality, and illusion through reference to a person facing the back of a cave where shadows are the only basis for understanding real objects.

CAVE is a darkened cubicle measuring 10 by 10 by 9 feet. Sound and three-dimensional images derived from background data are projected onto three walls and the floor. Wearing special glasses, visitors get a sensation of stepping inside the simulation.

CAVE's technology has been used for many simulations, perhaps the most famous of which is *Cosmic Voyage*, an IMAX film that made its debut in 1996 at the Smithsonian National Air and Space Museum in Washington, D.C. The museum cosponsored the film project with NSF and Motorola. *Cosmic Voyage* includes a four-minute segment of research-quality scientific visualization. The segment tells a story that begins shortly after the Big Bang, continues through the expansion of the

universe and the formation of galaxies, and ends with the collision of two spiral galaxies. The segment is the result of the collaborative efforts of NCSA scientific visualization experts, NSF-supported astronomers, two movie production companies, and numerous high-performance computing machines at multiple centers.

Donna Cox, professor of art and design at the University of Illinois, Urbana-Champaign, choreographed the various parts of the simulation segment. For the camera moves, she worked with staff at the Electronic Visualization Laboratory to create a voice-driven CAVE application called the Virtual Director, a virtual reality method for directing the computer graphics camera for real-time playback or animation recording. Approximately one-half of the sequence—the collision and the merging of two spiral galaxies—is based on a simulation carried out by Chris Mihos and Lars Hernquist of the University of California, Santa Cruz, on the San Diego Supercomputer Center's CRAY C90 system. As the galaxies merge and then draw apart, tidal forces and galactic rotation cause the galaxies to cast off stars and gas in the form of long, thin "tidal tails." The compression of interstellar gas into the merged galaxies fuels an intense burst of star formation. Mihos and Hernquist found that increasing the resolution of their simulation led to new science, "particularly," says Mihos, "the large number of small, condensing gas clouds in the colliding galaxies that could be related to the formation of young, luminous star clusters or small dwarf galaxies, which are seen in many observed galaxy collisions."

In February 2000, *Passport to the Universe* debuted at New York's Hayden Planetarium to critical praise. The digital film, made using Virtual Director software and other high-end computing and visualization resources from both the Alliance and NPACI, combines images of actual astronomical objects with simulations made by cosmology researchers to provide audiences with an unparalleled depiction of intergalactic travel.

Real Support, Real Time, Real Value

While galaxies are merging and drawing apart—at least virtually—there is realism in the value of NSF's support of the basic scientific explorations that have fueled developments in computer visualization over the past fifty years. As one voice in the complex community of this field, Ivan Sutherland reflects on the value of this support. "I have now reached an age where the Association for Computing Machinery (ACM), the Institute of Electrical and Electronics Engineers, Inc. (IEEE), and the Smithsonian Institution have seen fit to honor me in various ways," he says. "Such retrospective honors are not nearly so important as the prospective honor NSF did me with an NSF fellowship. The prospective honor made a giant difference in my ability to contribute to society."

To Learn More

NSF Directorate for Computer and Information Science and Engineering

www.cise.nsf.gov

NSF Science and Technology Center for Graphics and Visualization

www.cs.brown.edu/stc

Caltech Computer Graphics Research

www.gg.caltech.edu

University of North Carolina Graphics and Image Cluster

www.cs.unc.edu/research/graphics/

Cornell Theory Center

www.tc.cornell.edu

Cornell University Vision Group

www.cs.cornell.edu/vision

National Computational Science Alliance

<http://access.ncsa.uiuc.edu/index.alliance.html>

National Partnership for Advanced Computational Infrastructure

www.npaci.edu

SDSC Tele-manufacturing Facility

San Diego Supercomputer Center

www.sdsc.edu/tmf/

Pittsburgh Supercomputing Center

www.psc.edu

National Center for Atmospheric Research

www.ncar.ucar.edu/

Electronic Visualization Lab at University of Illinois at Chicago

www.evl.uic.edu/

An aerial photograph of a forest, where the trees are rendered in various shades of blue and cyan. The perspective is from above, showing the intricate patterns of the tree canopy and the dark, winding paths or roads that cut through the woods. The overall tone is cool and somewhat ethereal.

Environment

taking the
long view



N SF is supporting research to learn how the diverse parts of our environment—from individual species to ecosystems to global weather patterns—interact to form the world around us. A better understanding of the give-and-take between organisms and the environment is critical to the search for knowledge as well as for a healthy planet.



Although humans have been fascinated by the relationship between organisms and their environment since the days of Aristotle, ecology as a separate scientific discipline is only about a century old. Today the field is closely aligned in many minds with concerns about pollution and species extinction. The National Science Foundation began to make a serious investment in ecological research in the 1960s and in 1980 launched its pioneering Long-Term Ecological Research (LTER) program. Usually, researchers receive grants to conduct three-year studies that ask a relatively narrow range of questions. But with the LTER program, NSF has recognized that real understanding of the complex interplay among plants, animals, and the environment requires a longer and broader view. Currently more than 1,000 researchers are working at twenty-four ecologically distinct LTER sites, where studies often last for decades. The questions these NSF-funded ecologists are posing, and the answers they're getting, are emblematic of a maturing and vital discipline.

The Big Picture

A temperate coniferous forest teeming with hemlocks, red cedar, and firs. An Arctic tundra dotted with icy lakes and headwater streams. An East Coast city interlaced with deciduous trees, houses, and parks. A tallgrass prairie. A tropical rainforest. A coastal estuary. A fiery desert.

For every ecological domain on Earth, there seems to be an LTER site devoted to unmasking its secrets. Each location hosts an average of eighteen different principal investigators—often affiliated with nearby universities—who head up various studies that last anywhere from the few years it may take a graduate student to complete her thesis to the decades needed to understand the ongoing effects of, say, fire on the prairie. The sites themselves are much larger than the average experimental plot, ranging in size from the 3,000 acres under continuous study at the Harvard Forest LTER in Petersham, Massachusetts, to the 5 million acres that make up the Central Arizona/Phoenix site.

The rationale behind the LTER program is based on conclusions that environmental scientists reached by the end of the 1970s. One conclusion is that changes in many of the most important ecological processes, such as nutrient levels in the soil, occur slowly. Relatively rare events such as flash floods have a major impact on an ecosystem, but they can only be properly studied if researchers have, in effect, anticipated the occurrences with ongoing studies. Another conclusion is that many ecological processes vary greatly from year to year; only a long-term view can discern inherent patterns. Finally, the kind of long-term, multidisciplinary databases established by LTER researchers are critical for providing a context in which shorter-term studies can be understood.



Although each site boasts its own array of studies designed for that particular ecological system, all studies undertaken at an LTER site must address one or more of what ecologist Steward Pickett, project director for the Baltimore LTER, calls “the holy commandments of LTER.” These commandments come in the form of five questions that are fundamental to how any ecosystem functions: What controls the growth of plants? What controls the populations of plants and animals? What happens to the organic matter that plants produce? What controls the flow of nutrients and water in the system? How do disturbances affect the system?

Without periodic fire, the tallgrass prairies of central North America would disappear into a woodland/shrub habitat. At the NSF-funded Konza Prairie LTER site in Kansas, researchers seek to understand the interplay of prairie and fire by subjecting sixty experimental plots to short- and long-term intervals of burning.

While these five themes provide focus to individual LTER studies, they also allow researchers from very different locales to do an “apples-to-apples” comparison of their data so that even larger lessons can be learned. Clues to how an ecosystem functions are more readily apparent when scientists can compare how the same process works across ecologically diverse sites. For example, the LTER program allows researchers to observe how nutrients travel through two different types of grasslands and how grasslands differ from forests in terms of nutrient flow. To help make these kinds of comparisons, representatives from each LTER site meet formally twice a year and also communicate regularly via email and the LTER program’s Web site.

Key to the success of the LTER approach, of course, are long-term funding and large-scale areas. With the proper time and space, “you can do riskier experiments,” says NSF’s LTER program director Scott Collins, “or you can do experiments that take a long time to have an effect, or big experiments that require a lot of space, or ones that need a certain kind of team.”

Long-term studies also provide an increasingly important baseline of how the environment works—a baseline against which crucial management decisions can be measured. “As the sites are studied longer,” Collins says, “their value increases [because] the findings can be applied to policy and conservation issues.”

What follows is a brief tour through just a few of the LTER sites that are fulfilling the promise of long-term, large-scale environmental research. Studies at these sites have unraveled human health problems, helped to clean up the air, changed how forests are managed, exposed the effects of global change, and revealed how cities interact with their surrounding environment.

An Ecological Solution to a Medical Mystery

When young, otherwise healthy people in the remote Four Corners area of Arizona and New Mexico began dying of a mysterious acute respiratory disease in the spring of 1993, people were scared. Those who caught the disease got very sick, very quickly. Eventually twenty people died. At the time, some wondered if the disease was a biological warfare agent, a military experiment gone bad.

The Atlanta-based U.S. Centers for Disease Control and Prevention (CDC) sent scientists to the region to investigate. Tests of the victims’ blood yielded a surprising result: the people had become infected with a previously undetected kind of hantavirus. The hantavirus causes Hantavirus Pulmonary Syndrome, a serious respiratory illness that can be fatal.

Named after the Hantaan River in Korea, hantaviruses were known to spread from rodents to humans but until the Four Corners outbreak, the microbes had only been seen in Asia and Europe. Moving quickly, CDC investigators asked biologists at the University of New Mexico for help in collecting rodents and insects around the homes of people who had gotten sick. A likely suspect soon appeared when the infection popped up in one particular kind of mouse.

“The CDC called us and asked, ‘What mouse is this?’,” says University of New Mexico mammalogist and museum curator Terry Yates, who also serves as co-principal investigator at the NSF-funded Sevilleta LTER site—so-called because the site’s 230,000 acres are located within the Sevilleta National Wildlife Refuge, about an hour

south of Albuquerque. Yates told the CDC that the infected animal was a deer mouse, a close relative of the type of Old World mice that also carry hantaviruses and that transmit the disease through their droppings and urine.

Now the CDC knew what the disease was and how it was transmitted. But the investigators still didn't know why a disease carried by a common animal like the deer mouse seemed to be cropping up for the first time in North America. For answers, the CDC turned to what Sevilleta researcher Robert Parmenter calls "a bunch of rat trappers" who had been working on matters entirely unrelated to medical science at Sevilleta even before the site was admitted to NSF's LTER network in 1988.

The major research question at the Sevilleta LTER site was this: How do the Sevilleta's four major ecosystems (grassland, woodland, desert, and shrub steppe) respond to short-term and long-term fluctuations in climate? One way to address that question was to measure the population fluctuations of plants and animals. Climate changes affect vegetation, which in turn affects the amount and kind of food available to animals. Keeping track of the rodent populations was just one part of a multi-investigator project—but it turned out to be a crucial part of the CDC investigation.

Parmenter, who directs the Sevilleta Field Research Station, recalls being told by the CDC that "I could take all the time I wanted so long as [the rodent report] was ready by next Tuesday." He and his team of students and fellow professors "were gung-ho excited—working up the data, doing the analyses just as fast as we could."



Their conclusion? The hantavirus outbreak could be blamed on El Niño, a periodic pattern of change in the global circulation of oceans and atmosphere. Parmenter's team saw in their long-term data that massive rains associated with the 1991–92 El Niño had substantially boosted plant productivity in the Sevilleta after several years of drought. A banner year for plants was followed by a banner year for rodents. Rodent populations during the fall of 1992 and spring of 1993 surged as much as twenty times higher in some places as compared to previous years. The same phenomenon likely occurred in the nearby Four Corners region. More mice meant that more humans stood a greater chance of exposure to infected rodents as the people moved among their barns and outhouses and did their spring cleaning of cabins and trailers.

Data from the Sevilleta also helped to determine that the deadly hantavirus wasn't new to New Mexico. Yates and his colleagues tested tissue samples collected from rodents prior to 1993 and

As part of the NSF-supported LTER project in metropolitan Phoenix, Arizona State University graduate student Jennifer Edmonds collects water samples at the Salt River, east of Phoenix. The samples will be tested for nutrients and major ions as part of a project that helps researchers to better understand the relationship between urbanization and ecological conditions.

detected evidence of hantavirus. In other words, the virus had been in rodents all along—it was the change in climatic conditions that triggered the fatal outbreak in humans. Such knowledge may have helped save lives in 1998, when a particularly active El Niño event prompted health authorities to warn residents of the American Southwest to be careful when entering areas favored by mice. The events of 1993 continue to be felt directly at the Sevilleta LTER, which now counts among its studies one that aims to identify the ways in which hantavirus is spread from rodent to rodent.

Yates says, “This is a classic example of basic research done for totally different reasons coming to the rescue when a new problem arises.”

Contributing to a Cleaner World

LTER researchers are both medical and environmental detectives. Using many of the same skills that helped determine the cause of the hantavirus, these scientists are conducting studies that determine how pollution affects ecosystems. The results of these investigations are helping to create a healthier environment.

A case in point is the Hubbard Brook Experimental Forest, home to the longest continually operating ecosystem study in the United States. In 1955, scientists began research on the 8,000-acre site in New Hampshire’s White Mountain National Forest to figure out what makes a forest tick. NSF began funding research at the site in the 1960s; Hubbard Brook joined the LTER network in 1987.

The main research aim at Hubbard Brook is suitably large scale: By measuring all the chemical energy and nutrients that enter and leave this experimental site, researchers hope to learn what makes a forest, a forest.

“The approach we use is called the small watershed approach,” says Charles Driscoll, an environmental engineer at Syracuse University in Syracuse, New York, and a principal investigator for the Hubbard Brook LTER. A watershed is the whole area drained by a particular stream and its tributaries. The watersheds at Hubbard Brook span mountain valleys from ridgeline to ridgeline, encompassing the hillsides and the tributaries that drain into the streams on the valley floor. Researchers learn about the effects of both human and natural disturbances by measuring and comparing the transport of materials, such as water and nutrients, in and out of different watersheds.

The small watershed approach at Hubbard Brook has proven crucial to understanding the effects of acid rain. The term “acid rain” describes precipitation of any kind that contains acids, largely sulfuric and nitric acids. Natural processes release sulfur and nitrogen compounds into the air, where they react with water vapor to form acids. By burning gasoline, coal, and oil, humans are responsible for releasing even greater amounts of sulfur and nitrogen compounds, creating snow and rain that can carry life-stunting levels of acids into waterways and forests. By the 1970s, numerous lakes and streams in the heavily industrialized Northern Hemisphere became inhospitable to fish and other organisms. The link to forest degradation has been harder to prove, but in Europe people have coined a new word—*Waldsterben*—to describe the kind of “forest death” thought to be caused by too much acid rain.



The Birth of Long-Term Ecological Research

Today most of us take it for granted that the Earth's diverse systems, from forests, grasslands, and deserts to the oceans and the atmosphere, are interconnected. But in the early 1960s, thinking about the world as a set of interacting systems was a "totally revolutionary concept," says Joann Roskoski of NSF's Division of Environmental Biology. At the time, researchers took what the late influential ecologist Tom Callahan called a "critter-by-critter" approach, focusing on single species.

"That's fine as far as it goes," Callahan said, "but it doesn't say much about the bigger picture."

And the bigger picture is what the 1960s environmental movement was all about. During this decade, NSF helped move ecology to science's center stage by serving as the primary U.S. representative in the International Biological Program (IBP). The IBP, which was approved by the International Union of Biological Sciences and the International Council of Scientific Unions, was a controversial effort to coordinate a series of ecological projects conducted by scientific communities around the world. The pro-

gram's critics charged that the IBP focus was too vague and unwieldy. Amid the controversy, NSF decided that the major aspect of the U.S. program would be large-scale projects featuring new, multidisciplinary research—specifically, systems ecology, the analysis of ecosystems by means of computer modeling, a strikingly new approach at the time. A total of five different "biomes" were studied between 1968 and 1974: western coniferous forests, eastern deciduous forests, grasslands, tundra, and desert.

The IBP helped to consolidate ecosystem ecology; resulted in a permanent increase in funding for the field; stimulated the use of computer modeling in ecology; produced smaller-scale models of ecological systems; and trained a generation of researchers. "If you now look at a lot of the leadership in American ecology today, these folks cut their teeth on IBP," says the University of Tennessee's Frank Harris, who was NSF program director for ecosystem studies in 1980.

Still, researchers and policymakers came to realize that huge projects such as the IBP ultimately

had only limited applicability to the practical problems of environmental management. Attention began to turn to smaller-scale integrated projects such as the Hubbard Brook Ecosystem Study, which NSF had been funding since 1963, even before IBP. Results from Hubbard Brook, such as being able to predict how forests recover from clear-cutting and the discovery of acid rain in North America, demonstrated the power of taking an ecosystem approach to understanding the environment, but over a longer time scale than was typical of IBP projects.

Six years after the IBP ended, NSF launched its Long-Term Ecological Research (LTER) program, today's new standard for excellence in environmental science. So successful have LTER researchers been that in 1993 an international LTER program was launched after a meeting hosted by the U.S. LTER network. The international LTER effort now includes seventeen countries (with thirteen more in the wings), all of whom support scientific programs or networks that focus on ecological research over long temporal and large spatial scales.



Timothy Katz, site manager for the NSF-funded North Temperate Lakes LTER in Wisconsin, samples open-water fishes with a vertical gill net. Among the wealth of long-term data gathered from the lakes is evidence of time lags in how “invaders” affect lake communities. For example, in Sparkling Lake a kind of trout called cisco went extinct sixteen years after smelt found their way in.

Acid rain in North America was first documented in 1972 by Gene E. Likens, F. Herbert Bormann, and Noye M. Johnson at Hubbard Brook. Because Hubbard Brook researchers using the small watershed approach had long been monitoring the quality, not just quantity, of precipitation, they could tell that rainwater wasn’t quite what it used to be and that the acid problem was getting worse. Their work was important in the establishment of the National Acid Precipitation Assessment Program and the passage of the landmark Clean Air Act Amendments in 1990, which mandated reductions in sulfur dioxide emissions from power plants.

Although precipitation over the United States is not quite as acidic as it was in 1972, forests are still showing worrisome signs of decline. A 1996 Hubbard Brook study determined at least one reason why: Acid rain ravages the soil’s ability to support plant life.

“A lot of people thought that acid rain changes surface waters, but not the soil,” says Likens, director of the Institute of Ecosystem Studies in Millbrook, New York, and lead author of the 1996 Hubbard Brook study. “This was one of the first studies to clearly demonstrate the substantial effects of acid rain on soil.”

As it turned out, numerous minerals essential to life, including calcium and magnesium, dissolve more readily in highly acidic water. Thirty years of Hubbard Brook data on the chemical composition of soil, rain, and stream water showed that acid rain was and is seriously leaching calcium and magnesium from the forest soil—as rain falls, it reacts with soil minerals and washes them into the streams.

Can anything be done to bolster the soil’s resistance to acid rain? In 1999, Hubbard Brook researchers set out to address this question by sending up helicopters to drop a load of calcium pellets on a 30-acre watershed that, like the rest of the forest, has been depleted of calcium over the years.

“We’re going to look at the trees, the herbaceous plants, how salamanders respond, how microbes respond, and how aquatic organisms respond,” Driscoll says. In a few years, the researchers may be able to report whether calcium enrichment shows any signs of helping to restore damaged soil. Such a finding would be welcome news to New Englanders in the tourism and maple sugar industries, where concern is high about whether calcium levels in the soil have something to do with the notable decline in the region’s sugar maple trees. A full understanding of calcium’s role in the environment will take longer. That’s why Driscoll says the new study—like most Hubbard Brook studies—will continue “not just for a few months, but for fifty years.”

Says Driscoll, “Once we start, we don’t quit.”



Solving the Biocomplexity Puzzle

Studying only one piece of the environment—even one as big as an LTER site—provides only partial understanding of how the world works. Such is the nature of what NSF Director Rita Colwell calls “biocomplexity.” Eventually, all the pieces will need to conjoin in order to solve the puzzle.

One would-be puzzle master is the NSF-funded National Center for Ecological Analysis and Synthesis (NCEAS) at the University of California in Santa Barbara. NSF helped create NCEAS to organize and analyze ecological information from all over the globe, including sites within NSF’s Long-Term Ecological Research (LTER) program. The center does not collect new data itself; instead, NCEAS’ job is to integrate existing information so that the information is more useful for researchers, resource managers, and policymakers who are tackling environmental issues.

“Natural systems are complex,

and humans are altering these systems at an unprecedented rate,” says NCEAS Deputy Director Sandy Andelman. “We need to do a better job of harnessing the scientific information that’s relevant to those systems and putting it in a useable form.”

But gathering and integrating such information is a daunting task. There is no central repository in which ecological scientists can store their data. Most studies are conducted by individual researchers or small teams working on specific small, short-term projects. Since each project is slightly different, each data set is slightly different.

“Ecological data come in all kinds of shapes and forms,” Andelman says. She adds that, in ecology, “There is not a strong culture of multi-investigator, integrated planning of research Ecology and other related disciplines have amassed vast stores of relevant information, but because this infor-

mation is in so many different forms and formats and many different places, it is not accessible or useful.”

Hence the need for something like the NCEAS, which is collaborating with the San Diego Supercomputing Center and the LTER program to come up with the necessary advanced computing tools. NCEAS is also developing a set of desktop computer tools that will allow researchers to enter and catalog their data into the network using standardized data dictionaries. Eventually, researchers thousands of miles apart will be able to look at each other’s data with just a few clicks of the mouse.

“If people knew that their data could contribute to a larger question, most would happily make a little extra effort to put their data into a more useful format,” Andelman says. “But there hasn’t been that framework in place.” And now, thanks to NSF, there will be.

Counting the Blessings of Biodiversity

In addition to pollution, species extinction ranks high as a concern among those interested in how ecosystems function. According to the fossil record, several thousand plants and animals have disappeared over the last ten million years; during the time dinosaurs were alive, one species disappeared about every one to ten thousand years. But as the human population has grown, so has the rate of extinction—researchers now conservatively estimate that species are dying out at the dramatic rate of one a day.

The assumption, of course, is that this can't be good. More than a century ago, Charles Darwin first suggested that more species would make an ecosystem more productive. But researchers have struggled to test the notion rigorously, not just in the lab but in the field. It wasn't until 1996 that anyone had real evidence that biodiversity—sheer numbers of different species—is critical to the planet's well-being.

In an experiment that other ecologists have described as “brilliant” and “a first,” University of Minnesota ecologist David Tilman and other researchers at the Cedar Creek Natural History Area—an NSF-funded LTER site since 1982—demonstrated that plant communities with the greatest biodiversity yielded the greatest total plant growth year to year. These plant communities also were much more likely to hang on to essential nutrients that might otherwise have been leached from the soil.

Tilman's team approached the problem by constructing 147 miniature prairies within a section of the 5,500-acre experimental reserve at Cedar Creek, and planting each one with anywhere from one to twenty-four species. The burning, plowing, and planting were done by the spring of 1994. Then the researchers sat back to see which plots would end up doing best.

Actually, no one sat much. The researchers, aided by an army of undergraduates, have toiled ever since to meticulously weed the 100-square-foot plots of anything that didn't belong to what each plot was designed to contain, be it brown-eyed susans, bunch clover, or yarrow. A critical aspect of the study was that researchers randomly selected which species went into which plots. This kept the focus on the *number* rather than the type of species.

Why do more species make for a merrier ecosystem? Tilman has found that a diverse plant community uses the available energy resources more efficiently.

“Each species differs from others in a variety of traits,” says Tilman. “Some have high water requirements and grow well during the cool part of the year. Others grow well when it's really warm and dry. Each one in the system does what it's good at, if you will, but there's always something left to be done.” That is, conditions that are less than hospitable to some species will be readily exploited by others, leading to more lush growth overall. These processes, says Tilman, also explain why so many species can coexist in nature.

“It wasn't until we knew how rapidly species were going extinct that this issue really came to the forefront,” says Tilman. Still, more work needs to be done before biodiversity's role in a healthy ecosystem can be unequivocally celebrated. That's why Tilman and other Cedar Creek researchers have added a second experiment to the mix, this time using more than three hundred bigger plots, each about the size of an average suburban backyard. The extra area should allow for a better understanding of how, for example, plots with different numbers of species handle insects and disease.

“Nobody’s ever done what they’ve done,” says Samuel McNaughton, an ecosystem ecologist at Syracuse University in New York. “It’s an enormous amount of work. Tilman would not have been able to do this without NSF funding through the LTER program.”

Keeping Up with Global Change

From a focus on plant communities to a broader look at global climate change, LTER research is revealing how the components of our environment interact.

Albert Einstein once said that chance favors the prepared mind. So, too, are LTER scientists uniquely prepared to learn from seemingly chance fluctuations in global climate—what LTER program head Scott Collins calls “the surprise years.”

A good illustration of this can be found among the scores of lakes that make up the NSF-funded North Temperate Lakes (NTL) LTER site in Wisconsin. A member of the network since the LTER program’s start in 1980, the NTL site is managed by researchers at the University of Wisconsin at Madison. The NTL LTER includes two field stations: one in the Yahara Lake District of southern Wisconsin and the other—called the Trout Lake Station—in the state’s northern highlands. While the area boasts hundreds of lakes that are amenable to study, the sites’ principal investigators have chosen seven to consistently monitor over the long haul.

If researchers investigate only one lake, they don’t know whether their findings are unique to that lake, says University of Wisconsin limnologist Timothy Kratz, a principal investigator for the NTL LTER. Studying many lakes exposes patterns and commonalities that are visible only when researchers investigate environmental conditions over a broad region. The seven lakes of the NTL LTER were chosen because of their representative variety in size and location.



The number of lakes, their different sizes (ranging from quarter-acre bogs to 3,500-acre behemoths), and their distribution from lower to higher elevations, allowed Kathy Webster, then a doctoral student, and other NTL researchers in the late 1980s to conduct one of the first and most informative field studies of how lakes respond to drought.

Year in, year out since 1981, NTL researchers have measured the lakes’ chemical composition, tracking fluctuations in calcium, magnesium, alkalinity, and other factors. These persistent measurements paid off in the late 1980s, when the upper Midwest was hit by a major drought. “We were able to look at our lakes pre-drought, during the drought, and after the drought,” says Kratz. The results were surprising: Although all of the lakes lost water, only those lakes positioned higher in the landscape lost significant amounts of calcium, an essential nutrient for all organisms. The effect was all the more striking because the elevation difference between the highest and lowest study lakes was only about 33 feet.

An aerial view of a biodiversity experiment at the NSF-supported Cedar Creek Natural History Area in Minnesota. Researchers here have shown that plant communities with the largest variety of species exhibit the greatest total plant growth, one sign of a robust environment.

What could explain the different level of calcium loss? Groundwater, suggests Kratz. All of the lakes in the study are fed by groundwater seeping through the rocky soil. This groundwater carries with it an abundance of critical minerals, including calcium. But the drought caused the groundwater table to fall below the higher lakes, essentially shutting off their mineral supply.

In a prolonged drought, says Kratz, lakes in higher elevations might become calcium deficient, causing a cascade of biotic effects. Animals such as snails and crayfish would be in trouble, since they require calcium to make their shells. In turn, fish that eat snails would find it harder to get enough food. The higher lakes might also become more susceptible than their low-lying counterparts to the effects of acid rain, since the calcium and other minerals from groundwater can counteract the deleterious effects of acid precipitation.

If changes in the world's overall climate result in droughts that become more frequent—as some researchers predict with the advent of global warming—the chemistry of these two types of lakes will start to diverge. Data of the kind gathered at the North Temperate Lakes LTER should help both scientists and policymakers predict and cope with the environmental consequences of global climate change.

“We didn't know the particular event of interest would be a drought,” Kratz says. “But we had in place a system of measurements that would allow us to analyze the situation—whatever the event was.”

Cityscapes Are Landscapes, Too

Not all LTER sites are located in remote, rural areas. In 1997, NSF added two sites to the network specifically to examine human-dominated ecosystems—in other words, cities. One site is centered in Baltimore, Maryland, the other in Phoenix, Arizona.

The Central Arizona/Phoenix (CAP) site fans out to encompass nearly five million acres of Maricopa County. While much of the site's study area is urbanized, some portions are still agricultural field or desert, and there are also a few nature reserves. CAP researchers are in the early stages of laying the groundwork for long-term studies at the site. For one thing, they're busy identifying two hundred sampling sites that will encompass the city, the urban fringe, and enough spots on the very outer edge to ensure that some portion of the site will remain desert for the next thirty years.

“One of our exciting challenges will be to take those very standard common ecological measures that people use in the forest and desert and everywhere else, and say, well, is there an equivalent way to look at how the city operates?” says Charles Redman, Arizona State University archaeologist and co-director of the CAP-LTER. To tackle that challenge, Redman and co-director Nancy Grimm work with a research team that includes ecologists, geographers, remote sensing specialists, sociologists, hydrologists, and urban planners.

As a framework for their foray into the ecology of a city, the researchers are adopting a popular and relatively new ecological perspective that recognizes that rather than being uniform, an ecosystem is patchy, rather like a quilt. For example,

Wanted: A Complete Catalog of Creatures and Plants

Chytrids are not something people generally worry about. Yet this little-known group of fungi made news in 1998 when it was linked with a rash of frog deaths in Australia and Panama.

It had taken frog researchers several years to locate a chytrid specialist capable of identifying the deadly fungus, and even then the experts were surprised. “We didn’t know that any [chytrids] were parasites of vertebrates,” says Martha Powell, a chytrid specialist at the University of Alabama.

Chytrids aren’t alone in being poorly classified. Only about 1.5 million species have been identified so far out of the 13 million or so thought currently to exist (some estimates of the overall number are closer to 30 million). The gargantuan challenge of collecting and describing examples of all these unknown species falls to a steadily shrinking pool of scientists known as systematic biologists. With the advent of high-tech molecular techniques for studying evolutionary relationships,

taxonomy—the science of species classification—has come to seem faintly antiquated, even though biological research collections “remain the ultimate source of knowledge about the identity, relationships, and properties of the species with which we share the Earth,” according to Stephen Blackmore, chair of the Systematics Forum in the United Kingdom, who wrote about the problem in 1997 for the journal *Science*.

But even as “the inescapable need to know more about the diversity of life on Earth remains largely unmet,” wrote Blackmore, “declining funds are limiting the ability of institutes around the world to respond . . .” As of 1996, there were only about 7,000 systematists in the world, a workforce that Blackmore and others deem “clearly inadequate.”

Says James Rodman, NSF program director for systematics, “There are very few people studying the obscure groups” of species and many of those experts are beginning to retire.

One way the National Science Foundation is trying to address the problem is through its Partnerships for Enhancing Expertise in Taxonomy (PEET) program. PEET funds systematic biologists working to identify understudied groups like the chytrids. In fact, Powell and her colleagues are now working under a PEET grant to train at least three new Ph.D.s in the systematic biology of chytrids. Besides training the next generation of systematists, PEET projects are also making what is known about these species more widely available through the development of Web-accessible databases that contain information such as identification keys, photographs, distribution maps, and DNA sequences.

“Systematists,” wrote Blackmore, “hold the key to providing knowledge about biodiversity.” Knowing more about how the world functions requires learning more about each of the world’s parts, however small.

patches in a grassland might be recognized as areas that burned last year, areas that burned five years ago, and burned areas where bison are now grazing. Smaller patches exist within the larger patches: The bison might graze more heavily in some sections of the burned area than others, for example. There are patches of wildflowers, patches where bison have wallowed, and patches where manure piles have enriched the soil. Each time ecologists look closely at one type of patch, they can identify a mosaic of smaller patches that make up that larger patch. And if they can figure out what the patches are, how the patches change over time, and how the different types of patches affect one another, they might be able to figure out how the ecosystem functions as a whole.

Anyone who has flown over an urban area and looked at the gridlike mosaic below can imagine how easily cityscapes lend themselves to the hierarchical patch dynamics model. Still, it's a new approach where cities are concerned, says Jianguo Wu, a landscape ecologist at Arizona State University. And the patches within cities are new to ecologists.

"You can see very large patches—the built-up areas, the agricultural areas, the native desert areas," he says of the Phoenix site. "But if you zoom in, you see smaller patches. Walk into downtown Phoenix. There are trees, parking lots, concrete. They form a hierarchy of patches with different content, sizes, shapes, and other characteristics."

CAP researchers have gathered information about how land use in the Phoenix region changed from the early 1900s until today. The team has found that as the area became more urban, the patches became smaller and more regularly shaped. In the new millennium, the scientists want to see how this kind of more orderly patchiness affects ecological processes. For example, researchers would like to know how insects and other small animals move across the landscape, and how storm runoff carries away nutrients across the various patches, whether concrete or soil.

Grimm thinks that the patch dynamics model will help researchers integrate all the information they collect about the rapidly changing Phoenix metropolitan area. The model emphasizes linkages between different levels and types of patches such that researchers can design studies to ask: How might the actions of an individual eventually affect the ecology of a whole community-sized patch? If someone sells an undisturbed piece of desert property to a developer, for example, the ecosystem will change. What kind of development is built—whether there is one house per acre or a series of closely packed townhomes—will differently affect the ecological processes in the adjacent patches of remaining desert.

"Once the land use changes, the ecology changes," says Wu, adding, "What is really important is the dynamics—the impact of this patchiness on the ecological, physical, hydrological, and socioeconomic processes of the city."

Long-Term Research: A Model for NSF's Future

The LTER program has already demonstrated a remarkable return on NSF's investment. Thanks to NSF-supported research, we now have a better understanding of the complex interplay among plants, animals, people, and the environment.

In February 2000, the National Science Board (NSB), NSF's policymaking body, released a report urging that NSF expand the LTER program and make the environment a "central focus" of its research portfolio in the twenty-first century.

"Discoveries over the past decade or more have revealed new linkages between the environment and human health," says Eamon Kelly, chair of the National Science Board. "But just as we are beginning to better understand these linkages, the rate and scale of modifications to the environment are increasing. These alterations will present formidable challenges in the new century—challenges which we are now only minimally equipped to meet."

Preeminent ecologist Jane Lubchenco of Oregon State University chaired the NSB Task Force on the Environment, which was responsible for the report. "The LTER program is widely viewed as one of the outstanding successes of NSF," says Lubchenco, "and is the model for federal agencies as well as other countries for superb place-based ecological sciences. [The program is] very lean, very efficient, very productive."

The LTER program's success is one reason the task force recommended, among other things, that NSF boost its spending on environmental research by \$1 billion over a five-year period beginning in 2001. That kind of financial commitment would make environmental science and engineering one of the agency's highest priorities.

And none too soon, according to Lubchenco. "We're changing things faster than we understand them," she once said in a news interview. "We're changing the world in ways that it's never been changed before, at faster rates and over larger scales, and we don't know the consequences. It's a massive experiment, and we don't know the outcome."

To Learn More

NSF Division of Environmental Biology

Directorate for Biological Sciences
www.nsf.gov/bio/deb/start.htm

NSF Global Change Programs

Directorate for Geosciences
www.nsf.gov/geo/egch/

NSF Partnerships for Enhancing Expertise in Taxonomy (PEET)

www.nhm.ukans.edu/~peet

U.S. Long-Term Ecological Research Network

www.lternet.edu

International Long-Term Ecological Research Network

www.ilternet.edu

Sevilleta LTER Project

<http://sevilleta.unm.edu/>

Hubbard Brook Ecosystem Study

www.hbrook.sr.unh.edu/

Cedar Creek Natural History Area

www.lter.umn.edu/

North Temperate Lakes LTER

<http://limnosun.limnology.wisc.edu/>

Central Arizona-Phoenix LTER

<http://caplter.asu.edu/>


Environmental Science and Engineering for the 21st Century: The Role of the National Science Foundation National Science Board

www.nsf.gov/cgi-bin/getpub?nsb0022

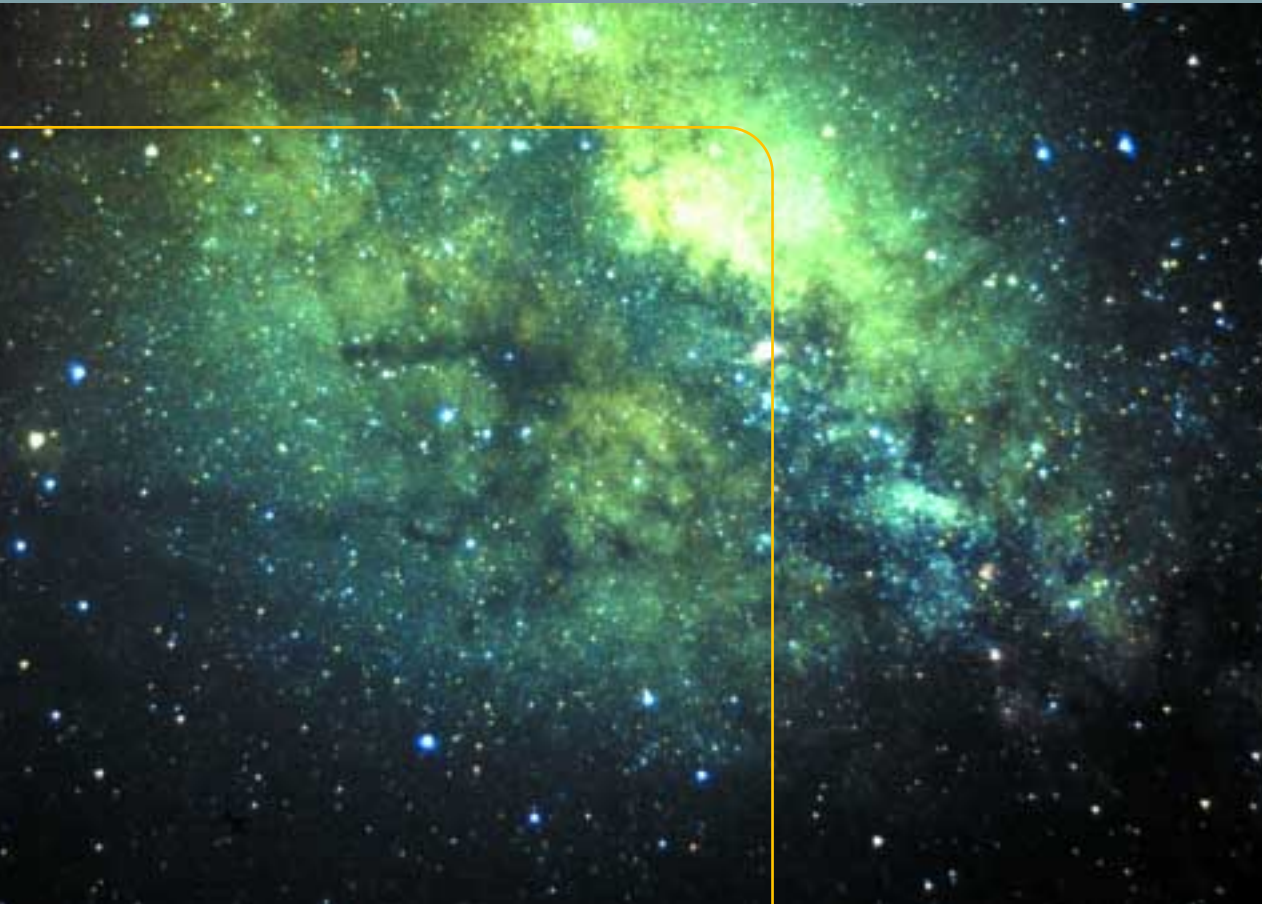


Astronomy

exploring the
expanding universe



U sing powerful instruments developed with NSF's support, investigators are closing in on fundamental truths about the universe. The work of these scientists creates new knowledge about the Sun, leads to the discovery of planets around distant stars, and uncloaks the majestic subtlety of the universe.



Ever since Galileo perfected the telescope and made the stars seem closer to Earth, scientists have been searching the heavens, asking fundamental questions about the universe and our place in it. Today's astronomers are finding that they don't have to go far for some of the answers. With major funding from NSF, some researchers are exploring the interior of the Sun by recording and studying sound waves generated near its surface. Others are discovering planets around distant stars and expressing optimism about finding still more, some of which may resemble Earth. With sophisticated equipment and techniques, we humans are finally "seeing" what lurks at the center of the Milky Way, hidden from direct view. We are making profound progress in uncovering the origins of the universe, estimating when it all began, and looking at its structure, including the more than 90 percent of its mass known today as "dark matter."

New Visions

“All of a sudden, astronomers have turned a big corner and glimpsed in the dim light of distant lampposts a universe more wondrous than they had previously known,” writes John Noble Wilford in the February 9, 1997, issue of the *New York Times*. “Other worlds are no longer the stuff of dreams and philosophic musings. They are out there, beckoning, with the potential to change forever humanity’s perspective on its place in the universe.”

Wilford is describing research by NSF-funded astronomers Geoffrey W. Marcy and R. Paul Butler of San Francisco State University, who were among the first to discover planets outside our solar system. Wilford’s words highlight the excitement and wonder of research in astronomy.

With these and other recent discoveries, astronomers and astrophysicists are taking a fresh look at the realities and mysteries of the universe. Indeed, all of humankind is learning how immense and complex is the space we inhabit. Yet as we start to understand some of the phenomena around us, many other mysteries arise.

NSF is not alone in funding studies of the skies; much work was done before NSF was established in 1950, and universities and other government agencies have done much since then to advance our understanding. But NSF funding—covering such things as state-of-the-art telescopes, supercomputer sites, and individual researchers—is one of the main reasons we have identified so many pieces of the puzzle that is our universe.

So how do researchers get a handle on something so big? Where do they start? For some astronomers, the answer is close to home.

Voyage to the Center of the Sun

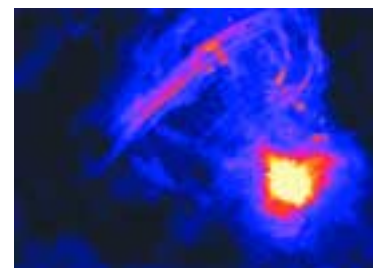
Despite its relative proximity to Earth, the Sun has kept its distance, reluctant to reveal its secrets. Until recently, its inner workings were a mystery of cosmic proportions.

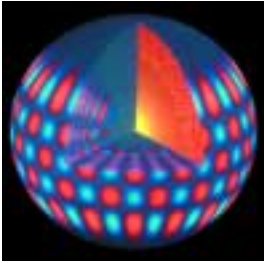
For many years, researchers have known that deep in the Sun’s interior, 600 million tons of hydrogen fuse into helium every second, radiating out the resulting energy. And while the mechanics of this conversion have been described in theory, the Sun’s interior has remained inaccessible. Now, however, the Sun is being “opened,” its internal structures probed, and its inner dynamics surveyed by NSF-supported scientists using investigative techniques—a branch of astronomy known as helioseismology.

“The Sun is the Rosetta stone for understanding other stars,” explains John Leibacher, an astronomer at the National Optical Astronomy Observatories in Tucson, Arizona, and director of the NSF-funded Global Oscillation Network Group, or GONG. The Rosetta stone is a tablet with an inscription written in Greek, Egyptian hieroglyphic, and Demotic. The stone’s discovery was the key to deciphering ancient Egyptian hieroglyphic and unlocking the secrets of that civilization.

GONG researchers study the Sun by analyzing the sound waves that travel through it. Much as the waves produced by earthquakes and explosions roll through the Earth, these solar sound waves pass through the Sun’s gaseous mass and set its surface pulsating like a drumhead. With six telescopes set up around the Earth collecting data every minute, GONG scientists are learning about the Sun’s structure, dynamics, and magnetic field by measuring and characterizing these pulsations.

NSF-funded researcher Andrea Ghez has discovered the presence of an enormous black hole at the center of our galaxy. Her work has enormous implications for our understanding of how galaxies evolve.





This computer representation depicts one of nearly ten million modes of sound wave oscillations of the Sun, showing receding regions in red tones and approaching regions in blue. Using the NSF-funded Global Oscillation Network Group (GONG) to measure these oscillations, astronomers are learning about the internal structure and dynamics of our nearest star.

Analysis of data from GONG and other sources shows that current theories about the structure of the Sun need additional work. For example, the convection zone—the region beneath the Sun’s surface where pockets of hot matter rise quickly and mix violently with ambient material—is much larger than originally thought. Furthermore, says Leibacher, the zone ends abruptly. “There is turbulent mixing and then quiet. We can locate the discontinuity with great precision.” Some research teams are probing deeper and examining the Sun’s core; still others are addressing such topics as sunspots—places of depressed temperature on the surface where the Sun’s magnetic field is particularly intense.

New insight into the Sun’s core came in the spring of 2000, when NSF-funded researchers analyzing GONG data announced that they had discovered a solar “heartbeat.” That is, they had found that some layers of gas circulating below the Sun’s surface speed up and slow down in a predictable pattern—about every sixteen months. This pattern appears to be connected to the cycle of eruptions seen on the Sun’s surface.

Such eruptions can cause significant disturbances in Earth’s own magnetic field, wreaking havoc with telecommunications and satellite systems. A major breakthrough in the ability to forecast these so-called solar storms also came in the spring of 2000, when NSF-funded astrophysicists, using ripples on the Sun’s surface to probe its interior, developed a technique to image explosive regions on the far side of the Sun. Such images should provide early warnings of potentially disruptive solar storms before they rotate toward Earth.

As our nearest star, the Sun has always been at the forefront of astrophysics and astronomy. (Astrophysicists study the physics of cosmic objects, while astronomers have a broader job description—they observe and explore all of the universe beyond Earth.) The more we learn about

the Sun, the more we understand about the structure and evolution of stars and, by extension, of galaxies and the universe. The Sun also is host to a family of nine planets and myriad asteroids and cometary bodies. As we investigate the richness of outer space, we often look for things that remind us of home.

New Tools, New Discoveries

Much of astronomy involves the search for the barely visible—a category that describes the overwhelming majority of objects in the universe, at least for the time being. One of today’s most effective tools for detecting what cannot be seen is Arecibo Observatory in Puerto Rico. The site is one of the world’s largest and most powerful telescopes for radar and radio astronomy.

Operated by Cornell University under a cooperative agreement with NSF, the Arecibo telescope collects extraterrestrial radio waves of almost imperceptible intensity in a 1,000-foot-wide dish. This telescope, used by scientists from around the world, is a dual-purpose instrument. About three-quarters of the time, the telescope detects, receives, amplifies, and records signals produced by distant astronomical objects. The rest of the time, it measures reflected radio signals that were transmitted by its antenna. The signals bounce off objects such as planets, comets, and asteroids, allowing researchers to determine each object’s size and motion.

It was at Arecibo in 1991 that Alexander Wolszczan of Pennsylvania State University discovered the first three planets found outside our solar system. With support from NSF, Wolszczan discovered these planets by timing the radio signals coming from a distant pulsar—a rapidly rotating neutron star—7,000 trillion miles from Earth in the constellation Virgo. He saw small, regular variations in the pulsar’s radio signal and interpreted them as a complicated wobble in the pulsar’s motion induced by planets orbiting the



Visualizing the Big Picture

While telescopes, spacecraft, and other means of collecting data are critical, not all researchers turn to the heavens for inspiration. Some turn to their computers to take a closer look at the big picture.

The Grand Challenge Cosmology Consortium (GC³) is a collaboration of cosmologists, astrophysicists, and computer scientists who are modeling the birth and early infancy of the universe. Consortium members use high performance computers at the NSF-supported Supercomputer Centers—the precursor of the current Partnerships for Advanced Computational Infrastructure program—to create a three-dimensional model of the formation of galaxies and large-scale structures in the early universe. The consortium uses some of the most powerful supercomputers available to perform the billions of calculations required to figure out how the universe came to be.

In an effort to understand the role of dark matter in galaxy cluster formation, Michael Norman and Gregory Bryan carried out a simulation at the National Center for Supercomputing Applications at the University of

Illinois at Urbana-Champaign in 1994. The simulation produced a model that accurately predicted the number and arrangement of galaxy clusters. The prediction was confirmed by recent observations by an orbiting X-ray satellite. While the simulation did not capture exactly the measurable ratio of luminous gas to dark matter, efforts are underway to improve the model's resolution. "Everyone is motivated to find out what dark matter is," says Norman, "but there is nothing definitive yet."

Perhaps the most intriguing aspect of the GC³ is its ability to simulate situations never seen by humans. In a public display of computer simulation, members of GC³ teamed up with IMAX to create the 1996 film *Cosmic Voyage*, a short feature that was nominated for an Academy Award. From the safety of their theater seats, audiences can view the life of the universe, from its explosive, Big Bang birth, to the current hubbub of galaxy life. The film also includes a startling animation of what would happen if two spiral galaxies—like the Milky Way and neighboring Andromeda Galaxy—were to collide.



As Wolszczan, Marcy, Butler, and others continue their search for new planets, other astronomers have found evidence of the most powerful magnetic field ever seen in the universe. They found it by observing the “afterglow” of subatomic particles ejected from a magnetar. This neutron star, illustrated above, has a magnetic field billions of times stronger than any on Earth and one hundred times stronger than any other previously known in the universe.

pulsar. Two of the planets are similar in mass to the Earth, while the mass of the third is about equal to that of our moon. It is unlikely that any of these newly discovered planets support life, because the tiny pulsar around which they orbit constantly bombards them with deadly electromagnetic radiation. Wolszczan’s work helps astronomers understand how planets are formed, and his discovery of planets around an object as exotic as a pulsar suggests that planets may be far more common than astronomers had previously thought.

In 1995, four years after Wolszczan’s discovery, two Swiss astronomers announced that they had found a fourth new planet, orbiting a star similar to the Sun. Two American astronomers, Geoffrey Marcy and Paul Butler, confirmed the discovery and, the following year, announced that their NSF-supported work culminated in the discovery of another two planets orbiting sun-like stars. Using an array of advanced technologies and sophisticated analytic techniques, Marcy, Butler, and other astronomers have since discovered more extrasolar planets. An especially astonishing discovery was made in 1999 by two independent NSF-supported teams of the first multi-planet system—other than our own—orbiting its own star. At least three planets were found by Marcy, Butler, and others to be circling the star Upsilon Andromedae, making it the first solar system ever seen to mimic our own.

By August 2000, the number of extrasolar planets had topped fifty, and more such sightings were expected. Based on the discovery of these planets, it seems as if the Milky Way is rife with stars supporting planetary systems. But what of the Galaxy itself? Is it a calm stellar metropolis, or are there more mysteries to uncover?

At the Center of the Milky Way

In the mid-eighteenth century, philosopher Immanuel Kant suggested that the Sun and its planets are embedded in a thin disk of stars. Gazing at the diffuse band of light we call the Milky Way on a dark night supports Kant’s bold statement. But understanding the nature and appearance of our galaxy is no small feat, for we live within a disk of obscuring gas and dust.

Our Sun is part of a large disk made up of stars and large clouds of molecular and atomic gas in motion around the Galaxy’s center. Our solar system orbits this center, located about 30,000 light-years away from Earth, at 500,000 miles per hour. It takes our solar system two hundred million years to make a single orbit of the galaxy.

Astronomers can infer the shape and appearance of our galaxy from elaborate observations, and, as a result, have created maps of our galaxy. Yet parts of the Milky Way remain hidden—blocked by light-years of obscuring material (gas and dust) spread between the stars.

Andrea Ghez is working to penetrate the mysteries of this interstellar material. Ghez is an astronomer at the University of California at Los Angeles and an NSF Young Investigator, a national award given to outstanding faculty at the beginning of their careers. Her observations of the central regions of the Milky Way have permitted her to examine its very heart. Ghez, like many others, theorized that the Galaxy’s core is the home of a supermassive black hole. “Although the notion has been around for more than two decades, it has been difficult to prove that [a black hole] exists,” says Ghez. Now it appears her observations offer that proof.

Using one of the two W. M. Keck 10-meter telescopes on Mauna Kea in Hawaii, Ghez looked at the innermost regions of the Galaxy’s core. For three years, she studied the motions of ninety stars. While scientists already knew that those

Detecting Planets Around Other Stars

In the vastness of the universe, are we humans alone? The answer depends on whether there are other planets that are endowed with the warm climate, diverse chemicals, and stable oceans that provided the conditions for biological evolution to proceed here on Earth.

We and other astronomers recently took an important step toward addressing some of these questions when we reported finding that planets do exist outside our own solar system Already the properties of these extrasolar planets have defied expectations, upsetting existing theories about how planets form.

It took a long time to find extrasolar planets because detecting them from Earth is extraordinarily difficult. Unlike stars, which, like our Sun, glow brightly from the nuclear reactions occurring within, planets shine primarily by light that is reflected off them from their host star.

Astronomers gained the means to find planets around other stars with a clever new technique that involves searching for a telltale wobble in the motion of a star. When planets orbit a star, they exert a gravitational force of attraction on it. The force on the star causes it to be pulled around in a small circle or oval in space. The circle or oval is simply a miniature replica of the planet's orbital path. Two embracing dancers similarly pull each other around in circles due to the attractive forces they exert on each other. This wob-

ble of a star gives away the presence of an orbiting planet, even though the planet cannot be seen directly.

However, this stellar wobble is very difficult to detect from far away. A new technique has proven to be extraordinarily successful. The key is the Doppler effect—the change in the appearance of light waves and other types of waves from an object that is moving away from or toward a viewer. When a star wobbles toward Earth, its light appears from Earth to be shifted more toward the blue, or shorter, wavelength, of the visible light spectrum than it would have if the star had not moved toward Earth. When the star wobbles away from Earth, the opposite effect occurs. The wavelengths are stretched. Light from the star appears to be shifted toward the red, or longer wavelength, end of the spectrum in a phenomenon known as red shift. Astronomers can determine the velocity of a star from the Doppler shift because the Doppler shift is proportional to the speed with which the star approaches or recedes from a viewer on Earth.

—Geoffrey W. Marcy and R. Paul Butler, NSF-funded astronomers at San Francisco State University and the University of California at Berkeley, respectively. Excerpted from “Detecting Planets Around Other Stars,” reprinted with permission. Encarta, May 1997





The Gemini 8-meter telescope on Mauna Kea, Hawaii, is one of the new tools astronomers are using to search for the barely visible. This telescope, along with other NSF-funded observatories—including Arecibo in Puerto Rico and the Very Large Array in New Mexico—enable astronomers to discover and explain the origins of the universe.

stars nearest the center of the Galaxy move quickly in their orbits, Ghez was astonished to discover that the stars nearest the center of the Milky Way were moving at speeds as high as 3 million miles per hour. Only a very large assembly of superconcentrated mass inside the stars' orbits could whip them around at those speeds. "The high density we observe at the very center of the Milky Way exceeds that inferred for any other galaxy, and leads us to conclude that our galaxy harbors a black hole with a mass 2.6 million times that of the Sun," Ghez notes.

Astronomers do not think that a supermassive black hole at the center of a galaxy is unique to the Milky Way. Rather, it appears to be quite typical of the almost innumerable galaxies in the observable universe. The fact that black holes may be the rule rather than the exception makes it even more important that we continue to study them.

The Origins of the Universe

By observing galaxies formed billions of years ago, astronomers have been able to paint an increasingly detailed picture of how the universe evolved. According to the widely accepted Big Bang theory,

our universe was born in an explosive moment approximately fifteen billion years ago. All of the universe's matter and energy—even the fabric of space itself—was compressed into an infinitesimally small volume and then began expanding at an incredible rate. Within minutes, the universe had grown to the size of the solar system and cooled enough so that equal numbers of protons, neutrons, and the simplest atomic nuclei had formed.

After several hundred thousand years of expansion and cooling, neutral atoms—atoms with equal numbers of protons and electrons—were able to form and separate out as distinct entities. Still later, immense gas clouds coalesced to form primitive galaxies and, from them, stars. Our own solar system formed relatively recently—about five billion years ago—when the universe was two-thirds its present size.

In April 2000, an international team of cosmologists supported in part by NSF, released the first detailed images of the universe in its infancy. The images reveal the structure that existed in the universe when it was a tiny fraction of its current age and one thousand times smaller and hotter than today. The project, dubbed BOOMERANG (Balloon

Observations of Millimetric Extragalactic Radiation and Geophysics) captured the images using an extremely sensitive telescope suspended from a balloon that circumnavigated the Antarctic in late 1998. The BOOMERANG images were the first to bring into sharp focus the faint glow of microwave radiation, called the cosmic microwave background, that filled the embryonic universe soon after the Big Bang. Analysis of the images already has shed light on the nature of matter and energy, and indicates that space is “flat.”

The roots of the Big Bang theory reach back to 1929, the year Edwin Hubble and his assistant Milton Humason discovered that the universe is expanding. Between 1912 and 1928, astronomer Vesto Slipher used a technique called photographic spectroscopy—the measurement of light spread out into bands by using prisms or diffraction gratings—to examine a number of diffuse, fuzzy patches. Eventually, Hubble used these measurements, referred to as spectra, to show that the patches were actually separate galaxies. Slipher, who did his work at Lowell Observatory in Flagstaff, Arizona, found that in the vast majority of his measurements the spectral lines appeared at longer, or redder, wavelengths. From this he inferred that the galaxies exhibiting such “red shifts” were moving away from Earth, a conclusion he based on the Doppler effect. This effect, discovered by Austrian mathematician and physicist Christian Doppler in 1842, arises from the relative motion between a source and an observer. This relative motion affects wavelengths and frequencies. Shifts in frequency are what make ambulance sirens and train whistles sound higher-pitched as they approach and lower-pitched as they move away.

Hubble took these findings and eventually determined the distances to many of Slipher’s galaxies. What he found was amazing: The galaxies were definitely moving away from Earth, but, the more distant the galaxy, the faster it retreated. Furthermore, Hubble and Humason discovered

that the ratio of a galaxy’s speed (as inferred from the amount of red shift) to its distance seemed to be about the same for all of the galaxies they observed. Because velocity appeared proportional to distance, Hubble reasoned, all that remained was to calculate that ratio—the ratio now referred to as the Hubble Constant.

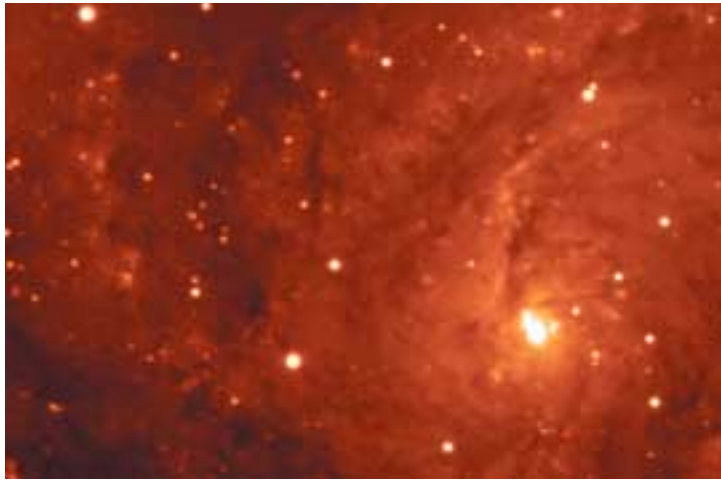
And what is the value of the Hubble Constant? After seventy years of increasingly precise measurements of extragalactic velocities and distances, astronomers are at last closing in on this elusive number.

Wendy Freedman is one of the scientists working to define the Hubble Constant. As head of an international team at the Carnegie Observatories in Pasadena, California, Freedman surveys the heavens using the Hubble Space Telescope to measure distances to other galaxies. With grants from NSF, she is building on the legacy of Henrietta Leavitt, who discovered in the early 1900s that the absolute brightness of Cepheid variable stars is related to the time it takes the stars to pulsate (its period). Scientists can measure the period of a Cepheid in a distant galaxy and measure its apparent brightness. Since they know the period, they know what the absolute brightness should be. The distance from Earth to the Cepheid variable star is inferred from the difference between absolute and apparent brightness. Freedman and her colleagues are using this method to determine distances to other galaxies. With these Cepheid distances, Freedman’s group calibrates other distance-determination methods to reach even more far-flung galaxies. This information, in turn, enables them to estimate the Hubble Constant.

Researchers closing in on a definitive value for the Hubble Constant are doing so in the midst of other exciting developments within astronomy. In 1998, two independent teams of astronomers, both with NSF support, concluded that the expansion of the universe is accelerating. Their

Radio telescopes from the NSF-funded Very Large Array in New Mexico are helping astronomers to map our universe.





This galaxy in the constellation Cygnus is nearly 20 million light-years from Earth. Galaxies such as this one are helping astronomers understand the expansion of the universe, its density, and organization.

unexpected findings electrified the scientific community with the suggestion that some unknown force was driving the universe to expand at an ever increasing rate. Earlier evidence had supported another possibility, that the gravitational attraction among galaxies would eventually slow the universe's growth. In its annual survey of the news, *Science* magazine named the accelerating universe as the science discovery of the year in 1998.

Jeremy Mould, director of Mount Stromlo and Siding Spring Observatories in Canberra, Australia, has studied another aspect of the expansion of the universe. Scientists generally assume that everything in the universe is moving uniformly away from everything else at a rate given by the Hubble Constant. Mould is interested in departures from this uniform Hubble flow. These motions are known as peculiar velocities of galaxies. Starting in 1992, Mould and his colleague John Huchra of the Harvard Smithsonian Center for Astrophysics used an NSF grant to study peculiar velocities of galaxies by creating a model of the universe and its velocity that had, among other things, galaxy clusters. These galaxies in clusters were accelerated by the gravitational field of all the galaxies in the locality. All other things being equal, a high-density universe produces large changes in velocity. This means that measurements of peculiar velocities of galaxies can be used to map the distribution of matter in the uni-

verse. Mould and Huchra's model has seeded major efforts to collect measurements of the actual density of the universe so as to map its mass distribution directly.

In the modular universe—where stars are organized into galaxies, galaxies into clusters, clusters into superclusters—studies of galaxies, such as those conducted by Mould, give us clues to the organization of larger structures. To appreciate Mould's contribution to our understanding of these organizing principles, consider that a rich galaxy cluster can contain thousands of galaxies, and each galaxy can contain tens of billions to hundreds of billions of stars. Astronomers now estimate that there are tens of billions of galaxies in the observable universe. Large, diffuse groupings of galaxies emerging from the empty grandeur of the universe show us how the universe is put together—and perhaps even how it all came to be.

Only one of those extragalactic islands of stars—the Andromeda Galaxy—is faintly visible to the naked eye from the Northern Hemisphere, while two small satellite galaxies of the Milky Way—the Large and Small Magellanic Clouds—can be seen from Earth's Southern Hemisphere. Telescopes augmented with various technologies have enabled astronomers—notably NSF grantee Gregory Bothun of the University of Oregon—to discover galaxies that, because of their extreme diffuseness, went undetected until the 1980s. These “low-surface-brightness” galaxies effectively are masked by the noise of the night sky, making their detection a painstaking process. More than one thousand of these very diffuse galaxies have been discovered in the past decade, but this is only the beginning. “Remarkably, these galaxies may be as numerous as all other galaxies combined,” says Bothun. “In other words, up to 50 percent of the general galaxy population of the universe has been missed, and this has important implications with respect to where matter is located in the universe.”



Why Cosmology?

Cosmologists work to understand how the universe came into being, why it looks as it does now, and what the future holds. They make astronomical observations that probe billions of years into the past, to the edge of the knowable universe. They seek the bases of scientific understanding, using the tools of modern physics, and fashion theories that provide unified and testable models of the evolution of the universe from its creation to the present, and into the future

Do physics and cosmology offer a plausible description of creation? As cosmologists and physicists push the boundary of our understanding of the universe ever closer to its beginning, one has to wonder whether the creation event itself is explainable by physics as we know it, or can ever know it

Clearly, these questions are at the heart of humankind's quest to understand our place in the cosmos. They involve some of the most fundamental unanswered questions of physical science. But why, in a time of great national needs and budget deficits, should the U.S. taxpayer support such seemingly impractical research . . . ?

In fact, far from being impractical, cosmological research produces important benefits for the nation and the world. . . . [I]t has unique technical spinoffs. Forefront research in cosmology drives developments in instrumentation for the collection,

manipulation, and detection of radiation at radio, infrared, visible, ultraviolet, X-ray, and gamma-ray wavelengths. The understanding and application of such types of radiation are the foundation for many important technologies, such as radar, communications, remote sensing, radiology, and many more

Our cosmology—every culture's cosmology—serves as an ethical foundation stone, rarely acknowledged but vital to the long-term survival of our culture For example, the notion of Earth as a limitless, indestructible home for humanity is vanishing as we realize that we live on a tiny spaceship of limited resources in a hostile environment. How can our species make the best of that? Cosmological time scales also offer a sobering perspective for viewing human behavior. Nature seems to be offering us millions, perhaps billions, of years of habitation on Earth. How can we increase the chances that humans can survive for a significant fraction of that time? Cosmology can turn humanity's thoughts outward and forward, to chart the backdrop against which the possible futures of our species can be measured. This is not irrelevant knowledge; it is vital.

—Excerpted from *Cosmology: A Research Briefing*. Reprinted with permission of the National Research Council, National Academy of Sciences.

The Hunt for Dark Matter

Even with all of the galaxies that Bothun and others expect to find, researchers still say much of the matter in the universe is unaccounted for.

According to the Big Bang theory, the nuclei of simple atoms such as hydrogen and helium would have started forming when the universe was about one second old. These processes yielded certain well-specified abundances of the elements deuterium (hydrogen with an extra neutron), helium, and lithium. Extensive observations and experiments appear to confirm the theory's predictions within specified uncertainties, provided one of two assumptions is made: (1) the total density of the universe is insufficient to keep it from expanding forever, or (2) the dominant mass component of the universe is not ordinary matter. Theorists who favor the second assumption need to find more mass in the universe, so they must infer a mass component that is not ordinary matter.

Part of the evidence for the second theory was compiled by Vera Rubin, an astronomer at the Carnegie Institution of Washington who received NSF funding to study orbital speeds of gas around the centers of galaxies. After clocking orbital speeds, Rubin used these measurements to examine the galaxies' rotational or orbital speeds and found that the speeds do not diminish near the edges. This was a profound discovery,

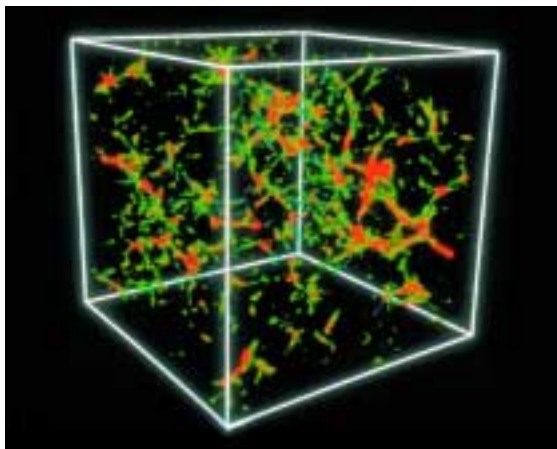
because scientists previously imagined that objects in a galaxy would orbit the center in the same way the planets in our galaxy orbit the Sun. In our galaxy, planets nearer the Sun orbit much faster than do those further away (Pluto's orbital speed is about one-tenth that of Mercury). But stars in the outer arms of the Milky Way spiral do not orbit slowly, as expected; they move as fast as the ones near the center.

What compels the material in the Milky Way's outer reaches to move so fast? It is the gravitational attraction of matter that we cannot see, at any wavelength. Whatever this matter is, there is much of it. In order to have such a strong gravitational pull, the invisible substance must be five to ten times more massive than the matter we can see. Astronomers now estimate that 90 to 99 percent of the total mass of the universe is this dark matter—it's out there, and we can see its gravitational effects, but no one knows what it is.

At one of NSF's Science and Technology Centers, the Center for Particle Astrophysics at the University of California at Berkeley, investigators are exploring a theory that dark matter consists of subatomic particles dubbed WIMPs, or "weakly interacting massive particles." These heavy particles generally pass undetected through ordinary matter. Center researchers Bernard Sadoulet and Walter Stockwell have devised an experiment in which a large crystal is cooled to almost absolute zero. This cooling restricts the movements of crystal atoms, permitting any heat generated by an interaction between a WIMP and the atoms to be recorded by monitoring instruments. A similar WIMP-detection project is under way in Antarctica, where the NSF-supported Antarctic Muon and Neutrino Detector Array (AMANDA) project uses the Antarctic ice sheet as the detector.

In the spring of 2000, NSF-supported astrophysicists made the first observations of an effect predicted by Einstein that may prove crucial in the measurement of dark matter. Einstein argued

Dark matter makes up most of the universe, but no one knows how much of it there is. Researchers use computer simulations such as this one to test different ratios of cold and hot (dark) matter in an attempt to learn more about the components of our universe



that gravity bends light. The researchers studied light from 145,000 very distant galaxies for evidence of distortion produced by the gravitational pull of dark matter, an effect called cosmic shear. By analyzing the cosmic shear in thousands of galaxies, the researchers were able to determine the distribution of dark matter over large regions of the sky.

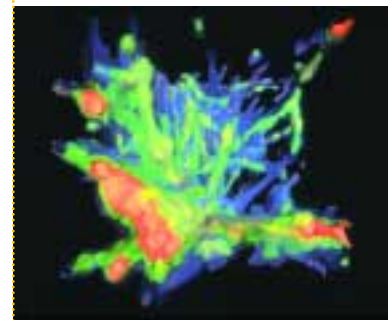
Cosmic shear “measures the structure of dark matter in the universe in a way that no other observational measurement can,” says Anthony Tyson of Bell Labs, one of the report’s authors. “We now have a powerful tool to test the foundations of cosmology.”

Shedding Light on Cosmic Voids

Even with more than 90 percent of its mass dark, the universe has revealed enough secrets to permit initial efforts at mapping its large-scale structure. Improved technologies have enabled astronomers to detect red shifts and infer velocities and distances for many thousands of galaxies. New research projects will plumb the secrets of nearly one million more. And yet, we have much more to learn from the hundreds of billions of galaxies still unexplored.

Helping in the exploration is an ingenious method, developed with help from NSF, that is commonly used to estimate distances to and map the locations of remote galaxies. R. Brent Tully of the University of Hawaii and his colleague at the NSF-funded National Radio Astronomy Observatory, J. Richard Fisher, discovered that the brighter a galaxy—that is, the larger or more massive it is, after correcting for distance—the faster it rotates. Using this relationship, scientists can measure the rotation speed of a galaxy. Once that is known, they know how bright the galaxy should be. Comparing this with its apparent brightness allows scientists to estimate the galaxy’s distance. The Tully-Fisher method, when properly calibrated using Cepheid variable stars, is proving to be an essential tool for mapping the universe.

In early 2000, researchers announced the discovery of a previously unknown quasar that qualified as the oldest ever found—indeed, as among the earliest structures to form in the universe. Quasars are extremely luminous bodies that emit up to ten thousand times the energy of the Milky Way. Eventually our maps will include everything we know about the universe—its newly revealed planets, the inner workings of the stars, distant nebula, and mysterious black holes. With our map in hand and our new understanding of how the universe began and continues to grow, we humans will have a better chance to understand our place in the vast cosmos.



Researchers at the Electronic Visualization Laboratory at the University of Illinois at Chicago used data provided by astronomers to create this image of our universe.

To Learn More

Arecibo Observatory

www.naic.edu/aboutao.htm

National Optical Astronomy Observatories

www.noao.edu

National Center for Supercomputing Applications

Multimedia Online Expo: Science for the Millennium
Whispers from the Cosmos
www.ncsa.uiuc.edu/Cyberia/Bima/BimaHome.html

Cosmos in a Computer

www.ncsa.uiuc.edu/Cyberia/Cosmos/CosmosCompHome.html

Center for Particle Astrophysics

<http://cfpa.berkeley.edu/home.html>

NSF Division of Astronomical Sciences

www.nsf.gov/mps/ast

Global Oscillation Network Group (GONG)

www.gong.noao.edu/index.html

Grand Challenge Cosmology Consortium (GC³)

http://zeus.ncsa.uiuc.edu:8080/GC3_Home_Page.html

National Radio Astronomy Observatory

www.nrao.edu

Carnegie Observatories

www.ociw.edu

Carnegie Institution of Washington

www.ciw.edu

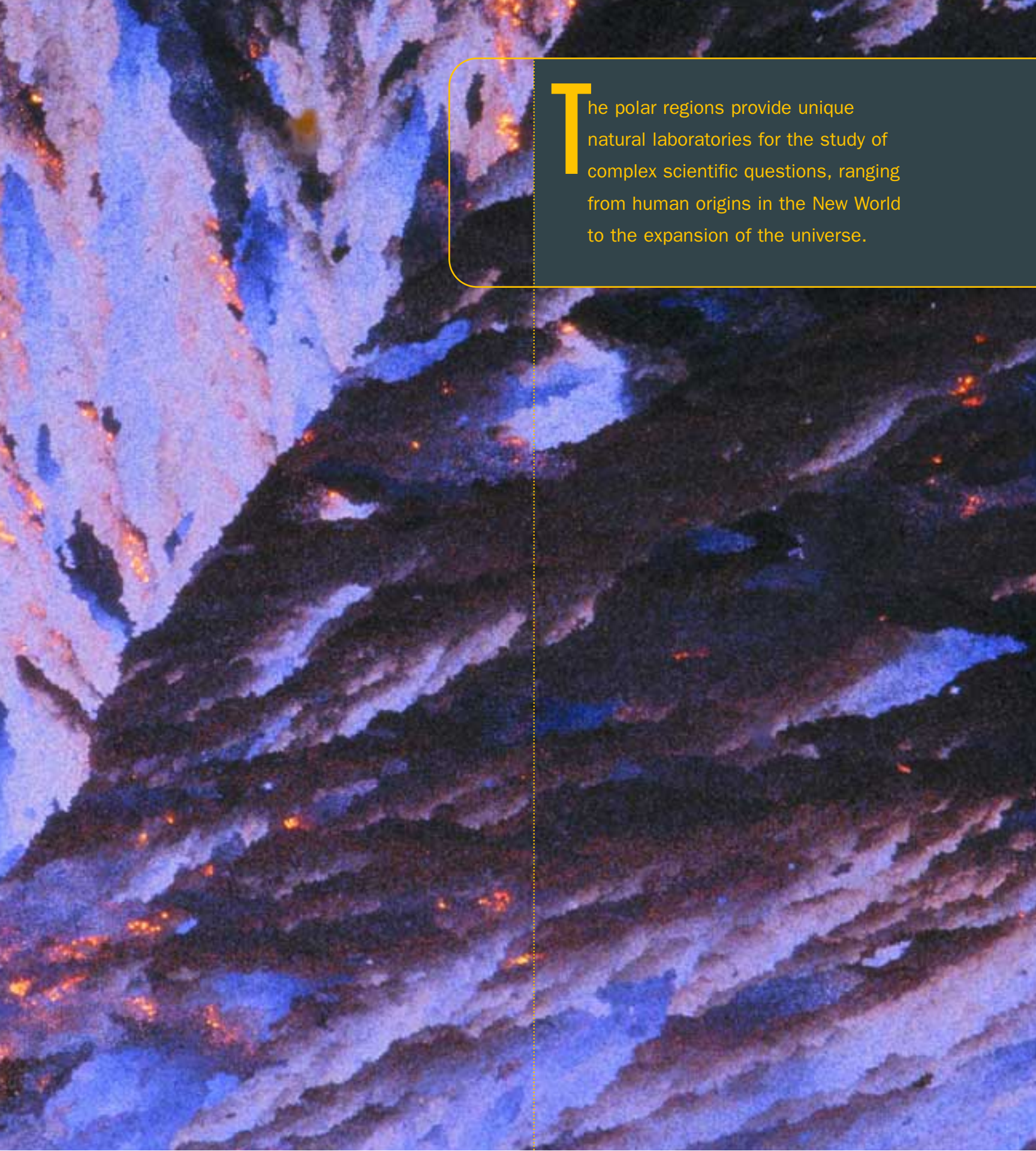
Harvard Smithsonian Center for Astrophysics

<http://sao-www.harvard.edu>

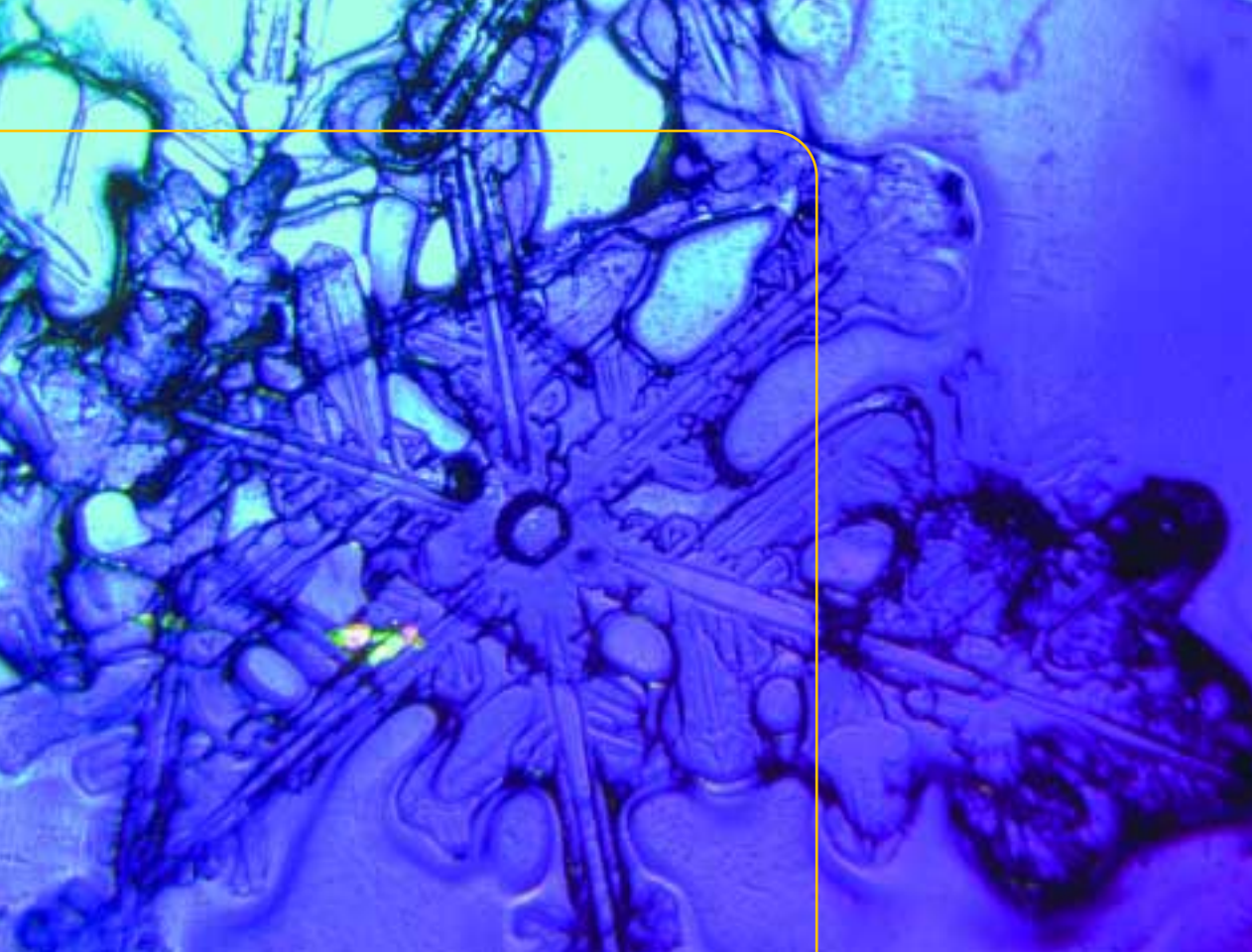
An aerial photograph of a rugged mountain range covered in snow. The scene is illuminated with a strong blue light, creating a cool, ethereal atmosphere. Several narrow, winding paths or ridges are highlighted with a warm orange glow, suggesting the presence of lights or perhaps a different type of snow. The overall texture is highly detailed, showing the intricate patterns of the snow and the dark, shadowed crevices between the peaks.

Science on the Edge

arctic and
antarctic discoveries

An aerial photograph of a polar region, likely Antarctica, showing a complex landscape of snow, ice, and dark terrain. The snow is illuminated with a blue light, and there are numerous small, bright orange or yellow spots scattered across the surface, possibly representing ice melt or mineral deposits. A dark, winding path or channel is visible in the upper left quadrant. The overall scene is a mix of white, blue, and dark grey/black tones.

The polar regions provide unique natural laboratories for the study of complex scientific questions, ranging from human origins in the New World to the expansion of the universe.



People have studied the polar regions for centuries. The extreme cold and stark beauty of the Arctic and Antarctic capture the imaginations of explorers, naturalists, and armchair travelers. In the latter half of the twentieth century, NSF-funded scientists discovered that the Arctic and the Antarctic have much to teach us about our Earth and its atmosphere, oceans, and climate. For example, cores drilled from the great ice sheets of Greenland and Antarctica tell a story of global climate changes throughout history. During NSF's lifetime, the extreme environments of the Arctic and Antarctic have become learning environments.

A Surprising Abundance of Life

Both the Arctic and Antarctic seem beyond life: icy, treeless, hostile places. Yet these polar regions host a surprising abundance of life, ranging from the microbial to the awe-inspiring, from bacteria to bowhead whales.

Important differences mark North and South. The North Pole lies in the middle of an ocean surrounded by land, while the South Pole rises from the center of a continent surrounded by an ocean. In the Arctic, human habitation stretches back for thousands of years. The Inuit and other indigenous peoples in the Arctic continue to carry out age-old traditions while adopting modern technology for subsistence hunting and fishing. The Antarctic has no “native” human populations but hosts a visiting population of scientists and support personnel every year. Human migration and methods of interacting with the environment form important research topics for NSF-supported social scientists who work in the Arctic, while the human scientists in the Antarctic focus on the effects of isolated and confined environments.

The poles were still poorly understood places when scientists the world over organized a special effort called the International Geophysical Year (IGY) to study the Earth and Sun on an unprecedented scale. The IGY, which ran from July 1957 to December 1958, was modeled on two previous International Polar Years and brought NSF firmly into the realm of polar science.

During the First Polar Year (1882–83), scientists and explorers journeyed to the icy margins of the Earth to collect data on weather patterns, the Earth’s magnetic force, and other polar phenomena that affected navigation and shipping in the era of expanding commerce and industrial development. In all, the First Polar Year inspired fifteen expeditions (twelve to the Arctic and three to the Antarctic) by eleven nations. Along the way, researchers established twelve research stations.

By the Second Polar Year (1932–33), new fields of science had evolved, such as ionospheric physics, which peers into the outer layer of Earth’s atmosphere. Scientists at the time turned to the polar regions to study the aurora phenomena—known in the Northern Hemisphere as the “northern lights”—and their relation to magnetic variations, cosmic radiation, and radio wave disturbances. How did the sun, the atmosphere, and the Earth’s interior interact at the poles? Could scientists learn how to anticipate the magnetic storms that sometimes disrupt radio-based communications? Data collected during the Second Polar Year contributed to new meteorological maps for the Northern Hemisphere and verified the effects of magnetic storms on radio waves.

The United States has supported research at the Amundsen-Scott South Pole Station continuously since 1956. The current station, completed in 1975, is being redeveloped to meet the changing needs of the U.S. science community. Today’s research at the South Pole includes astronomy, astrophysics, and atmospheric monitoring—e.g. ozone depletion and greenhouse gas concentrations. To the left in the picture is the geodesic dome that currently houses the main station buildings. On the right, a ski-equipped Hercules airplane waits on the South Pole skiway.



Near Antarctica's coast lie the McMurdo Dry Valleys, a long-term ecological research site funded by the NSF. The bizarre rock formation shown here, called a "ventifact," was sculpted by wind-blown particles of ice and stone. Ventifacts are common to dry, windy places like Antarctica, the high deserts, and Mars. In fact, the Dry Valleys served as practice terrain prior to NASA's launch of the Viking probe to Mars.



Still, scientists lacked a complete picture of how ice, atmosphere, land, and oceans worked together at the poles as a system of cause and effect.

Technological advancements in rockets, satellites, and instrumentation during the 1940s and 1950s allowed more and better measurements in the remote Arctic and Antarctic. By the time of the 1957–58 IGY, researchers were free to explore the ocean floor as well as the upper atmosphere: they could use nuclear-powered submarines to plunge under the ice cap and discover new ocean ridges, and launch rocket-powered satellites to make remote geophysical measurements. For the first time, the polar regions became year-round research platforms available for widespread international cooperation. Furthermore, everyday

citizens became involved in scientific observations. People in the far north and the far south recorded their own aurora sightings and temperature readings, information that was funneled to scientists. Sixty-seven countries participated in the IGY, including the United States and the Soviet Union. Despite Cold War tensions between east and west, the world was engaged in cooperative, coordinated science at the poles and in other parts of the world.

The IGY set the stage for polar research at NSF in two ways. First, scientists came to think of the poles as natural laboratories in which to capture and integrate diverse data about “the heavens and the earth.” Second, polar research became a cooperative international undertaking. Following the IGY, the twelve countries that had established some sixty research stations in Antarctica concluded a treaty to use Antarctica for peaceful purposes only, to freely exchange scientific information, to prohibit nuclear explosions and disposal of radioactive wastes, and to maintain free access to any area on the continent. By 1999, the Antarctic Treaty had forty-four parties, representing two-thirds of the world’s human population; other agreements were made, too, including a protocol for improved environmental protection of Antarctica.

The 1990s also saw cooperation blossom up north. In 1996, the eight Arctic nation-states established the Arctic Council—the result of a process of negotiations aimed at protecting the Arctic environment while also allowing for vital research.



Ice Cores Hold Earth's Climate

As ice forms, gasses and other materials are trapped in the layers that build up over time. This makes the polar regions time machines. With more than 500,000 years of snow and ice accumulation, the ice sheets are ideal places for paleoclimatologists to set up their tubular drills and extract cores—long cylinders of sediment and rock—in order to read the history captured therein.

Working in the center of Antarctica's ice sheet, near the Russian research base of Vostok, a group of researchers from the United States, Russia, and France have extracted the world's deepest core. As a result, the scientists have differentiated more than four ice ages, or about 400,000 years of history.

What researchers are discovering is that Earth's climate is not stable, and never has been. Ice ages are punctuated by interglacial periods of relative warmth, such as the one marking the close of the twentieth century. The interglacial periods have been marked by sudden shifts in temperature, wind patterns, and sea levels.

"Some of these rapid changes occur in two decades," says Paul Mayewski,

a glaciologist from the University of New Hampshire and a thirty-year veteran of NSF-funded research in Antarctica. "Some [of the pattern changes] actually start in less than two years." While he finds these dramatic shifts surprising, he also notes that Antarctic cores are in sync with the climate data found in the ice cores from Greenland.

Mayewski and his colleagues learn about these changes by examining the chemical indicators, such as sea salt, within the extracted ice cores. High sea salt levels signal increased storminess and stronger winds. In addition, measurements of oxygen isotopes in the ice reveal cooling during periods of increased sea salt. Other tests probe for indicators of wind patterns, volcanic activity, and sea level.

However, the researchers still don't know what caused the rapid climate pattern changes evidenced in the ice cores.

"We need to understand how these changes work in order to make a better assessment of natural climatic change," Mayewski says, "and a better assessment of the human impact on the future climate."



Inupiat whalers wait by the sea ice edge near Barrow, Alaska. When a bowhead approaches, they will slip their seal skin umiak into the water, anticipating where the whale will surface. According to the *Principles for the Conduct of Research in the Arctic*, a set of interagency guidelines adopted under the leadership of NSF, Arctic peoples are partners in research. As experts of survival in the North, indigenous elders have already helped scientists understand, for example, how the beaver population can affect whale migration patterns.

Human Migration and Local Knowledge

Scientists are only the most recent human arrivals to the poles—people have lived in the Arctic for thousands of years and the region offered the first migratory route for humans moving into North America. At least twelve thousand years ago, and possibly earlier, newcomers to North America are thought to have crossed to present-day Alaska from northeast Asia via Beringia, a vast plain—now submerged—that once connected the two land masses. Until recently, scientists believed that the newcomers entered the present-day Yukon Territory after crossing the land bridge, then headed south through an inland route. But recently, a science team funded by NSF offered evidence in support of another theory, which suggests that rather than going inland, the newcomers used watercraft along the southern margin of Beringia and southward along the northwest coast of North America. This may have enabled humans to enter

the southern areas of the Americas prior to the melting of the continental glaciers. In 1997, NSF-funded researchers excavated a cave on Prince of Wales Island, Alaska, and found parts of a human jaw and pelvis dating to between 9,200 and 9,800 years ago, the oldest human bones ever found in Alaska. Isotope analysis of the bones showed that the person had subsisted on a marine diet. These first peoples would have had plenty of fish and other marine resources to eat as they moved in skin-covered boats along the Pacific Coast south to Peru and Chile during the last ice age.

While the story of the first people to arrive in North America continues to unfold, another side of the story tells of the close collaboration between scientists and contemporary indigenous communities in the Arctic. During their excavations of the cave on Prince of Wales Island, the archaeologists sought and attained the approval and collaboration of the tribal governments in Alaska. Alaska Native interns work on the site and present research papers at archaeology meetings. Tribal councils discuss news of scientific discoveries. This relationship of mutual trust and learning exemplifies the *Principles for the Conduct of Research in the Arctic*, a set of guidelines based on the ethical responsibility of researchers working in the North to consult, listen to, and involve the people of the North.

The *Principles*, adopted in 1990 by the NSF-chaired Interagency Arctic Research Policy Committee, echo the wish of Arctic peoples that science involve them as partners. After all, science consists in part of good, systematic observation, a critical element in the long-term survival of indigenous peoples who have for generations carved out economies and cultures in a challenging

environment. What's more, indigenous peoples have developed time-tested technologies, such as toggle harpoons and skin boats, well suited for the North. NSF-supported research teams, including Native elders and social scientists, have tapped into this locally held knowledge of the Arctic environment to enrich ecological models and to document oral traditions.

For example, from 1995 to 1997 researchers conducting an NSF-funded study of beluga whale ecology in the Bering Sea asked Native whalers and elders to analyze patterns of whale migration. Surprisingly, the elders began to talk not only about belugas—the white whales with the “smirk”—but also about beavers. As the beaver population rises, more streams leading to the bay are dammed, spawning habitat for the salmon disappears, and fewer fish are available as prey for the belugas. Thus, the belugas may start to bypass the river mouth during their migrations.

The Importance of Sea Ice

Another important topic for researchers is sea ice. Polar sea ice undergoes tremendous changes every year. During the winter, the Arctic ice pack grows to the size of the United States; in the summer, half of the ice disappears. On the other side of the globe, ice at the South Pole covers nearly 98 percent of the Antarctic continent and averages one mile thick. The sea ice surrounding Antarctica changes in size depending on the season, ranging from roughly 4 million square miles in February (the Antarctic summer) to 19 million in August. So huge is the Antarctic ice pack that it accounts for 90 percent of the world's ice and 70 percent of its fresh water.

Like Doing Research on the Moon

NSF began managing the entire U.S. Antarctic Program (USAP) in 1970, providing not only research facilitation but also overall logistics management. The program maintains three year-round research stations and two research vessels capable of navigating through ice, as well as laboratories, telescopes, and other major instruments positioned across the continent. Besides developing the U.S. scientific agenda in cooperation with researchers, NSF provides for the health, safety, and overall well-being of 3,500 American scientists and support personnel, most of whom arrive and depart between October and February, when the continent is readily accessible by plane or ship.

Due to the continent's remote location and the fact that all provisions, building materials, fuel, equipment, and instruments must be brought in by ship or cargo plane, scientists say the experience of working in Antarctica is “like doing research on the moon.” Each year, NSF improves the connections between the USAP and the rest of the world, making the region a little less isolated. All of the research stations now have Internet connections, and NSF hopes to extend the program's telecommunications capabilities so that one day scientists can operate equipment remotely and view real-time displays of data from their home institutions.

Given the amount of water that sea ice alternately puts into or pulls out of the ocean and the atmosphere, sea ice variability plays a major role in global climate change. During the International Geophysical Year scientists from the United States and the Soviet Union spent entire winters on ice islands in the Arctic, measuring depth, salinity, temperature, and other factors to model the extreme variability of sea ice. Forty years later, NSF-funded researchers repeated much of the work done in the IGY but this time with modern means, greatly improving our understanding of sea ice variability and the connections to climate change.

From the fall of 1997 through the fall of 1998, the Canadian ice-breaker ship known as *Des Groseillers* was frozen into the Arctic ice pack for scientific studies related to a multinational project known as SHEBA, or Surface Heat Budget of the Arctic. NSF, the U.S. Office of Naval Research, and the Japanese government cooperated in funding this massive study of heat flow among the water, ice, and air of the northernmost Arctic. For a full year, researchers documented how ice, clouds, snow, and the ocean interact and exchange energy. SHEBA researchers are now off the ice and back in the laboratories to integrate and analyze the vast amount of data they have collected but already they have reported a number of surprises.

One unexpected finding concerned the salinity of the water. When the scientists first arrived at the Arctic ice pack in October 1997, they discovered that the water was much fresher than it had been when the same area was analyzed twenty years earlier. They concluded that the melting of the ice pack during the summer of 1997 caused the water to be proportionally less salty. Such a change can have serious consequences for marine life as well as for how ocean water circulates and interacts with the atmosphere. In addition to altering salinity, melting sea ice also raises worldwide sea levels, with potentially significant effects for coastal cities and towns.

All of which, of course, raises questions about the nature of the warm weather associated with sea ice melting. Over the last one hundred years, overall global climate has warmed, on average, about 0.9°F with the Arctic leading the way. Temperatures at the North Pole have risen nearly

Two researchers walk from the ice-breaker *Des Groseillers* toward their lab, one of more than a dozen huts and tents on the ice where scientists conducted their work. The ship served as a floating field camp for the NSF-funded SHEBA experiment, an international study of heat flow in the Arctic. Frozen into the ice in the Beaufort Sea on October 2, 1997, the ship and its researchers drifted with the Arctic ice for a full year, travelling nearly 2,700 miles.



Why the Ozone Hole? A Writer Explains

Why did the ozone hole develop over Antarctica, and not over Detroit or some other manufacturing center where chlorofluorocarbons, or CFCs, are released prodigiously? The reasons are explained by Rebecca L. Johnson, who participated in NSF's Antarctic Artists and Writers Program in 1991, 1994, and 1997.

In winter, the stratosphere above the Antarctic continent gets colder than it does anywhere else on Earth. Temperatures frequently drop below -112°F . Antarctica is also one of the windiest places on Earth. In May and June, strong winds in the stratosphere begin to blow clockwise around the continent. These howling stratospheric winds gradually form an enormous ring of moving air, called the Antarctic polar vortex, that swirls around and around, far above the frozen land

During the winter, temperatures inside the Antarctic polar vortex fall so low that water vapor and several other types of molecules in the stratosphere condense into extremely small icy particles. These icy particles, in turn, make up polar stratospheric clouds (PSCs). When the sun sets in the Antarctic around the end of March each year, its disappearance marks the beginning of a long, dark winter. Once the last rays of sunlight have faded away, temperatures on land and in the air fall very quickly.

In the stratosphere, high-altitude winds that create the polar vortex begin to blow around the continent.

Isolated from warmer air outside the vortex, the air inside gets colder and colder. Eventually, it is cold enough for PSCs to form. And that is when the trouble really begins.

Drifting around inside the polar vortex are reservoir molecules that have bonded with chlorine atoms and in so doing prevented them—so far—from attacking ozone. When PSCs form above Antarctica, chlorine reservoir molecules bind to the icy particles that make up the clouds. Once this happens, complex chemical reactions begin to take place that result in molecules of chlorine gas (Cl_2) being released from the reservoirs. In this form, however, chlorine doesn't attack ozone. It just collects inside the vortex. All through the long, dark winter, especially during July and August, the chemical reactions taking place on the surfaces of the PSC particles continue, and more and more Cl_2 builds up inside the vortex. At this point, the stage is set for ozone destruction. All that is needed is a trigger to get the process going.

That trigger comes in late August, when the sun begins to rise. As the first rays of spring sunlight strike the stratosphere high over the frozen continent, conditions change very rapidly. The UV rays coming from the sun strike the Cl_2 molecules inside the vortex. The molecules break apart, releasing billions of chlorine atoms that begin an attack on ozone molecules. The result

is massive ozone destruction. Before long, so much ozone is destroyed inside the vortex that an ozone hole is formed.

Ozone destruction continues—and the hole remains—until conditions in the stratosphere above Antarctica change. This change usually begins in early October, when the continent and the air above it finally begin to warm up. Warmer temperatures in the stratosphere melt the icy particles that make up PSCs. The PSCs disappear, and the reservoir molecules that were bound to the icy particles are released. Free at last, the reservoir molecules bind chlorine atoms once again, and ozone destruction stops.

By early November, the strong stratospheric winds circling Antarctica die down, and the polar vortex breaks up. As it does, ozone-rich air from outside the vortex flows in, and much of the ozone that was destroyed is replaced. In a sense, the hole in the ozone layer fills in. Usually by the end of November, the amount of ozone in the stratosphere over Antarctica has almost returned to normal. The next winter, however, the cycle will begin again.

From *Investigating the Ozone Hole* by Rebecca L. Johnson. © 1993 by Lerner Publications Company. Used by permission of the publisher. All rights reserved. Ms. Johnson is also the author of *Science on the Ice: An Antarctic Journal* (1995) and *Braving the Frozen Frontier: Women Working in Antarctica* (1997).



The dim, late-summer sun brightens the Ferrar Glacier in the Transantarctic Mountains of Antarctica. What can still seem like the most remote and forbidding region on Earth has become a model of ongoing international scientific cooperation, with the National Science Foundation playing a lead role.

3.6°F per decade in the last thirty years, significantly faster than in other regions of the world. The Antarctic is warming up, as well. Ice shelves have been shrinking; according to some reports, the 502-square-mile Wordie Ice Shelf disappeared completely between 1966 and 1989.

NSF-funded scientists who participated in the Scientific Ice Expeditions (SCICEX) program have confirmed that there is an acceleration in sea ice shrinkage. The SCICEX program provided the opportunity to use U.S. Navy submarines for Arctic research during the 1990s. Data from the SCICEX cruises demonstrate that the Arctic sea ice cover is showing signs of diminished extent and seasonal duration. What's more, ice observed in the 1990s was more than three feet thinner compared to measurements taken two to four decades earlier. Together, the SHEBA and SCICEX projects have

revealed a major climatic factor—shrinking sea ice—that is now being incorporated into forecasts of global climate variability. If the ice pack continues to decrease in coverage and thickness, researchers suggest the possibility of a nearly ice-free Arctic—an area that has been covered by ice for at least three million years—and a vastly changed world.

What is the source of the warming trend? Part of the challenge in answering this question is learning how to separate the effects of human activity (such as the introduction into the atmosphere of “greenhouse” gases like carbon dioxide) from warming and cooling cycles that occur naturally. In the polar regions, average temperatures have fluctuated on various time scales, from the tens of thousands of years to one hundred thousand years. Further study of ice and sediment cores will provide a more detailed picture of ice sheet behavior during warmer intervals of Earth's history. Because Earth was warmer in the distant geologic past, studies of this complex period should shed light on the future effects of global warming.

Studying Extremes Above and Below

Ice is not the only substance of interest at the poles. These extreme environments offer windows into realms yet to be explored. The universe, for example. How did the universe evolve? Will the universe continue to expand? Astronomers use a year-round observatory at the South Pole to answer these questions, taking advantage of the Pole's natural features: the dark, dry, and cold environment makes for easier detection of infrared wavelengths and small particles. Infrared and submillimeter radio telescopes at the South Pole detect wavelengths obscured at most other observing sites. NSF-funded researchers use the Antarctic ice sheet to capture invisible, subatomic particles called neutrinos in order to gain insight into violent astrophysical events such as black hole collapses and supernova explosions.

Another territory ripe for exploration can be found deep below the ice. Thousands of feet under the Antarctic surface, below the Russian-run research station known as Vostok, lies Lake Vostok. The subglacial lake, roughly the size of Lake Ontario, has been isolated from Earth's ecosystem for millions of years. Cut off from the rest of the Earth, Lake Vostok may be home to ancient species of microbes that have been able to survive in this extreme environment. As part of a joint U.S., French, and Russian research project, Russian teams have drilled down into the ice covering the lake and extracted the world's longest, deepest ice core. They stopped drilling at about 395 feet above the ice-water interface to prevent possible contamination of the underlying lake by kerosene-based drilling fluid.

The upper 9,800 feet of the ice core provide a continuous paleoclimatic record of the last 400,000 years. The record shows that there have been four complete climatic cycles, including four ice age or glacial periods associated with the development of large ice sheets over the Northern Hemisphere, and four warmer interglacial periods.

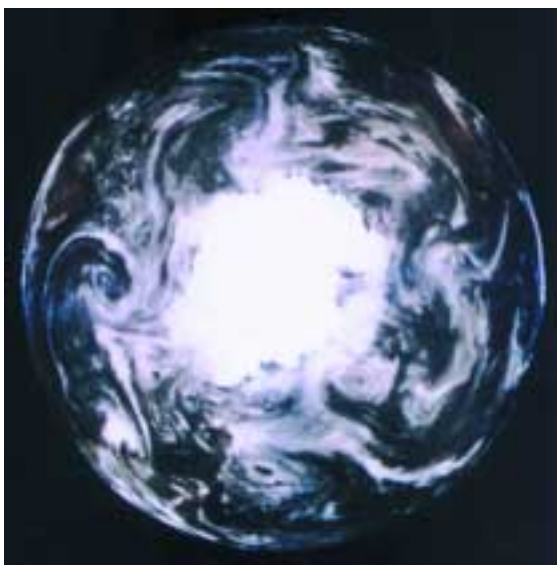
In addition, NSF-funded scientists discovered that the core contains bacterial forms, showing that microbes existed under the ice and probably still thrive in the lake. Supporting this theory is a July 2000 report by a separate team of NSF-funded researchers that they have discovered metabolically active bacteria surviving in South Pole snow.

How do such "extremophiles" survive? Where do they get their energy—from geothermal activity? Studying the microbes and their unique and isolated environment will tell scientists more about whether life may be able to exist in harsh conditions elsewhere in the solar system. Indeed, Lake Vostok appears to resemble conditions on Jupiter's frozen moon Europa. Scientists and engineers are now working on methods to sample the subglacial lake while preventing contamination.

In 1999, NSF-funded researchers sailed aboard a U.S. Navy nuclear submarine (the USS *Hawkbill*, shown here poking through the ice), to map the oceanic ridges and basins beneath the Arctic ice cap and to study ocean currents that may have an effect on global climate. The project, called Scientific Ice Expedition (SCICEX) '99, was the fifth in a series of annual missions, all taking advantage of sophisticated scientific instruments aboard highly maneuverable warships.



Antarctica as pictured by the spacecraft Galileo on its way to Jupiter. The picture was taken in early December, a time of year when the ozone hole over the South Pole is small to nonexistent. During the cold Antarctic winters—April through August—icy stratospheric particles form, which interact with atmospheric chemicals to foster ozone destruction upon the return of sunlight in late August. The ozone hole grows until October, when warmer temperatures begin to melt the icy particles. Because stratospheric ozone protects living things against harmful radiation, NSF-funded researchers at the Pole are working hard to better understand the cause and effects of ozone depletion.



Moving up in scale from microbes, biologists continue to discover important adaptations among larger extremophiles. In the late 1960s, physiologist Arthur L. DeVries discovered with the help of NSF funds that Antarctic notothenioid fish are protected from subzero temperatures by antifreeze glycoproteins in their blood. Continuing studies to unravel the workings of fish antifreeze could have profound implications in a number of areas—from human organ transplantation to agriculture and beyond. As it happens, Arctic cod have similar glycoproteins. These proteins bind to ice crystals and keep them from growing. Yet NSF-funded studies in the 1990s revealed that the Arctic cod and Antarctic notothenioid actually belong to two different orders of fish that diverged in evolution some forty million years ago. This is a striking case of convergent evolution in polar environments: the fish took different routes toward the identical solution of how to stay alive in ice water.

Ozone Hole over Antarctica

Life at the margins may be extreme, but it is also fragile. The British Antarctic Survey's first documentation of the Antarctic ozone hole in 1985 and subsequent NSF-funded study of the phenomenon alerted the world to the danger of chlorofluorocarbons, or CFCs. That research team, led by 1999 National Medal of Science winner Susan Solomon, conducted observations that have significantly advanced our understanding of the global ozone layer and changed the direction of ozone research.

Stratospheric ozone protects against ultraviolet radiation. The breakdown of this ozone layer by CFC molecules can have harmful effects on a range of life forms, from bacteria to humans. The long, cold, dark Antarctic winters allow the formation of polar stratospheric clouds, the particles of which form an ideal surface for ozone destruction. The returning sunlight provides energy to start the complex chemical reaction that results in the depletion of ozone. The ozone hole above Antarctica typically lasts about four months, from mid-August to late November.

During this period, increased intensity of ultraviolet radiation has been correlated with extensive DNA damage in the eggs and larvae of Antarctic fish. Embryos of limpets, starfish, and other invertebrates do not grow properly. Other species have developed defenses. The Antarctic pearl wort, a mosslike plant on rocky islands, developed a pigment called flavenoid that makes it more tolerant of ultraviolet radiation.

In the northern polar regions, ozone levels in the early 1990s measured 10 percent lower than those estimated in the late 1970s. The Arctic does experience ozone depletion, but to a lesser degree than the Antarctic. Unlike the Antarctic, large-scale weather systems disturb the wind flow in the Arctic and prevent the temperature in the stratosphere from being as cold. Therefore fewer stratospheric clouds are formed to provide surfaces for the

production of ozone-depleting compounds. Some clouds do form, however, and allow the chemical reactions that deplete ozone. Ozone depletion has a direct effect on human inhabitants, but research has only just begun on the effects of increased ultraviolet radiation on terrestrial and aquatic ecosystems and societies and settlements in the Arctic.

The good news is that countries around the world have agreed to ban the manufacture of CFCs through the Montreal Protocol. The contributions of Antarctic researchers led to swift policy action and because of that the ozone layer should recover in the future. In the meantime, however, NSF-funded research continues to monitor the level of the CFCs still lingering in the atmosphere. The polar regions will continue to play an important role as early warning systems for the rest of the globe.

Knowledge of the Whole

Knowledge of life in extreme environments helps us to understand not only how life may have begun on Earth, but also what we may find beyond our own planet. Records from ice and sediment cores reveal past climate patterns, helping scientists to anticipate future scenarios and maybe allowing policymakers to make more informed decisions. Following ethical principles in partnership with Arctic communities brings researchers to a deeper understanding of their own scientific methods while enabling them to listen to local knowledge and oral traditions.

What will happen to the sea ice in the Arctic and the massive glaciers in the Antarctic? How will ecosystems adapt to the rapid changes observed over the last few years? Data captured at the poles show that the Earth is a total system where cause and effect know no north or south. The Arctic and Antarctic both register the effects of, and have their own influence on, global circulation patterns in the ocean and atmosphere.

NSF has enabled science to reach the most remote and seemingly forbidding regions on Earth, only to discover that these regions may hold the key to a global understanding. As scientists make discoveries at the ice's edge, they join earlier generations of hunters, explorers, and navigators in a time-honored quest for knowledge of the extreme, leading to knowledge of the whole.

To Learn More

NSF U.S. Antarctic Program

www.nsf.gov/od/opp/antarct/usap.htm

Antarctic Muon and Neutrino Detector Array (AMANDA)

<http://amanda.berkeley.edu>

Center for Astrophysical Research in Antarctica

<http://astro.uchicago.edu/cara/home.html>

McMurdo Dry Valleys Long-Term Ecological Research (LTER)

<http://huey.colorado.edu>

Scientific Committee on Antarctic Research

www.scar.org

Scientific Committee on Antarctic Research Global Change and the Antarctic

www.antrc.utas.edu.au/scar/

NSF Arctic Program

www.nsf.gov/od/opp/arctic/

Arctic Research Consortium of the United States

www.arcus.org

International Arctic Environment Data Directory

www.grida.no/prog/polar/add/

Alaska Native Knowledge Network

www.ankn.uaf.edu

Center for Global Change and Arctic System Research

www.cgc.uaf.edu

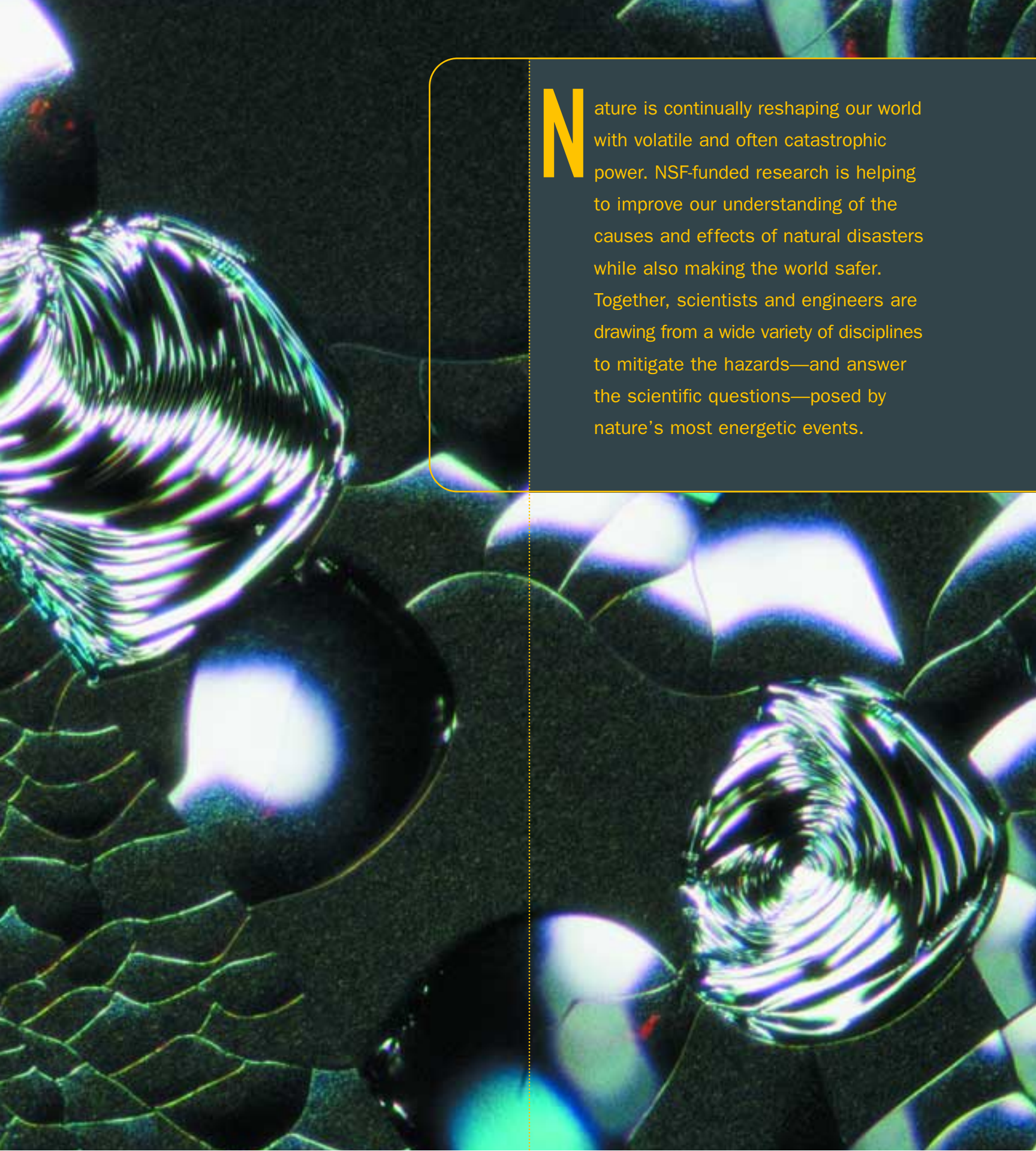
SHEBA Home Page

<http://sheba.apl.washington.edu>



Disasters & Hazard Mitigation

**living more safely
on a restless planet**



Nature is continually reshaping our world with volatile and often catastrophic power. NSF-funded research is helping to improve our understanding of the causes and effects of natural disasters while also making the world safer. Together, scientists and engineers are drawing from a wide variety of disciplines to mitigate the hazards—and answer the scientific questions—posed by nature’s most energetic events.



Natural disasters are complex and often global in their effects. That is why the hallmark of NSF's long involvement in disaster research has been to encourage the exchange of ideas across national boundaries as well as scientific disciplines. To find answers in this high-stakes field, NSF programs marshal a wide range of researchers, including atmospheric scientists, engineers, geologists, sociologists, economists, seismologists, biologists, political scientists, and others. Their work takes them to wherever nature is in turmoil—earthquakes in Japan, volcanoes in the Philippines, hurricanes in the Atlantic, and floods on America's Great Plains. The resulting discoveries about the inner workings and human risk associated with nature's most extreme events are making both warning and mitigation increasingly possible.

The Forces Underlying the Fury

The economic cost of natural disasters in the United States has averaged as much as \$1 billion a week since 1989—and is expected to rise, according to a 1999 NSF-supported study. Because natural disasters can have such brutal consequences, it's easy to think of them in terms of human misery that, somehow, must be mitigated. But society cannot mitigate what it does not understand. Natural disasters are, after all, a part of nature, and though human activities can influence the impact of extreme events, researchers must first learn as much as possible about the basic physical forces underlying the fury. At NSF, most of the research into natural disasters and their mitigation takes place within the Directorate for Geosciences, the Directorate for Engineering, and the Directorate for Social, Behavioral, and Economic Sciences.

Take, for example, earthquakes and volcanoes. Almost from its inception, NSF has been a critical player in the global effort to understand and cope with these giant Earth-altering forces. NSF funded a series of explorations during 1957–58—dubbed the International Geophysical Year—and again in the 1960s. These explorations confirmed a wild idea that scientists had begun to suspect was true: the Earth's seafloors, rather than being congruous like the rind of a melon, were actually disparate pieces that, at least in some places, were slowly moving away from each other. These findings pushed geophysicists toward the modern theory of plate tectonics. Researchers now know that the upper part of Earth's crust is broken up into a number of rigid sections or plates, and that these plates float atop soft-solid rock kept in a molten state by an unimaginably hot inner core. As the plates drift, they not only separate but also collide and slide past each other, forming valleys and mountain ranges. Occasionally, some of the molten rock breaks through—and a volcano is born. When two plates grind past each other, the shuddering friction generates earthquakes.



Of the one million or so earthquakes that rattle the planet each year, only a few—about one each week—are large enough to grab our attention. Predicting when and where the next “big one” will take place is still far from a certainty. Short-term forecasts are sometimes pegged to swarms of smaller quakes that may signal mounting stress at a fault. Or a sudden change in underground water temperature or composition may be significant: this type of signal led to the successful evacuation of a million people before a major earthquake struck near the city of Haicheng, China, in 1975—the first earthquake to be scientifically foretold.

NSF-funded researchers are making headway on the difficult question of earthquake prediction by narrowing their focus to specific regions of the world. Because the behavior of seismic waves is so strongly affected by the different kinds of soil and geological structures through which the waves must travel, the effects of an earthquake can vary widely from place to place, even along the same fault. A soft-soil area such as a lakebed, for example, will shake more than a rocky hill. Knowing this, scientists and engineers at the NSF-sponsored Southern California Earthquake Center in Los Angeles have reassessed the consequences of earthquakes along faults in the surrounding region. The scientists were able to simulate the anticipated effects of future local quakes by using sophisticated computer models of the Los Angeles basin that accounted for fault geometry and motion, sediment composition, and other factors that can reflect, prolong, or

With funding from the National Science Foundation, scientists have made significant advances in the accuracy of storm prediction since the first tornado forecast in 1948.

amplify quaking motion. Such modeling, supplemented with data from new digital seismic recorders capable of sensing a broad range of actual earthquake vibrations, can help researchers and residents of quake-prone areas to anticipate—at least in a general way—when and where the next big temblor will hit and what damage may result.

Even as local efforts to understand earthquake activity improve, scientists are finding new ways to take another look at the big picture. In June 1999, NSF-funded researchers joined an international team headed to the east coast of Japan to establish long-term seafloor observatories in one of the world's busiest earthquake zones: the so-called Japan Trench, where two of Earth's biggest tectonic plates are colliding. The international team of scientists drilled holes about one kilometer deep into the ocean floor along the trench, which itself is two kilometers underwater. They then installed instruments at the bottom of these boreholes to monitor the amount of seismic activity there. Robotically controlled vehicles similar to those used to investigate the sunken Titanic will periodically travel to and from the seafloor observatories and help provide scientists with long-term observations of one of the planet's most active quake regions.

Another way that NSF is helping researchers gather data close to the moment of seismic activity is through its funding of the Earthquake Engineering Research Institute (EERI) in Oakland, California. Besides encouraging regular communication among engineers, geoscientists, architects, planners, public officials, and social scientists concerned about natural disasters, EERI quickly assembles and deploys teams of researchers on fact-finding missions in the wake of earthquakes—anywhere in the world—soon after they occur.

Reducing the Risk

Though researchers cannot yet precisely predict the timing and location of earthquakes, NSF has long recognized that more can be done to minimize—or mitigate—the damage that quakes can cause. Toward that end, in 1977 Congress passed the Earthquake Hazards Reduction Act, which put NSF in charge of a substantial part of earthquake mitigation research efforts in the United States. Earthquake-related studies, especially with regard to structural and geotechnical engineering, now make up the bulk of NSF's natural disasters research under the guidance of the Natural Hazards Reduction Program in the Directorate for Engineering.

Why engineering? Because most of the immediate deaths from earthquakes occur when buildings collapse, and the huge economic losses associated with the biggest quakes stem from damage to the structures and infrastructures that make up cities and towns. In 1997, NSF officially charged three earthquake centers with a major portion of the responsibility for conducting and coordinating earthquake engineering research in the United States. The centers, each constituting a consortium of public and private institutions, are based at the University of California at Berkeley, the University of Illinois at Urbana-Champaign, and the State University of New York at Buffalo.

The NSF-funded earthquake centers are models of cooperation, including not only geoscientists and engineers but also economists, sociologists, political scientists, and contributors from a host of other disciplines. The Buffalo center, for example, recently studied the potential economic impact of an earthquake in the Memphis, Tennessee, area near the epicenter of several major quakes that struck in 1811-12. Participants in the study included researchers from the University of Delaware's Disaster Research Center, who examined economic, political, and social elements of the hazard. The Delaware researchers have also studied the



Climate Change—Disaster in Slow Motion

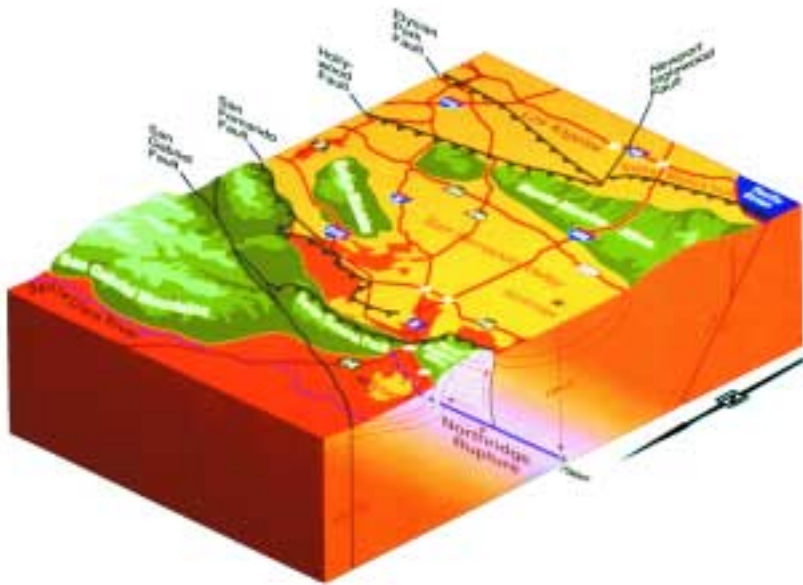
Before 1950, climatologists spent most of their time describing and comparing the current-day climates of different regions. Even the relatively recent climatic past remained a mystery to them, and interactions between the atmosphere and the oceans that researchers now know drive global climate change were too complex to study with the mathematical tools at hand. But then came the computer revolution, funded to a significant degree by NSF, and today much of nature's turbulence, past and present, is available for study.

With the advent of NSF-sponsored supercomputers, climatologists began building models of atmospheric change that now embrace millions of years of oceanic, atmospheric, biological, geological, and solar processes. For example, by the late 1980s NSF-supported researchers at the University of Washington were able to reconstruct the wide extremes of temperatures that existed 250 million years ago within the giant supercontinent of Pangaea.

In 1999, climate modelers at the NSF-funded National Center for Atmospheric Research in Boulder, Colorado, managed to accurately simulate a century of known climate history. The scientists then carried

these simulations a century into the future. Their model suggests that if carbon dioxide emissions continue to rise at their current pace, there will likely be a boost in global temperatures as well as a 40 percent jump in winter rain and snow within the southwest region and Great Plains of the United States. The model also shows that the warming effect would be more severe in the United States than in Europe or Asia.

While global warming might not rival earthquakes and hurricanes for dramatic immediacy, such gradual but significant climate changes can indeed have disastrous consequences for human society. As ice caps melt, sea levels will rise, threatening coastal habitation and commerce. Warmer temperatures will also radically alter when, where, and whether farmers can grow certain crops. Climate models that can predict such events with a fair degree of certainty—and perhaps suggest what can be done to minimize their impact—will make an invaluable contribution to the field of natural hazards research. Accustomed to the urgency of saving lives, natural disaster researchers now face the challenge of preserving a way of life, as well.



This geological model of the 1994 Northridge earthquake was created by researchers at the NSF-funded Earthquake Engineering Research Center at the University of California at Berkeley. This three-dimensional view of the 6.7 magnitude earthquake gives scientists a better understanding of the geological forces behind earthquakes.

impact that the Loma Prieta earthquake (1989) and Hurricane Andrew (1992) had on businesses in the Santa Cruz and Miami areas, respectively. Kathleen Tierney, a sociologist at the University of Delaware and a co-principal investigator for the Buffalo earthquake consortium, says the few previous studies of long-term disaster impacts focused on individuals and families rather than on businesses. The new Delaware research should help both policymakers and business owners better understand the economic impacts of disasters and devise more effective ways of coping with them.

While understanding the economic impact of disasters is important, the heart of the earthquake centers' mission is to design safer buildings. In 1967, the University of California at Berkeley center installed what is still the nation's largest "shake table." The twenty-foot-by-twenty-foot platform reproduces the seismic waves of various earthquakes, allowing engineers to test model structures. After the Loma Prieta quake, NSF funded an upgrade of the table from two- to three-dimensional wave motions; additional digital controls and sensors will soon allow offsite researchers to monitor experiments at the shake table in real time via a computer network.

Ultimately, says William Anderson, senior advisor in NSF's Division of Civil and Mechanical Systems, the research community may be able to conceptually link geophysical and geotechnical research—such as computer models of faults and soil liquefaction—to the engineering simulations of building parts, creating a unified, integrated mathematical model of disaster.

The need for such research has been underscored numerous times in the latter part of the twentieth century. Early in the morning on January 17, 1994, southern California suddenly heaved and swayed. Deep beneath the town of Northridge, less than 25 miles from downtown Los Angeles, one giant chunk of the Earth's crust slipped over another, jolting the people and structures above with a 6.7 magnitude earthquake. (On the logarithmic Richter scale, 7.0 constitutes a major earthquake. Although the Richter scale has no upper limit, the largest known shocks have had magnitudes in the 8.8 to 8.9 range.) More than twelve thousand buildings were shaken so hard they collapsed or sustained serious damage, while many of the region's vital freeways and bridges disintegrated or were rendered impassable. Sixty people died and Californians suffered more than \$25 billion in economic losses.

One year later and halfway around the world, the city of Kobe, Japan, endured its first catastrophic earthquake in a century, a 6.9 magnitude temblor. More than six thousand people died and almost two hundred thousand buildings were destroyed or damaged. Fires spread across the city while helpless firefighters failed to draw a drop of water from the shattered pipes. Besides the horrific loss of life, the devastation in Kobe cost between \$100 and \$200 billion.

The widespread destruction from these disasters has been especially alarming to experts because both cities sit atop a seismically active coastal region known as the Pacific Rim, which is capable of bestirring earthquakes of even greater violence. Close inspection of the rubble from both earthquake sites revealed one of the main

contributing factors to the devastation: Buildings with steel frames exhibited cracks at the welded joints between columns and beams. Experts had expected old masonry and reinforced-concrete structures to crumble, but steel-framed buildings were supposed to be relatively safe. In Kobe, the steel frames failed catastrophically: more than one in eight simply collapsed. In Northridge, more than two-thirds of the multistory steel-framed buildings suffered damage.

Immediately after these disasters, NSF-sponsored researchers put new emphasis on developing better connection designs. In five short years, researchers have learned to reduce stresses on welds by altering the joints in the frames, in some cases by perforating or trimming the projecting rims (i.e., flanges) of the steel I-beams. These safer construction techniques have been included in new building code recommendations issued by the Federal Emergency Management Agency for all U.S. buildings in earthquake-prone regions.

NSF-funded researchers are finding many other ways to make buildings safer during earthquakes. Shih Chih Liu, program director of NSF's infrastructure and information systems program, says new high-performance concrete uses ash or small steel bars for better tensile strength and corrosion resistance. It took smart thinking to concoct the new concrete but other work is aimed at making the buildings themselves "smart." NSF-funded engineering professor Deborah Chung at the State University of New York at Buffalo recently invented a smart concrete that acts as a sensor capable of monitoring its own response to stress. The concrete contains short carbon fibers that lower the concrete's tendency to resist the flow of electricity (a quality that researchers call "resistivity"). Deformations to the material—as can occur during earthquakes—cause resistivity to rise, a change that can be gauged by a simple electrical contact with the concrete. The greater the signal, the greater the presumed damage. NSF-funded engineers have also developed systems such as swinging counterweights, which dampen the oscillations of

buildings, and slippery foundations that are shaped like ball bearings in a bowl—the bearings allow the structure's footings to shift sideways nearly independently of the structure above.

Other NSF-supported advances include the development of smart shock absorbers for buildings, bridges, and other structures. As the structure shakes or sways, electrical signals from motion sensors in the structure cause a special fluid in the shock absorbers to become thicker or thinner (ranging between the consistency of light oil to one more like pudding), depending on what's needed to slow or speed the movement of the shock absorbers' pistons.

How well these efforts translate into saved lives and minimized economic losses depends on how widely they are shared. In the new millennium, NSF plans to develop the Network for Earthquake Engineering Simulation (NEES)—a kind of overarching cybersystem for earthquake engineering experimental research. Through NEES, researchers around the world can remotely access a complete system of laboratory and field experimentation facilities, of which there are currently more than thirty in the United States alone.

The 1995 earthquake that devastated Kobe, Japan, destroyed a section of the Nishinomiya-ko Bridge. The Kobe earthquake demonstrated the vital importance of NSF-funded research into "smart" materials and other earthquake-resistant construction techniques.



Hot Heads

Volcanoes are close cousins of earthquakes, arising as they do from the same powerful motions of the planet's tectonic plates. Despite their fiery reputation for chaos and destruction, however, only about sixty volcanoes erupt each year, usually with more bravado than brawn. What's more, most volcanoes are on the ocean floor where plate boundaries are converging or spreading over "hot spots"—large subterranean pools of magma.

This is not to say that volcanoes pose no peril. Over the last three hundred years more than 260,000 people have died from volcanic activity. The 1991 eruption of the Philippines' Mount Pinatubo killed more than three hundred people and devastated the area's economy. When Mount St. Helens blew its stack in the state of Washington in 1980, 57 people died, nearly 7,000 big game animals were killed, more than 12 million salmon perished, forests were devastated, and the economy took a nearly \$1 billion hit.

On May 18, 1980, a 5.1 magnitude earthquake shook Mount St. Helens. The bulge and surrounding area slid away in a gigantic rockslide and debris avalanche, releasing pressure and triggering a major pumice and ash eruption of the volcano. Thirteen hundred feet of the peak collapsed. As a result, 24 square miles of valley were filled by a debris avalanche; 250 square miles of recreation, timber, and private lands were damaged by a lateral blast; and an estimated 200 million cubic yards of materials were deposited into the river channels.



All of this reinforces the need for better ways to model and predict volcanic activity. One way to both study and monitor a volcano is to place a gas sensing device called COSPEC along the volcano's flanks. COSPEC (for "correlation spectrometer") measures how much sulfur dioxide gas is escaping from the volcano's interior. A jump in the amount of sulfur dioxide suggests an imminent eruption. Still, a few hours' or, at most, a few days' warning is the best that scientists can manage with current knowledge and technology. And sometimes, of course, there is no discernible warning at all.

In 1993, nine members of a scientific expedition who were taking gas samples died when a sudden spasm of molten rock and ash erupted from the crater of a volcano called Galeras in Colombia. The tragedy prompted one of the survivors, Stanley Williams of Arizona State University, to organize a conference that would enable scientists to standardize their methods and make data consistent from one volcano observatory to another. The 1997 NSF-funded conference brought together virtually every scientist then working with COSPEC—some twenty-five volcanologists from fourteen countries. Williams has also developed a remote-access instrument called GASPEC that measures another early-warning gas, carbon dioxide.

Other volcano-monitoring efforts funded in part by NSF include a network of seismometers (instruments that measure ground vibrations caused by earthquakes) and an array of Earth-orbiting satellites called the Global Positioning System (GPS). The GPS can alert scientists to volcano-related ground deformations at the millimeter scale—deformations that might signal an imminent eruption.



How's the Weather Up There?

In the spring of 1989, six million people in Canada, Sweden, and the United States lost electric power for up to nine hours thanks to stormy weather—not on Earth, but on the Sun. During particularly vigorous solar storms, billions of tons of plasma erupt from the Sun's gaseous outer layer (called the corona), speed toward Earth at hundreds of miles per second, and disrupt the Earth's magnetic field.

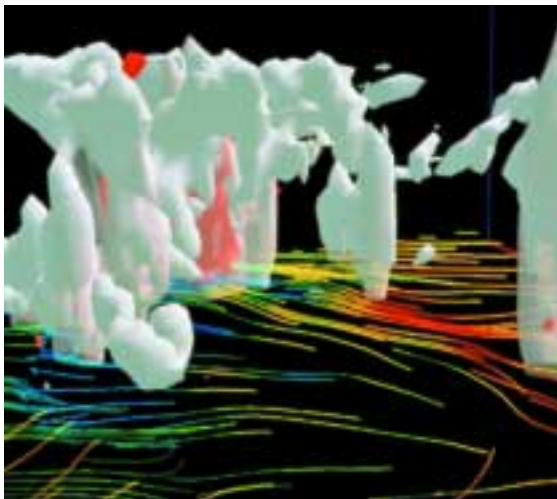
Although they also produce spectacularly beautiful auroras—those colorful atmospheric streamers known as the northern lights—"coronal mass ejections" constitute a poorly understood natural hazard of growing concern to the scientists at NSF's National Center for Atmospheric Research (NCAR). That's because the ejections are associated with features on the

Sun known as sunspots, whose activity follows an eleven-year cycle. And not only is the most recent sunspot cycle expected to reach its maximum activity in the year 2000, but overall, these so-called solar maximums have become twice as powerful as they were in the early 1900s. With our civilization's well-being tied ever more closely to power stations and satellite-based communication systems, the atmospheric disturbances triggered by solar storms pose a potentially significant threat.

From 1980 to 1989, the NSF-funded *Solar Maximum Mission* satellite collected the most detailed data yet on coronal mass ejections. NCAR researchers used this data to develop a new suite of observation tools that work in space and on the ground.

For example, a special electronic camera called CHIP (for "chromospheric helium imaging photometer") perches on the volcanic flanks of Hawaii's Mauna Loa and snaps highly detailed pictures of the solar disk and corona every three minutes. These pictures are frequent enough to provide scientists with a movie loop of ejections as they develop and burst forth. Other satellite-borne instruments—some launched and retrieved by the space shuttle *Discovery* to escape distortions caused by Earth's dusty atmosphere—mine the Sun's radiation for clues about its magnetic behavior. Along with piecing together the basic science behind solar storms, these instruments should help scientists do a better job of predicting the next serious bout of bad space weather.

Researchers at the NSF-funded National Center for Atmospheric Research in Boulder, Colorado, use computer models to learn more about tornadoes, hurricanes, and other weather events. These models enable atmospheric scientists to more accurately predict when and where severe storms will hit. Greater forecasting accuracy can save lives and minimize property damage.



Stormy Weather

While earthquakes and volcanoes capture much of the public's imagination, weather-related disasters can wreak far more economic havoc. According to the Worldwatch Institute, 1998 set a new record for global economic losses related to extreme weather—\$89 billion, a 48 percent increase over the previous record of \$60 billion in 1996 and far more than the accumulated losses for the entire decade of the 1980s.

A major player in the world's efforts to learn about and live with extreme weather is the National Center for Atmospheric Research (NCAR) in Boulder, Colorado, funded by NSF's Division of Atmospheric Sciences. Central to NCAR's activities is the use of supercomputers to develop large-scale simulations of atmospheric and ocean dynamics. These models help to explain the formation of tornadoes, windstorms, and hurricanes, as well as more mundane climatic events. For example, in the late 1970s, NCAR researcher Joseph Klemp, working with Robert Wilhelmson of the NSF-funded supercomputing center at the University of Illinois, developed the first successful model of the most dangerous of all thunderstorms, the "supercell" storm. In a thunderstorm, air moves up and down in a turbulent mix. A single-cell storm means that there is just one updraft/downdraft component, which generally produces only moderately severe weather. A multicell storm can kick out the occasional tornado, but sometimes a main, intensely rotating updraft develops within a multicell storm and transforms it into a supercell storm capable

of producing the most devastating weather, complete with violent tornadoes, raging winds, hail, and flooding.

The model developed by Klemp and Wilhelmson confirmed other researchers' observations that this special, rotating brand of thunderstorm could develop by splitting into two separate storm cells. According to their simulation, the southern storm in the pair was the most likely to concentrate its powers to make a tornado. Meteorological modelers have since improved these simulations to the point where researchers can study the ability of rotations midway up in a thunderstorm to develop tornado-like whirls at the ground. Such work, coupled with NSF-sponsored ground reconnaissance of tornadoes, may eventually solve the mystery of how tornadoes are born, which, in turn, could lead to better warning systems.

Warning systems can save lives, but whether or not a building survives a tornado's onslaught depends largely on how it was constructed. Since the 1970s, scientists and engineers at the NSF-funded Texas Tech (University) Institute for Disaster Research have been picking through the aftermath of tornadoes' fury for clues about what predisposes a structure to survival. When the researchers first began their work, it was common for emergency preparedness manuals to recommend that during a tornado building residents open their windows so that pressure inside the building could equalize with the low-pressure interior of the approaching twister. But after much dogged detective work, the Texas Tech researchers were surprised to learn that rather than exploding from unequal pressure, the walls of homes destroyed by tornadoes appeared to flatten when winds pried up the roof, just as aerodynamic forces will lift up an airplane wing. Wind was also discovered to contribute to structural damage by blowing debris from poorly built homes into homes that were otherwise sound.

The key to survivable housing—at least in all but the worst cases of tornadoes—turns out to be roofs that are firmly anchored to walls and walls



The Human Factor

Most hurricanes kill and destroy with a surge of seawater. Not Hurricane Andrew—the monster of 1992—a storm that led to at least fifty deaths and more than \$30 billion in property damage in southern Florida. Sufficient warning enabled people to evacuate from dangerous beaches even as the worst of the storm miraculously skirted downtown Miami. But Andrew pummeled south Florida with particularly intense air currents that leveled well-built homes and demolished Homestead Air Force Base. The damage from the winds was more severe than expected, given that the region's building codes had been considered among the best in the country. As it turned out, however, enforcement of those codes had grown lax during the region's recent building boom.

All the science-based predictions and warnings in the world will not mitigate a natural disaster made more devastating by human folly. Ironically, improved hazard warnings in the United States may be one of the factors encouraging more and more people to move to homes on the earthquake- and hurricane-prone coasts. As noted in a 1999 report by the National Research Council's Board on Natural Disasters, 80 percent of Florida's population now lives within 22 miles of the beach—a fivefold increase since 1950. A steady rise in the migration to cities has also made more people more vulnerable to the effects of natural disasters as they live amidst aging infrastructures increasingly susceptible to the slightest ill wind or tremor. Urban growth also translates into more pavement

and less exposed soil, which forces rain to run off rather than soak into the ground and tends to increase flood damage. All of this means that the sharply upward trend in the costs of natural disasters is attributable not so much to the occurrence of more hazards but rather to human choices that place more of our structures and possessions at risk.

Sometimes, too, steps taken with the best of intentions to limit the dangers of natural hazards can turn out to amplify the problem. The intense rains and flooding that occurred in 1993 along the Mississippi River provide an example. The levees and dikes that had been built along the river to protect communities from the occasional mid-level flood allowed more development in the area and also effectively eliminated the flood plain, exacerbating the damage caused by the unusually massive surge of water in 1993.

"Disasters by Design: A Reassessment of Natural Hazards in the United States," a five-year-long NSF-funded study, was released in the spring of 1999. The study compiled the thoughts of 132 experts on how communities can better prepare themselves by evaluating potential local threats up to two hundred years in the future, determining acceptable losses, and then planning for them.

Says study leader Dennis Mileti of the University of Colorado's Natural Hazards Research and Applications Information Center, "We need to change the culture to think about designing communities for our great-grandchildren's children's children."

that are firmly anchored to foundations. Wide eaves along the roofline, which can act as handles for powerful winds, should be avoided. And the researchers found that weak points in the structure, such as garage doors and opened windows, actually increase the risk of damage by inviting in winds that will blow down the opposing walls, exposing people to injury from breaking glass and flying wreckage. The advice might be simple—shut your windows during a tornado rather than open them—but it is rooted in the long investigation of complex physical forces.

Trustworthy Tools

Our ability to understand tornadoes and other natural forces is only as good as the tools researchers have to study them. One highlight in this regard is Doppler radar, developed in the mid-1970s with the help of NSF funds. Since the 1960s, meteorologists' ability to predict violent weather patterns has depended largely on two kinds of technology: an array of orbiting space satellites that observe Earth's environment on a scale not previously possible, and ground-based radar technology. Radar peers inside clouds for clues about their potential for severe weather by sending out electromagnetic pulses that bounce off particles and return with valuable information about the location and intensity of precipitation. Most weather radars send out signals with relatively short wavelengths that, while offering a precise picture of a cloud's interior, can be absorbed by the very particles they're supposed to measure. On the other hand, Doppler radar uses longer wavelengths, so that even distant weather systems will appear on the radar screen with accurately rendered intensity. What's more, Doppler radar provides additional information (such as the velocity at which precipitation is moving) that is critical to short-term forecasting.

In the last decade, the National Weather Service has installed Doppler radar systems at fixed locations across the country, improving meteorologists' ability to issue timely flash flood and severe thunderstorm warnings and cutting by more than 60 percent the number of tornadoes that strike

without public notice. Recently NSF-funded scientists have also begun experimenting with more-advanced mobile Doppler instruments mounted on flatbed trucks, which allow the hardier breed of researcher to chase down storms for even more precise readings.

With Doppler radar, NCAR scientists helped a University of Chicago wind expert, the late T. Theodore Fujita, to confirm in the 1980s a whole new atmospheric hazard—the microburst. Microbursts are concentrated blasts of downdrafts from thunderstorms that have been responsible for airplane crashes killing more than five hundred people in the United States. And in 1999, NCAR researchers began testing whether Doppler radar systems installed on airplanes can detect so-called convective turbulence, associated with storms and clouds, which can rip sections off small planes and injure crew and passengers.

Another significant new observing technology developed at NCAR is a probe employed by hurricane-hunting aircraft. The probes are dropped from government planes into offshore hurricanes to profile previously hard-to-measure factors such as low-level winds, pressures, and temperatures around the storm's eye. Data from these probes have greatly improved the National Weather Service's ability to predict the course and intensity of hurricanes. Hurricanes develop over the warm tropical oceans and have sustained winds in excess of 75 miles per hour. One hundred years ago, coastal residents generally had less than a day's warning before a hurricane struck. Today, thanks to satellites and radar, these same residents know days in advance that a hurricane is maturing and moving their way.

El Niño Bears Unwanted Gifts

Hurricanes are dramatic examples of how the atmosphere and the oceans interact to drive the course of Earth's climate in sometimes perilous ways. Another example is El Niño, a weak warm current of water that appears for several weeks each Christmas off the coast of Ecuador and Peru. Every three to five years, however, this otherwise

mild-mannered current becomes a real “hazard spawner,” says NCAR senior scientist Michael Glantz, by growing in size and strength and lasting for many months. Unusual weather conditions result as tropical monsoons that normally center over Indonesia shift eastward, influencing atmospheric wind patterns around the world. Massive fish kills, droughts, heavy rains: These are just some of the gifts that a robust El Niño can bear.

After a particularly devastating El Niño event in 1982–83, researchers vowed not to be caught off guard again. NSF coordinated a global scientific effort to set up a network of ocean-drifting, data-gathering buoys in the Pacific Ocean. In the spring of 1997, the investment paid off when the instruments began recording abnormally high temperatures off the coast of Peru, giving scientists and policymakers their first inkling of an El Niño event that would turn out to be the most devastating in fifty years. Supplemented with satellite observations, the advance warning from the buoys allowed farmers in Central and South America to steel themselves for record-breaking drought and Californians to fix their roofs before the onset of an unprecedented rainy season that also caused life-threatening floods and mudslides. Now NCAR researchers are incorporating what they’ve learned about this massive El Niño event into supercomputer-based climate models designed to simulate atmospheric circulation changes over the course of decades and even centuries. And in May 1999, NCAR began working with the United Nations Environment Programme to conduct a nineteen-month study of the impact of the 1997–98 El Niño, with the goal of developing programs to help countries better prepare themselves for the day when El Niño makes a muscular comeback.

A Safer Future

In recognition of the rising dangers and costs associated with natural disasters around the world, the United Nations declared the 1990s the International Decade for Natural Disaster Reduction. At the close of the decade, NSF could look back on fifty years of sponsored programs whose aims have been—and continue to be—to better under-

stand and prepare for the kinds of extreme natural events that can prove disastrous for human communities. While the world can never be absolutely safe, its human inhabitants can at least rest easier in the knowledge that nature’s violence holds less sway in an age where scientists and engineers are working so closely together to mitigate what cannot be controlled.

To Learn More

NSF Directorate for Engineering

www.eng.nsf.gov

NSF Directorate for Geosciences

www.geo.nsf.gov/

NSF Directorate for Social, Behavioral, and Economic Sciences

www.nsf.gov/sbe

Network for Earthquake Engineering Simulation (NEES)

www.eng.nsf.gov/nees

Earthquake Engineering Research Institute (EERI)

www.eeri.org

Federal Emergency Management Agency

www.fema.gov

Mid-America Earthquake Center

(at the University of Illinois at Urbana-Champaign)

<http://mae.ce.uiuc.edu>

Multidisciplinary Center for Earthquake Engineering Research (at the State University of New York at Buffalo)

<http://mceer.buffalo.edu>

National Center for Atmospheric Research (NCAR)

www.ncar.ucar.edu/ncar/

National Information Service for Earthquake Engineering (at the University of California at Berkeley)

<http://nisee.ce.berkeley.edu>

National Weather Service

www.nws.noaa.gov

Pacific Earthquake Engineering Research Center

<http://peer.berkeley.edu>

Southern California Earthquake Center

www.scec.org

U.S. Geological Survey Hazards Research

www.usgs.gov/themes/hazard.html

U.S. Geological Survey Cascades Volcano Observatory

<http://vulcan.wr.usgs.gov/home.html>

University of Oklahoma Center for Analysis and Prediction of Storms (CAPS)

www.caps.ou.edu

About the Photographs

The National Science Foundation is profoundly grateful to photographer and NSF grantee Felice Frankel for her contribution to *America's Investment in the Future*. Her photographs are compelling visual metaphors for the scientific and technological advances celebrated in this book. While they are not literal representations of the research described, Frankel's images enable the Foundation to communicate the dramatic impact of the basic research it advances.

Frankel is an artist-in-residence and research scientist at the Massachusetts Institute of Technology. Her first NSF grant was awarded in 1997 for "Envisioning Science," a project in which she works with students and researchers to raise the standards in scientific imaging and visual expression of data. She is writing a handbook for scientists on how to communicate their research through accurate and compelling images. MIT Press will publish *Envisioning Science* in 2001. Frankel and colleagues from MIT and around the country are also establishing an initiative to promote new collaborations among researchers, imaging experts,



and science writers. The initiative will begin with the Image and Meaning: Envisioning and Communicating Science and Technology conference from June 13-16, 2001 (<http://web.mit.edu/i-m/>). The conference is partially funded by NSF in partnership with various corporations.

Frankel has been a Guggenheim fellow and a Loeb Scholar at Harvard University, and has received grants from the National Endowment for the Arts, the Camille and Henry Dreyfus Foundation, and the Graham Foundation. In 1997, Frankel co-authored *On the Surface of Things: Images of the Extraordinary in Science* with George Whitesides, National Medal of Science winner and Mallinckrodt Professor of Chemistry at Harvard University. Frankel, who began her career as a landscape photographer, also wrote the award-winning *Modern Landscape Architecture: Redefining the Garden*.



Internet

This extreme close-up of a computer monitor screen symbolizes the transforming power of the Internet, which NSF was instrumental in building. The interlocking pixels suggest the complex network of processors, packets, switches, and wires that make up the global network of networks.



Advanced Materials

Miniaturized wireless communication devices, nonlinear optical crystals, artificial skin, and thin metals are just some of the discoveries made possible by NSF's longstanding support of materials research. The freestanding origami-like microstructures in this photograph were formed by printing a pattern of thin metal on glass capillaries.

From the laboratory of Rebecca Jackman, Scott Brittain, and George Whitesides, Department of Chemistry and Chemical Biology, Harvard University.



Education

NSF-funded education projects and information technologies capture the imagination of students and spark their interest in science, mathematics, engineering, and technology. This scanning electron micrograph of a CD-ROM, taken at MIT's Microsystems Technology Laboratories, reveals the dots and empty spaces (the 1s and 0s) of the disk's binary code. The result: everything from the music of Mozart to the adventures of The Magic School Bus®.

Micrograph taken with the help of postdoctoral fellow Albert Folch, Department of Electrical Engineering and Computer Science, Massachusetts Institute of Technology.



Manufacturing

A microrotor, the blades of which are depicted here, is just one example of MEMS, or microelectromechanical systems—machines built at diameters less than a human hair. Part of a microscale revolution in instrumentation design, MEMS has become a multibillion-dollar industry thanks in large part to early, basic research funded by NSF.

Research from the laboratory of Martin Schmidt, Stephen Senturia, and Chunang-Chia Lin, Department of Electrical Engineering and Computer Science, Massachusetts Institute of Technology.



Arabidopsis

Through the eye of the photographer, even the mustard weed, *Arabidopsis thaliana*, becomes a work of art. With support from NSF, plant biologists the world over are cooperating in research to create a genetic map of *Arabidopsis* and thereby unlock the mysteries of all flowering plants.

From the laboratory of Gerald Fink, Whitehead Institute, Massachusetts Institute of Technology.



Decision Sciences

A femtosecond is one quadrillionth of a second. In this photo, femtosecond laser pulses have created micron-sized holes in quartz. NSF-funded mathematicians have systematically studied the complex decision-making pathways that lead to winning strategies—femtoseconds of thought captured in elegant, timeless theorems.

From the laboratory of Eric Mazur and Eli Glezer, Harvard University.



Visualization

Computer visualization techniques pioneered by NSF-funded researchers reveal otherwise hidden details of complex events—the evolution of a storm, the beating of a heart. For this image, Frankel photographed a printed version of the ferrofluid pictured on the cover. The pattern serves as another visualization of the ferrofluid’s gryphon-like nature.



Environment

What better symbol is there of the environment’s enduring, yet fragile, nature than the butterfly? Nightly, the tropical morpho butterfly folds its wings to display camouflaging browns and grays. But sunlight striking the morpho’s wings at just the right angle reflects a brilliant, mate-attracting blue, as captured here by Frankel. The environment in all its mysterious beauty remains a vital focus of NSF-sponsored research.



Astronomy

The human race has long yearned to explore and understand worlds beyond our own. This close-up of a telescope lens, so suggestive of a planet’s curving horizon, celebrates the many avenues of astronomical research, including the support of observatories worldwide, made possible with support from NSF.

Lens courtesy of Philip and Phylis Morrison, Massachusetts Institute of Technology.



Science on the Edge

Scientists and engineers endure harsh conditions at the Earth’s icy Poles to find abundant answers to many questions, from global climate change to the cosmic origins of life. Residing in relative comfort, Frankel shot this image of ice crystals condensing and growing on her windowpane in winter.



Disasters & Hazard Mitigation

This photograph shows cracking of a silicon chip that was previously deposited by a plasma-enhanced chemical vapor. By understanding the conditions that cause such cracking, researchers gain new insight into silicon microfabrication processes required to create high-powered micromachines. Just as this laboratory “disaster” leads to a greater understanding of matter and manufacturing, so NSF-funded research helps us better understand and mitigate the effects of natural disasters.

Research from the laboratory of Martin Schmidt and Arturo Ayon, Massachusetts Institute of Technology.

Photo Captions and Credits

The National Science Foundation is grateful to the many scientists, engineers, and institutions that have submitted photographs of their work to NSF. Over the years, these contributions have enabled NSF to build a collection of images (the NSF Collection) that enable the Foundation to better communicate about the research and education programs it funds.

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Oceanographic Institution

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Page 3: Anwar Huq

Internet

- Page 6: NSF funding played a role in the development of the fiber optic technology that powers today's Internet.
Photographer: Ken Reid/FPG International
Page 7: Greg Foss/
Pittsburgh Supercomputing Center
Page 9: Photo illustration by Adam Saynuk
Page 10: Frank Summers/Princeton University,
National Center for Supercomputing
Applications
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Education

- Page 34: Visitors go *Beyond Numbers* and investigate the stretches, curves, and angles of mathematics at the New York Hall of Science. The traveling exhibit was developed at the Maryland Science Center.
Peter Howard
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Page 39: Diane Soderholm/MIT
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Page 42: Bill Winn/University of Washington
Page 43: Scholastic's *The Magic School Bus*®, the Emmy award-winning animated science adventure series for children based on Scholastic's best-selling book series of the same name. Scholastic and *The Magic School Bus*® are trademarks of Scholastic Inc. © Scholastic Inc. All rights reserved.
Page 44: Teachers Experiencing Antarctica/
Rice University
Page 45: PhotoDisc

Manufacturing

- Page 50: At the NSF-supported Laboratory for Manufacturing and Productivity at MIT, researchers have developed a three-dimensional printing (3DP) process for the rapid and flexible production of parts and tools. 3DP works by building parts in layers from a computer (CAD) model. In the part shown here, a surface texture was defined in CAD and then mapped onto different solids. Such surface textures can be used to enhance heat transfer or create a prescribed surface roughness, among other things.
Emanuel M. Sachs/MIT

- Page 51: Rodney Hill/Engineering Research Center, University of Michigan
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- Page 57: NSF supported a study of molten glass. The glass was pulled into microthin optical fibers that can carry 1,000 times more information than an electrical wire. Photo courtesy of Corning Glass Works
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Arabidopsis

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- Page 94: Electronic Visualization Laboratory/University of Illinois at Chicago
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- Pgs.96-97: This image from a CAVE virtual reality roller coaster ride lets viewers design and ride their roller coaster. Visualization courtesy of Jason Leigh/Electronic Visualization Laboratory, University of Illinois at Chicago
- Page 99: The mathematics of fractals has given scientists and engineers the ability to visualize and understand complex systems. NSF Collection
- Page 100: John Rosenberg/Pittsburgh Supercomputing Center

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- Page 110: North Temperate Lakes/University of Wisconsin LTER
- Page 111: A view from the top of the crane at the Wind River Canopy Research Facility on the Olympic Peninsula in Washington. The crane is used to help study forest canopy organisms and interactions. Jerry Franklin
- Page 113: G. David Tilman/Cedar Creek Natural History Area, University of Minnesota
- Page 115: Close-up of a chytrid, a little known group of fungi linked with frog deaths in Australia and Panama. Martha J. Powell/University of Alabama

Astronomy

Page 120: NSF Collection

Page 121: National Radio Astronomy Observatory.

Page 122: Association of Universities for Research in Astronomy, Inc. (AURA). All rights reserved.

Page 123: The head-on collision of two neutron stars. This is an extract from a more complete analysis of the changes in pressure and density that occur from the collision and eventual coalescence of two stars that have reached the final phase in their evolution. Charles Evans, California Institute of Technology; Visualization by Ray Idaszak and Donna Cox, Illinois Supercomputer Center.

Page 124: Dr. Robert Mallozzi/University of Alabama in Huntsville and Marshall Spaceflight Center

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Page 141: Antarctica as photographed from the spacecraft *Galileo*. NASA

Page 142: Ferrar Glacier, Stuart Klipper

Page 143: *USS Hawkbill*, 1998 Commander Submarine Force, U.S. Pacific Fleet

Page 144: NASA

Disasters & Hazard Mitigation

Page 148: The remains of trees leveled by the eruption of Mount St. Helens. David E. Wieprecht/USGS

Page 149: University Corporation for Atmospheric Research, Inc.

Page 151: A sand dune on Hog Island, one of NSF's Long-Term Ecological Research Program sites. Bruce Hayden/University of Virginia/NSF

Page 152: Northridge Collection/Earthquake Engineering Research Center/University of California, Berkeley

Page 153: Christopher R. Thewalt/Great Hanshin Bridge Collection/Earthquake Engineering Research Center/University of California, Berkeley

Page 154: Austin Post/U.S. Geological Survey

Page 155: An x-ray satellite image of a solar storm. NASA/NSSDC

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Acknowledgments



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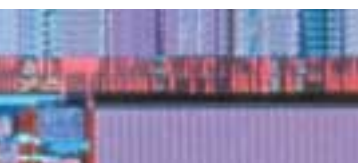
America's Investment in the Future was developed by NSF's Office of Legislative and Public Affairs (OLPA), under the guidance of Acting Director Michael Sieverts. Ellen Weir, acting head of OLPA's Communications Resources Section, is the project director.

The book reflects the vision of former OLPA Director Julia A. Moore, currently a public policy scholar at the Woodrow Wilson International Center for Scholars. Stacy Springer, former head of the Communications Resources Section, oversaw the project through much of its development.

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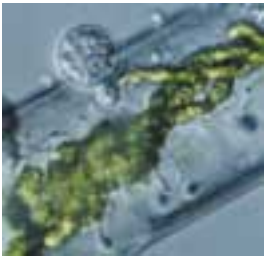
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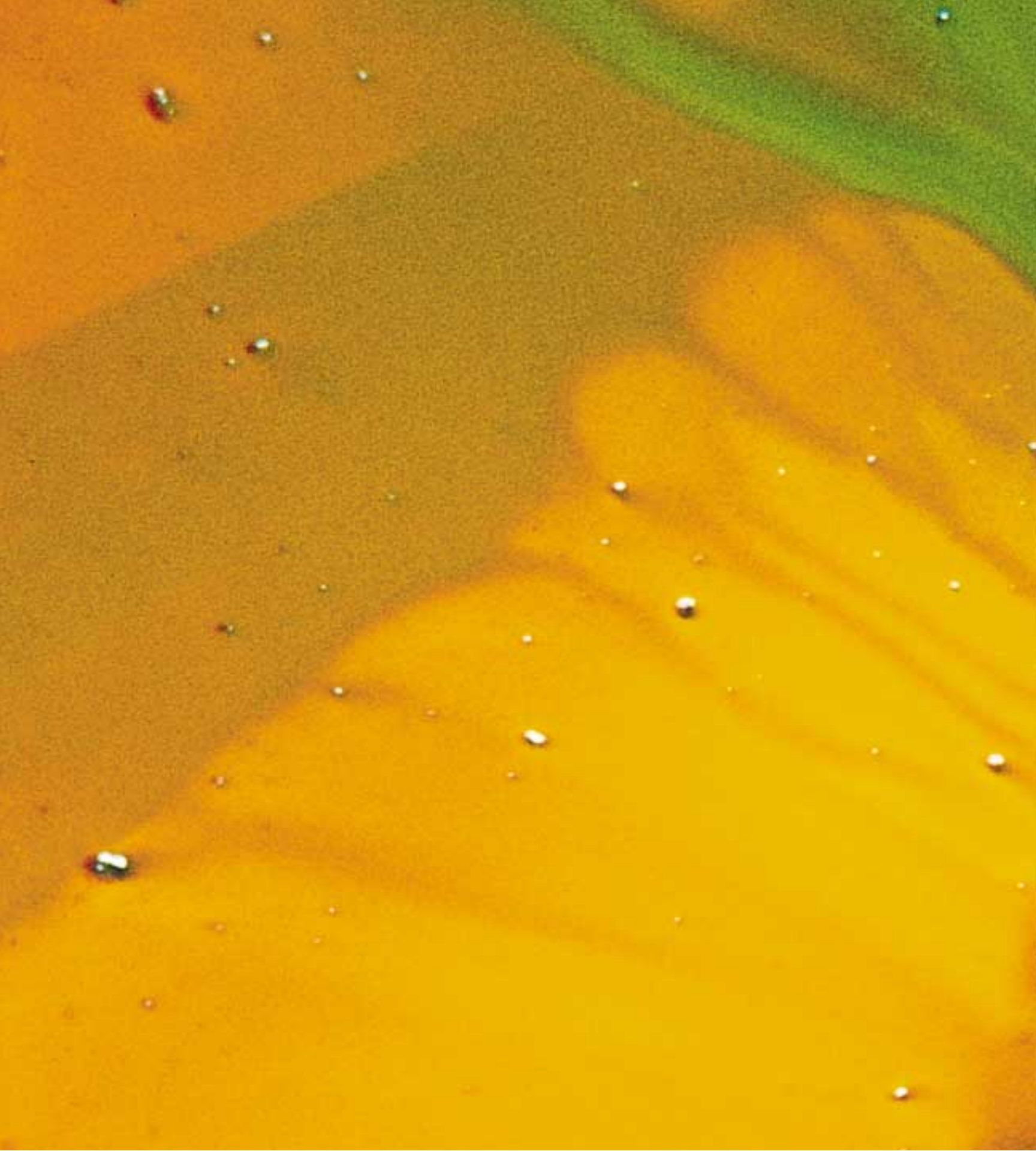
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