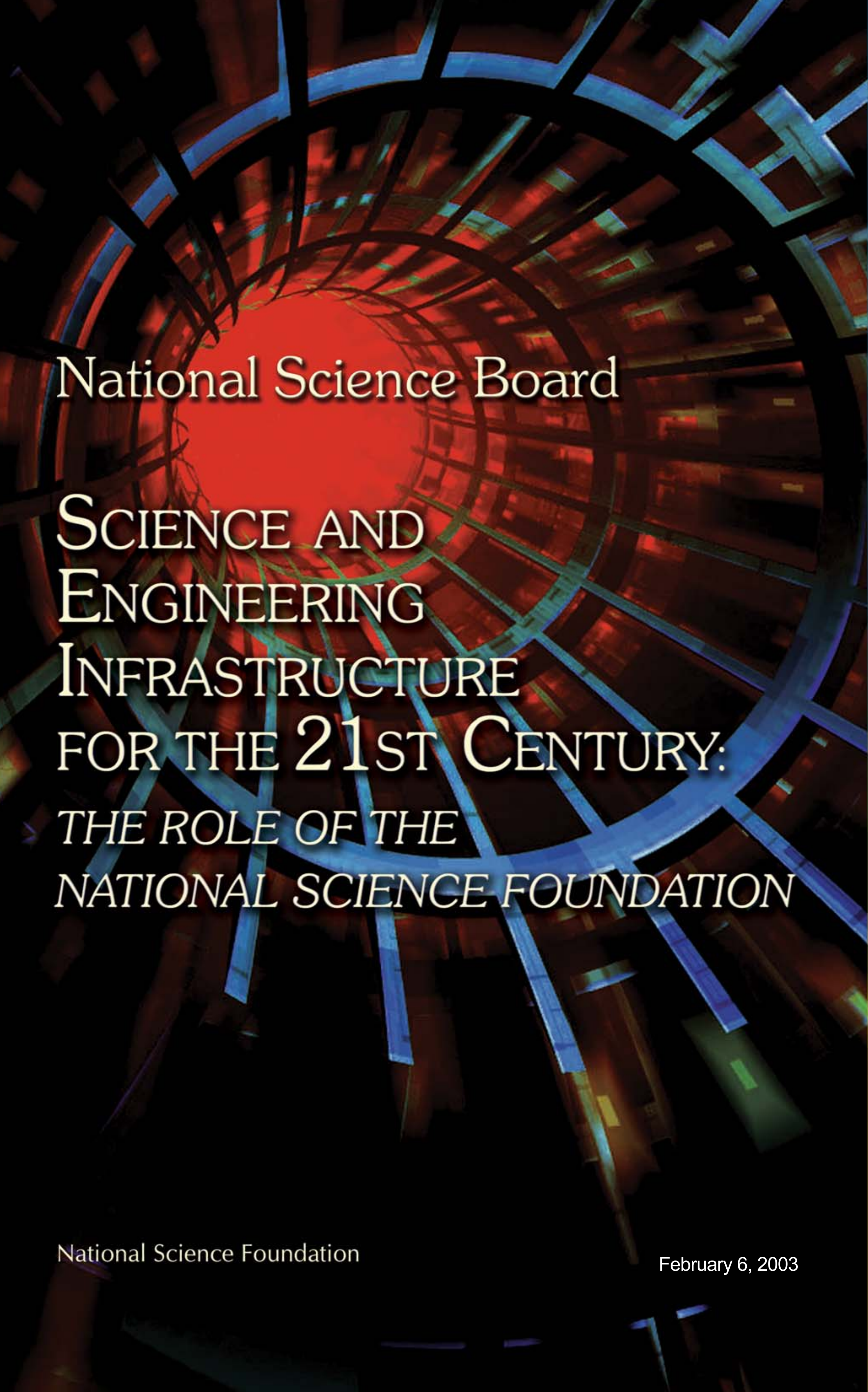

National Science Board

Science and Engineering Infrastructure for the 21st Century:

The Role of the National Science Foundation

National Science Foundation

February 6, 2003

NSB

NSB 02-190

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The National Science Board consists of 24 members plus the Director of the National Science Foundation. Appointed by the President, the Board serves as the policy-making body of the Foundation and provides advice to the President and the Congress on matters of national science and engineering policy.

National Science Board
Committee On Programs and Plans
Task Force On Science and Engineering Infrastructure

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Contents

Preface

Experimental and observational research depends upon the quality of the infrastructure and the tools that are accessible to the researcher. Modern tools provide more coverage, more precision and more accuracy for experiments and observations. Indeed, some modern tools open experimental vistas that are closed to those lacking modern infrastructure and tools.

Fueled by exponential growth in computing power, communication bandwidth, and data storage, the Nation's research infrastructure is increasingly characterized by interconnected, distributed systems of hardware, software, information bases, and expert systems. The new research tools arising from this activity enable scientists and engineers to be more productive and to approach more complex and different frontier tasks than they could in the past. Also, because of their distributed character, these tools are becoming more accessible to increasing numbers of researchers and educators across the Nation, thus putting more ideas to work.

This change has created unprecedented challenges and opportunities for 21st century scientists and engineers. Consequently, in September 2000, the National Science Board established the Task Force on Science and Engineering Infrastructure within its Committee on Programs and Plans. The task force was created to assess the current state of U.S. S&E academic research infrastructure, examine its role in enabling S&E advances, and identify requirements for a future infrastructure capability.

This report, *Science and Engineering Infrastructure for the 21st Century*, presents the findings and recommendations developed by the task force and approved unanimously by the National Science Board. The report aims to inform the national dialogue on S&E infrastructure and highlight the role of NSF as well as the larger resource and management strategies of interest to Federal policymakers.

On behalf of the National Science Board, I wish to commend Dr. John White, the chair of the task force, and the other task force members – Dr. Anita Jones, Dr. Jane Lubchenco, Dr. Robert Richardson, Dr. Michael Rossmann, and Dr. Mark Wrighton of the National Science Board, and Dr. Mary Clutter, NSF Assistant Director for Biological Sciences. Mr. Paul Herer of the NSF Office of Integrative Activities provided superb and tireless support as the executive secretary to the task force.

The Board is especially grateful for the strong support provided throughout by the Director of the National Science Foundation, Dr. Rita Colwell, and by NSF's Deputy Director, Dr. Joseph Bordogna.

Warren M. Washington
Chair, National Science Board

Acknowledgements

Several of our colleagues were critical to initiation of the National Science Board's study. These include former National Science Board (NSB) Chair Eamon Kelly, and former Chairman of the NSB Committee on Programs and Plans, John Armstrong, who oversaw the initial phase of this inquiry. Extensive contributions were also made by former members of the Task Force on Science and Engineering Infrastructure (INF): Robert Eisenstein, Vera Rubin, and Warren Washington. Later, Dr. Washington, as NSB Chair, helped to guide this study to its completion.

A number of people assisted the task force as speakers and presenters, including Daniel Atkins, University of Michigan; Robin Staffin, Department of Energy; and William Stamper, National Aeronautics and Space Administration. We also wish to thank Office of Management and Budget staff, Sarah Horrigan and David Radzanowski, and Office of Science and Technology Policy staff, Michael Holland, who encouraged us and helped shape the direction of our inquiry in numerous productive conversations.

We appreciate the unstinting support of National Science Foundation (NSF) staff. In particular, the NSF Assistant Directors and office heads, former and current, worked closely with the task force, frequently submitting written documents, making presentations, and participating in meetings. We would like to thank NSF staff members Stephanie Bianchi, Leslie Christovich, Pamela Green, Stephen Mahaney, and Brett Mervis, all of whom made unique contributions to the report. We also thank the NSB Office staff who guided and supported all aspects of the Board's effort, including Gerard Glaser, Marta Cehelsky, Janice Baker, Catherine Hines, Jean Pomeroy, and Robert Webber.

Finally, we are grateful for the participation of many members of the science and engineering community who provided helpful comments and suggestions when the draft report was released for public comment on the NSF/NSB Web site. (These individuals are listed in Appendix C.)

Executive Summary

This report, based on a study conducted by the National Science Board (NSB), aims to inform the national dialogue on the current state and future direction of the science and engineering (S&E) infrastructure. It highlights the role of the National Science Foundation (NSF) as well as the larger resource and management strategies of interest to Federal policymakers in both the executive and legislative branches.

Context and Framework for the Study

There can be no doubt that a modern and effective research infrastructure is critical to maintaining U.S. leadership in S&E. New tools have opened vast research frontiers and fueled technological innovation in fields such as biotechnology, nanotechnology, and communications. The degree to which infrastructure is regarded as central to experimental research is indicated by the number of Nobel Prizes awarded for the development of new instrument technology. During the past twenty years, eight Nobel Prizes in physics were awarded for technologies such as the electron and scanning tunneling microscopes, laser and neutron spectroscopy, particle detectors, and the integrated circuit.[1]

Recent concepts of infrastructure are expanding to include distributed systems of hardware, software, information bases, and automated aids for data analysis and interpretation. Enabled by information technology, a qualitatively different and new S&E infrastructure has evolved, delivering greater computational power, increased access, distribution and shared use, and new research tools, such as data analysis and interpretation aids, Web-accessible databases, archives, and collaboratories. Many viable research questions can be answered only through the use of new generations of these powerful tools.

Among Federal agencies, NSF is a leader in providing the academic community with access to forefront instrumentation and facilities. Much of this infrastructure is intended to address currently intractable research questions, the answers to which may transform current scientific thinking. In an era of fast-paced discovery, it is imperative that NSF's infrastructure investments provide the maximum benefit to the entire S&E community. NSF must be prepared to assume a greater S&E infrastructure role for the benefit of the Nation.

[1] Nobel e-Museum (http://www.nobel.se).

Strategy for the Conduct of the Study

The Board, through its Task Force on S&E Infrastructure (INF), engaged in a number of activities designed to assess the general state and direction of the academic research infrastructure and illuminate the most promising future opportunities. These activities included reviewing the current literature, analyzing quantitative survey data, soliciting input from experts in the S&E community, discussing infrastructure topics with representatives from the Office of Management and Budget (OMB), Office of Science and Technology Policy (OSTP), and other Federal agencies, and surveying NSF's principal directorates and offices on S&E infrastructure needs and opportunities. A draft report was released for public comment on the NSB/NSF Web site. Many comments were received and carefully considered in producing the final draft of this report (see Appendix C).

Principal Findings and Recommendations

Over the past decade, the funding for academic research infrastructure has not kept pace with rapidly changing technology, expanding research opportunities, and increasing numbers of users. Information technology and other technologies have enabled the development of many new S&E tools and made others more powerful, remotely usable, and connectable. The new tools being developed make researchers more productive and able to do more complex and different tasks than they could in the past. An increasing number of researchers and educators, working as individuals and in groups, need to be connected to a sophisticated array of facilities, instruments, databases, technical literature and data. Hence, there is an urgent need to increase Federal investments to provide access for scientists and engineers to the latest and best S&E infrastructure, as well as to update infrastructure currently in place.

To address these concerns, the Board makes the following five recommendations[2]:

Recommendation 1:

Increase the share of the NSF budget devoted to S&E infrastructure in order to provide individual investigators and groups of investigators with the tools they need to work at the frontier.

The current 22 percent of the NSF budget devoted to infrastructure is too low to provide adequate small- and medium-scale infrastructure and needed investment in cyberinfrastructure. A share closer to the higher end of the historic range (22–27 percent) is desirable. It is hoped that significant additional resources for infrastructure will be provided through future growth of the NSF budget.

[2] The NSB will periodically assess the implementation of these recommendations.

Recommendation 2:

Give special emphasis to the following four categories of infrastructure needs:[3]

- **Increase research to advance instrument technology and build next-generation observational, communications, data analysis and interpretation, and other computational tools.**

Instrumentation research is often difficult and risky, requiring the successful integration of theoretical knowledge, engineering and software design, and information technology. In contrast to most other infrastructure technologies, commercially available data analysis and data interpretation software typically lags well behind university-developed software, which is often not funded or under funded, limiting its use and accessibility. This research will accelerate the development of instrument technology to ensure that future research instruments and tools are as efficient and effective as possible.

- **Address the increased need for midsize infrastructure.**

While there are special NSF programs for addressing “small” and “large” infrastructure needs, none exist for infrastructure projects costing between millions and tens of millions of dollars. This report cites numerous examples of unfunded midsize infrastructure needs that have long been identified as high priorities. NSF should increase the level of funding for midsize infrastructure, as well as develop new funding mechanisms, as appropriate, to support midsize projects.

- **Increase support for large facility projects.**

Several large facility projects have been approved for funding by the NSB but have not been funded. At present, an annual investment of at least $350 million is needed over several years to address the backlog of facility projects construction. Postponing this investment now will not only increase the future cost of these projects but also result in the loss of U.S. leadership in key research fields.

- **Develop and deploy an advanced cyberinfrastructure to enable new S&E in the 21st century.**

This investment should address leading-edge computation as well as visualization facilities, data analysis and interpretation toolkits and workbenches, data archives and libraries, and networks of much greater power and in substantially greater quantity. Providing access to moderate-cost computation, storage, analysis, visualization, and communication for every researcher will lead to an even more productive national research enterprise. Design of these new technologies and capabilities must be guided by the needs of a variety of potential users, including scientists and engineers from many

[3] The order of presentation does not imply a priority ranking.

disciplines. This important undertaking requires a significant investment in software and technical staff, as well as hardware. This new infrastructure will play a critical role in creating tomorrow's research vistas.

Recommendation 3:

Expand education and training opportunities at new and existing research facilities.

Investment in S&E infrastructure is critical to developing a 21st century S&E workforce. Education, training and outreach activities should be vital elements of all major research facility programs. Educating people to understand how S&E instruments and facilities work and how they uniquely contribute to knowledge in their targeted disciplines is critical. Outreach should span many diverse communities, including existing researchers and educators who may become new users, undergraduate and graduate students who may design and use future instruments, and kindergarten through grade twelve (K-12) students, who may be motivated to become scientists and engineers. There are also opportunities to expand access to state-of-the-art S&E infrastructure to faculty and students at primarily undergraduate colleges and universities.

Recommendation 4:

Strengthen the infrastructure planning and budgeting process through the following actions:

- Foster systematic assessments of U.S. academic research infrastructure needs for both disciplinary and cross-disciplinary fields of research. Re-assess current surveys of infrastructure needs to determine if they fully measure and are responsive to current requirements.

- Develop specific criteria and indicators to assist in establishing priorities and balancing infrastructure investments across S&E disciplines and fields.

- Develop and implement budgets for infrastructure projects that include the total costs to be incurred over the entire life-cycle of the project, including research, planning, design, construction, commissioning, maintenance, operations, and, to the extent possible, research funding.

- Conduct an assessment to determine the most effective NSF budget structure for supporting S&E infrastructure projects throughout their life-cycles, including the early research and development that is often difficult and risky.

Because of the need for the Federal Government to act holistically in addressing the requirements of the Nation's science and engineering enterprise, the Board developed a fifth recommendation, aimed principally at the Office of Management and Budget (OMB), the Office of Science and Technology Policy (OSTP), and the National Science and Technology Council (NSTC).

RECOMMENDATION 5:

Develop interagency plans and strategies to do the following:

- Work with the relevant Federal agencies and the S&E community to establish interagency infrastructure priorities that rely on competitive merit review to select S&E infrastructure projects.
- Stimulate the development and deployment of new infrastructure technologies to foster a new decade of infrastructure innovation.
- Develop the next generation of the high-end high-performance computing and networking infrastructure needed to enable a broadly based S&E community to work at the research frontier.
- Facilitate international partnerships to enable the mutual support and use of research facilities across national boundaries.
- Protect the Nation's massive investment in S&E infrastructure against accidental or malicious attacks and misuse.

CONCLUSION

Rapidly changing infrastructure technology has simultaneously created a challenge and an opportunity for the U.S. S&E enterprise. The challenge is how to maintain and revitalize an academic research infrastructure that has eroded over many years due to obsolescence and chronic underinvestment. The opportunity is to build a new infrastructure that will create future research frontiers and enable a broader segment of the S&E community. The challenge and opportunity must be addressed by an integrated strategy. As current infrastructure is replaced and upgraded, the next-generation infrastructure must be created. The young people who are trained using state-of-the-art instruments and facilities are the ones who will demand and create the new tools and make the breakthroughs that will extend the science and technology envelope. Training these young people will ensure that the U.S. maintains international leadership in the key scientific and engineering fields that are vital for a strong economy, social order, and national security.

CHAPTER ONE

INTRODUCTION

BACKGROUND

Since the beginning of civilization, the tools humans invented and used have enabled them to pursue and realize their dreams. New tools have opened vast research and education vistas and enabled scientists and engineers to explore new regimes of time and space. Advanced techniques in areas such as microscopy, spectroscopy, and laser technology have made it possible to image and manipulate individual atoms and fabricate new materials. Advances in radio astronomy and instrumentation at the South Pole have allowed scientists to probe the furthest reaches of time and space and unlock secrets of the universe. Communications and computational technologies, such as interoperable databases and informatics, are revolutionizing such fields as biology and the social sciences. With the advent of high-speed computer-communication networks, greater numbers of educational institutions now have access to cutting-edge research and education tools and infrastructure.

The National Science Board commissioned this study in September 2000 to assess the current state of U.S. S&E academic research infrastructure, examine its role in enabling S&E advances, and identify requirements for a future capability of appropriate quality and size to ensure continuing U.S. S&E leadership. This report aims to inform the national dialogue on S&E infrastructure and highlight the role of NSF as well as the larger resource and management strategies of interest to Federal policymakers in both the executive and legislative branches.

It is useful to distinguish between the terms "tool" and "infrastructure." *Webster's Third New International Dictionary* provides only one definition of infrastructure: "an underlying foundation or basic framework (as of an organization or system)." It provides many definitions of tool, the most applicable being "anything used as a means of accomplishing a task or purpose." Given these definitions, it may be useful to assume that infrastructure not only includes tools but also provides the basis, foundation, and/or support for the creation of tools.

"Research infrastructure" is a term that is commonly used to describe the tools, services, and installations that are needed for the science and engineering (S&E) research community to function and for researchers to do their work. For the purposes of this study, it includes: (1) hardware (tools, equipment, instrumentation, platforms and facilities), (2) software (enabling computer systems, libraries, databases, data analysis and data interpretation systems, and communication networks), (3) the technical support (human or automated) and services needed to operate the infrastructure and keep it working effectively, and (4) the special environments and installations (such as buildings and research space) necessary to effectively create, deploy, access, and use the research tools.[4]

An increasing amount of the equipment and systems that enable the advancement of research are large-scale, complex, and costly. "Facility" is frequently used to describe such equipment because typically the equipment requires special sites or buildings to house it and a dedicated staff to effectively maintain the equipment. Increasingly, many researchers working in related disciplines share the use of such large facilities, either on site or remotely. "Cyberinfrastructure" is used in this report to connote a comprehensive infrastructure based upon distributed networks of computers, information resources, online instruments, data analysis and interpretation tools, relevant computerized tutorials for the use of such technology, and human interfaces. The term provides a way to discuss the infrastructure enabled by distributed computer-communications technology in contrast to the more traditional physical infrastructure.[5]

There can be no doubt that a modern and effective research infrastructure is critical to maintaining U.S. leadership in S&E. The degree to which infrastructure is regarded as central to experimental research is indicated by the number of Nobel Prizes awarded for the development of new instrument technology. During the past 20 years, eight Nobel Prizes in physics were awarded for technologies such as the electron and scanning tunneling microscopes, laser and neutron spectroscopy, particle detectors, and the integrated circuit.[6]

Much has changed since the last major assessments of the academic S&E infrastructure were conducted over a decade ago. For example:

- Research questions require approaches that are increasingly multidisciplinary and involve a broader spectrum of disciplines. Collaboration among disciplines is increasing at an unprecedented rate.

- Researchers are addressing phenomena that are beyond the temporal and spatial limits of current measurement capabilities. Many viable research questions can be answered only through the use of new generations of powerful tools.

- Enabled by information technology (IT), a qualitatively different and new S&E infrastructure has evolved, delivering greater computational power, increased access, distribution and shared use, and new research tools, such as flexible, programmable statistics packages, many forms of automated aids for data interpretation, and Web-accessible databases, archives, and collaboratories. IT enables the collection and processing of

[4] As used in this report, research infrastructure does not include the S&E workforce of researchers, educators and other professionals, i.e. what is commonly referred to as the "human infrastructure."
[5] Report of the NSF Advisory Panel on Cyberinfrastructure, *Revolutionizing Science and Engineering through Cyberinfrastructure,* Dan Atkins (Chair), National Science Foundation, Arlington, Virginia, February 2003.
[6] Nobel e-Museum (http://www.nobel.se).

data that could not have been collected or processed before. Increasingly, researchers are expressing a compelling need for access to these new IT-based research tools.

- International cooperation and partnerships are increasingly used to construct and operate large and costly research facilities. With many international projects looming on the horizon, the U.S. Congress and the Office of Management and Budget (OMB) are concerned about the management of these complex relationships.

- The reality of today's world requires that academe secure its research infrastructure and institute safeguards for its working environment and critical systems. Issues are also being raised about the security of information developed by scientists and engineers, such as genomic databases.

These changes have created unprecedented challenges and opportunities for 21st century scientists and engineers. Consequently, the National Science Board (NSB) determined that a fresh assessment of the national infrastructure for academic S&E research was needed to ensure its future quality and availability.

The Charge to the Task Force

In September 2000 the NSB established the Task Force on Science and Engineering Infrastructure (INF), under the auspices of its Committee on Programs and Plans (CPP). In summary, the INF was charged to:

"Undertake and guide an assessment of the fundamental science and engineering infrastructure in the United States...with the aim of informing the national dialogue on S&E infrastructure, highlighting the role of NSF and the larger resource and management strategies of interest to Federal policymakers in both the executive and legislative branches. The workplan should enable an assessment of the current status of the national S&E infrastructure, the changing needs of science and engineering, and the requirements for a capability of appropriate quality and size to insure continuing U.S. leadership."[7]

In its early organizing meetings and in discussions with the CPP, the INF defined the scope and terms of reference for the study. Because the charge focused on "fundamental science and engineering," the INF decided to address primarily the infrastructure needs of the academic research community, including infrastructure at national laboratories or in other countries, as long as it served the needs of academic researchers. The INF also determined that the study should focus on "research" infrastructure, in contrast to

[7] The complete charge to the INF is included in Appendix A.

infrastructure serving purely educational purposes, such as classrooms, teaching laboratories, and training facilities. However, the INF recognized that many cutting-edge research facilities are “dual use,” in that they provide excellent opportunities for education and training as well as research. Such infrastructure was included within this study.

Finally, while the study was concerned with the status of the entire academic research infrastructure, the task force decided that it should provide an in-depth analysis of NSF’s infrastructure policies, programs, and activities, including a look at future needs, challenges and opportunities. This approach was taken for the purpose of providing specific advice to the NSF Director and the National Science Board. While other research and development (R&D) agencies, such as the National Aeronautics and Space Administration (NASA), Department of Energy (DoE), Department of Defense (DoD), and National Institutes of Health (NIH) play an important role in serving the infrastructure needs of academic researchers, detailed analyses of their infrastructure support programs are not provided in this report.

STRATEGY FOR CONDUCTING THE STUDY

In responding to its charge, the task force recognized certain limits in what it could do. Conducting a new comprehensive survey of academic institutions was not deemed to be practical, in that it would take too much time to accomplish. As an alternative, the INF engaged in a number of parallel activities designed to assess the general state and direction of the academic research infrastructure and illuminate the most promising future opportunities. The principal activities were the following:

- The INF surveyed the current literature, including reviewing and considering the findings of more than 60 reports, studies, and planning documents.[8]
- Representatives from other agencies, such as NASA, DoE, OMB and the Office of Science and Technology Policy (OSTP) made presentations to the INF and responded to many questions. In addition, specialists were invited to address the task force on relevant topics at several meetings.
- The seven NSF directorates[9] and the Office of Polar Programs (OPP) provided assessments of the current state of the research infrastructure serving the S&E fields they support, as well as an assessment of future infrastructure needs and opportunities through 2010. Senior staff in these organizations also made presentations and supplied additional material to the task force and frequently attended its meetings.
- On numerous occasions, drafts of the report were presented to and discussed with the NSF Director's Policy Group, the NSB Committee on Programs and Plans, and the full National Science Board.
- The draft report was then released for public comment on the NSB/NSF Web site. Many comments were received.[10] Feedback from a wide range of sources was carefully considered in producing the final draft of this report, which was unanimously approved by the NSB on February 6, 2003.

[8] This literature list appears in Appendix B.
[9] The seven directorates are Biological Sciences (BIO); Computer and Information Science and Engineering (CISE); Education and Human Resources (EHR); Engineering (ENG); Geosciences (GEO); Mathematical and Physical Sciences (MPS); and Social, Behavioral, and Economic Sciences (SBE).
[10] See Appendix C for Sources of Public Comment.

CHAPTER TWO

THE CONTEXT FOR S&E INFRASTRUCTURE

HISTORY AND CURRENT STATUS

Today S&E research is carried out in laboratories supported by government, academe, and industry. Before 1900, however, there were relatively few government-supported research activities. In 1862 Congress passed the Morrill Act, which made it possible for the many new States to establish agricultural and technical (land-grant) colleges for their citizens. Although originally started as technical colleges, many of them grew, with additional State and Federal aid, into large public universities with premier research programs.

Before World War II, universities were regarded as peripheral to the Federal research enterprise. In the years between World War I and World War II, the immigration of scientists from Europe helped to develop American superiority in fields such as physics and engineering. World War II dramatically expanded Federal support for academic and industrial R&D. The war presented a scientific and engineering challenge to the United States - to provide weapons based on advanced concepts and new discoveries that would help defeat the enemy. Large national laboratories, such as Los Alamos National Laboratory, were founded in the midst of the war.

The modern research university came of age after World War II when the Federal Government decided that sustained investments in science would improve the lives of citizens and the security of the Nation. The Federal Government increased its support for students in higher education through programs such as the GI bill. It also established NSF in 1950 and NASA in 1957. An infusion of Federal funds made it possible for universities to purchase the increasingly expensive scientific equipment and advanced instrumentation that were central to the expansion of both the R&D and teaching functions of the university.

The advent of the cold war combined with the wartime demonstration of the significant potential for commercial and military applications of scientific research led to vast increases in government funding for R&D in defense-related technologies. The result was a significant expansion of the R&D facilities of private firms and government laboratories. Concomitantly, the Federal

Government increased its support for academic research and the infrastructure required to support it.[11]

The U.S. government has been a partner with industry and academe in creating the S&E infrastructure for many critical new industries, ranging from agriculture to aircraft to biotechnology to computing and communications. This infrastructure extends across the Earth's oceans, throughout its skies, and from pole to pole. Most of the Nation's academic research infrastructure is now distributed throughout nearly 700 institutions of higher education; and it extends into more than 200 Federal laboratories and hundreds of nonprofit research institutions. Many of these laboratories have traditions of shared use by researchers and students from the Nation's universities and colleges. In this role, participating Federal laboratories have become extensions of the academic research infrastructure.

DETECTING GRAVITY WAVES

Laser Interferometer Gravitational Wave Observatories in Hanford, Washington, and Livingston, Louisiana, attempt to detect gravity waves reaching Earth from a host of cataclysmic cosmic phenomena. Detection would allow scientists to observe such phenomena as the collisions and coalescences of neutron stars and black holes, supernovae, and other cosmic processes. The observatories' educational activities involve large numbers of students and teachers from grade school through doctoral studies. CREDIT: California Institute of Technology

[11] This history is based heavily on two sources: (1) David C. Mowery and Nathan Rosenberg, "U.S. National Innovation System" in *National Innovation Systems: A Comparative Analysis*, ed. Richard R. Nelson, Oxford University Press, 1993; and (2) Vannevar Bush, Office of Scientific Research and Development, *Science – The Endless Frontier, A Report to the President on a Program for Postwar Scientific Research*, July 1945 (NSF 90-8).

Assessing the current status of the academic research infrastructure is a difficult undertaking. Periodic surveys of universities and colleges attempt to address various aspects of this infrastructure. But the gaps in the information collected and analyzed leave many important questions unanswered.

EXPENDITURES FOR ACADEMIC EQUIPMENT AND INSTRUMENTATION

A national survey of academic research instrumentation needs, conducted nearly a decade ago, provides the latest available information on annual expenditures for instruments with a total cost of $20,000 or more. As indicated in Table 1, in 1993, the purchase of academic research instrumentation totaled $1,203 million, an increase of 6 percent over the amount reported in the previous survey in 1988. The Federal Government provided $624 million, or 52 percent of the total.

TABLE 1.
1993 EXPENDITURES FOR PURCHASE OF ACADEMIC RESEARCH INSTRUMENTATION

	$ Millions	% Total
All Sources of Support	1,203	100%
Federal Sources	624	52%
NSF	213	18%
NIH	117	10%
DoD	106	9%
Other Agencies	186	15%
Non-Federal Sources	580	48%
Academic Institutions	292	24%
State Government	102	8%
Foundations, Bonds and Private Donations	105	9%
Industry	80	7%

SOURCE: Academic Research Instruments: Expenditures 1993, Needs 1994, NSF-96-324.

NSF provided $213 million in support of research infrastructure during 1993, while NIH provided $117 million and DoD contributed $106 million. Of the non-federal sources of funding, the largest single source came from the academic institutions. A sizable contribution of $105 million came from private, non-profit foundations, gifts, bonds, and other donations.

A more recent survey of academic R&D expenditures reveals that, in 1999, slightly more than $1.3 billion in current funds was spent for academic research equipment.[12] Such expenditures grew at an average annual rate of 4.2 percent (in constant 1996 dollars) between 1983 and 1999. The share of research

[12] Research equipment received either as part of research grants or as separate equipment grants.

equipment expenditures funded by the Federal Government declined from 62 percent to 58 percent between 1983 and 1999. In addition, total annual R&D equipment expenditures as a percentage of total R&D expenditures were lower in 1999 (5 percent) than they were in 1983 (6 percent).[13] As a point of comparison, during the past decade NSF support of equipment within a research grant has declined from 6.9 percent to 4.4 percent of the total grant budget.[14]

CAPITAL RESEARCH CONSTRUCTION

Biennual surveys of U.S. research-performing colleges and universities reveal how these institutions fund capital research construction (costing $100,000 or more), in contrast to research instrumentation. The Federal Government's contribution to construction funds at the Nation's research-performing colleges and universities has varied over the past decade. In 1986-87 it accounted for 6 percent of total funds for new construction and repair/renovation of research facilities at public and private universities and colleges. This percentage increased steadily to 14.1 percent in 1992-93 and then declined to 8.8 percent in 1996-97. Recent data indicate this percentage declined to 6.2 percent in 1998-99.[15]

Table 2 indicates that, in 1996-97, research-performing institutions derived their S&E capital projects funds from three major sources: the Federal Government, State and local governments, and other institutional resources (consisting of private donations, institutional funds, tax-exempt bonds, and other sources).

TABLE 2.
SOURCES OF FUNDS TO CONSTRUCT AND REPAIR/RENOVATE S&E RESEARCH SPACE: 1996-97

Source of Funds	Percent of funds for new construction	Percent of funds for repair/renovation
Federal Government	8.7%	9.1%
State/Local Government	31.1%	25.5%
Other Institutional Resources	60.2%	65.4%
TOTAL	100%	100%
TOTAL COST	$3.1 billion	$1.3 billion

NOTE: Only projects costing $100,000 or more

SOURCE: National Science Foundation/SRS, 1998 Survey of Scientific and Engineering Research Facilities at Colleges and Universities.

The Federal Government directly accounted for 8.7 percent of all new construction funds ($271 million) and 9.1 percent ($121 million) of all repair/renovation funds. Additionally, some Federal funding was provided through

[13] NSF, *Academic Science and Engineering R&D Expenditures: Fiscal Year 1999, Detailed Statistical Tables*, NSF 01-329; and NSF, unpublished tabulations.
[14] NSF Enterprise Information System (NSF proprietary data system).
[15] National Science Board, *Science and Engineering Indicators 2002*, NSB 02-1, January 2002.

indirect cost recovery on grants and/or contracts from the Federal Government. These overhead payments are used to defray the indirect costs of conducting federally funded research and are counted as institutional funding.

Another NSF survey representing 580 research-performing institutions[16] provides some information on the current amount, distribution and condition of academic research space, which includes laboratories, facilities, and major equipment costing at least $1 million. As Table 3 indicates, in 1988 there were 112 million net assignable square feet (NASF) of S&E research space. By 2001 the NASF had increased by 38 percent to 155 million NASF.

Table 3.
Academic Research Space by S&E Field, 1988-2001

Field	Net assignable square feet (NASF) in millions					% NASF reported as adequate	% Additional NASF needed
	1988	1992	1996	1999	2001	2001	2001
All fields	112	122	136	150	155	29%	27%
Agricultural sciences	18	20	22	25	27	30%	11%
Biological sciences	24	28	30	32	33	27%	32%
Computer sciences	1	2	2	2	2	27%	109%
Earth, atmospheric, and ocean sciences	6	7	7	8	8	38%	26%
Engineering	16	18	22	25	26	23%	26%
Medical sciences	19	22	25	27	28	23%	34%
Physical sciences & mathematics	17	17	19	20	20	33%	25%
Psychology & social sciences	6	6	7	9	9	38%	32%
Other sciences	4	2	2	3	3	72%	18%

NOTE: Components may not add to totals due to rounding.

SOURCE: Survey of Scientific and Engineering Research Facilities, 2001, NSF/SRS.

Doctorate-granting institutions represented 95 percent of the space, with the top 100 institutions having 71 percent and minority-serving institutions having 5 percent. In addition, 71 percent of institutions surveyed reported inadequate research space, while 51 percent reported a deficit of greater than 25 percent. The greatest deficit was reported by computer sciences, with only 27 percent of the space reported as adequate, and more than double the current space required to make up the perceived deficit. To meet their current research commitments, the research-performing institutions reported that they needed an additional 40 million NASF of S&E research space or 27 percent more than they had.

Maintaining the academic research infrastructure in a modern and effective state over the past decade has been especially challenging because of the increasing cost to construct and maintain research facilities and the

[16] NSF/SRS, *Scientific and Engineering Research Facilities, 2001, Detailed Statistical Tables*. NSF 02-307, 2002.

concomitant expansion of the research enterprise, with substantially greater numbers of faculty and students engaged in S&E research.[17]

The problem is exacerbated by the recurrent Federal funding of research below full economic cost, which has made it difficult for academic institutions to set aside sufficient funds for infrastructure maintenance and replacement. A recent RAND study estimated that the true cost of facilities and administration (F&A) for research projects is about 31 percent of the total Federal grant. Because of limits placed on Federal F&A rates, the share that the Federal Government actually pays is between 24 percent and 28 percent. This share amounts to between $0.7 billion and $1.5 billion in annual costs that are not reimbursed. Moreover, the infrastructure component in negotiated F&A rates has increased since the late 1980s, from under 6 percent in 1988 to almost 9 percent in 1999.[18]

UNMET NEEDS

Determining what colleges and universities *need* for S&E infrastructure is a difficult and complex task. Nevertheless, over the past decade a number of diverse studies and reports have charted a growing gap between the academic research infrastructure that is needed and the infrastructure provided. For example:

- A 1995 study by the National Science and Technology Council (NSTC) indicated that the academic research infrastructure in the U.S. is in need of significant renewal, conservatively estimating the facilities and instrumentation needed to make up the deficit at $8.7 billion.[19]

- In 1998, an NSF survey estimated costs for deferred capital projects to construct, repair, or renovate academic research facilities at $11.4 billion, including $7.0 billion to construct new facilities and $4.4 billion to repair/renovate existing facilities.[20]

- A 2001 report to the Director of NIH estimated that $5.6 billion was required to address inadequate and/or outdated biomedical research infrastructure. The report recommended new funds for NIH facility improvement grants in FY 2002, a Federal loan guarantee program to support facility construction and renovation, and the removal of arbitrary caps of the Federal F&A rate.[21]

- In 2001, the Director of NASA reported a $900 million construction backlog and said that $2 billion more was needed to revitalize and modernize research infrastructure.[22]

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[17] The number of doctoral-level academic researchers increased from 82,300 in 1973 to 150,100 in 1993, and to 168,100 in 1999. *S&E Indicators 2002,* 5-23.
[18] Charles A. Goldman and T. Williams, *Paying for University Research Facilities and Administration*, RAND, (MR-1135-1-OSTP), Washington, D.C., 2000.
[19] National Science and Technology Council, *Final Report on Academic Research Infrastructure: A Federal Plan for Renewal*, Washington D.C., March 17, 1995.
[20] NSF Division of Science Resources Statistics, *Science and Engineering Research Facilities at Colleges and Universities, 1998*, NSF-01-301, October 2000.
[21] NIH Working Group on Construction of Research Facilities, *A Report to the Advisory Committee of the Director,* National Institutes of Health, July 6, 2001.
[22] Daniel S. Goldin, *Aerospace Daily*, October 17, 2001.

- A recent study indicated that DoE's Office of Science laboratories and facilities, many of which are operated by universities, are aging and in disrepair – over 60 percent of the space is more than 30 years old. A DoE strategic plan identified more than $2 billion of needed capital investment projects over the next 10 years (FY 2002 through FY 2011).[23]

- In FY 2001 an informal survey of NSF directorates and the OPP estimated that future academic S&E infrastructure needs through 2010 would cost an additional $18 billion.[24]

- An NSF blue-ribbon advisory panel recently estimated that an additional $850 million per year in cyberinfrastructure would be needed to sustain the ongoing revolution in S&E.[25]

ENGINEERING LIVING TISSUE

At Georgia Tech/Emory Center for the Engineering of Living Tissues, an NSF Engineering Research Center, graduate students examine a sample in a bioreactor for potential use in engineering cartilage tissue. Ultimately this work will lead to biological (non-synthetic) devices for organ and tissue replacement, repair, and therapeutic uses in the human body. CREDIT: Georgia Tech/ Emory Center for Engineering of Living Tissue

While these surveys and studies provide a rough measure of the magnitude of the problem, they say little about the cost of lost S&E opportunities. In a number of critical research fields, the lack of quality infrastructure is limiting S&E progress. For example:

- The lack of long-term stable support for "wetware" archives is preventing more rapid advances in post-genomic discoveries.

- The lack of a large-scale network infrastructure in which the next generation of secure network protocols and architectures could be developed and tested will hamper any significant deployment of these applications.

[23] U.S. Department of Energy, *Infrastructure Frontier: A Quick Look Survey of the Office of Science Laboratory Infrastructure*, April 2001.
[24] Unpublished internal survey of NSF directorates.
[25] Report of the NSF Advisory Panel on Cyberinfrastructure, Daniel E. Atkins (Chair), *Revolutionizing Science and Engineering through Cyberinfrastructure,* National Science Foundation, February 2003.

- The lack of support for new social science surveys, especially the collection of data in foreign countries, is limiting our scientific understanding of political events, human opinion and behavior.

- The lack of synchrotron radiation facilities with orders-of-magnitude increase in luminosity is limiting our ability to extend the frontiers in such areas as structural biology, genomics, proteomics, materials, and nanoscience.

THE IMPORTANCE OF PARTNERSHIPS

The international dimensions of research and education are increasingly essential to U.S. science and engineering. As S&E infrastructure projects grow in size, cost, and complexity, collaboration and partnerships are increasingly required to enable them. These partnerships increase both the quality of the research enterprise and its impact on the economy and society.

The very nature of the S&E enterprise is global, often requiring access to geographically dispersed materials, phenomena, and expertise, as well as collaborative logistical support. It also requires open and timely communication, sharing, and validation of findings, data, and data analysis procedures. Projects in areas such as global change, genomics, astronomy, space exploration, and high-energy physics have a global reach and often require expertise and resources that no single country possesses. Further, the increasing cost of large-scale facilities often requires nations to share the expense.

LISTENING TO THE UNIVERSE

The Atacama Large Millimeter Array (ALMA) will be the world's most sensitive, highest resolution millimeter wavelength radio telescope. It will consist of sixty-four 12-meter diameter reflector antennas built on a high (5000 meters) site near the village of San Pedro de Atacama, Chile, by an international partnership. The U.S. side of the project is run by the National Radio Astronomy Observatory, operated by Associated Universities, Inc. under cooperative agreement with NSF. The international partners include Canada and the European Southern Observatory. CREDIT: European Southern Observatory

INTO THE LOOKING GLASS

NSF provides the world's astronomers with two identical 8-meter telescopes in Hawaii and Chile, known as the Gemini Observatory. Shown here is the mirror of the telescope at Mauna Kea, Hawaii. The telescope is optimized for observations in infrared light. The thin mirror is sufficiently flexible that its shape can be continuously adjusted to correct for distortion caused by the atmosphere. The observatory is an international collaboration with the United Kingdom, Canada, Australia, Chile, Argentina, and Brazil. CREDIT: NSF/The Association of Universities for Research in Astronomy/National Optical Astronomy Observatories

The number of government-funded infrastructure projects that entail international collaboration has increased steadily over the last decade. For example, NSF currently supports a substantial and growing number of projects with international partnering. Among them are the twin Gemini Telescopes, the Large Hadron Collider, the IceCube Neutrino Observatory at the South Pole, the Laser Interferometer Gravitational Wave Observatory, the Ocean Drilling Program, and the Atacama Large Millimeter Array.

In the future, a growing number of large infrastructure projects will be carried out through international collaborations and partnerships. The Internet, the World Wide Web, and other large distributed and networked databases will facilitate this trend by channeling new technologies, researchers, users, and resources from around the globe.[26]

All large future infrastructure projects should be considered from the perspective of potential international partnering, or at a minimum of close cooperation regarding competing national-scale projects. An additional challenge is maintaining interest in and political support for long-term international projects. Any absence of follow through on high-profile projects could increase the danger of the U.S. becoming known as an unreliable international partner.

Interagency coordination of large infrastructure projects is also extremely important. For example, successful management of the U.S. astronomy and astrophysics research enterprise requires close coordination among NASA, NSF, DoD, DoE and many private and State-supported facilities. Likewise,

[26] NSB, *Toward a More Effective Role for the U.S. Government in International Science and Engineering,* NSB-01-187. November 2001.

SCIENCE AT THE SOUTH POLE

At the Amundsen-Scott South Pole Station, the new station that is still under construction stands beside the almost-buried geodesic dome of the old station. The station will support 150 people and research ranging from astrophysics to microbiology and climatology. CREDIT: NSF/USAP photo by SSGT Lee Harshman, U.S. Air Force, February 2003

implementation of the U.S. polar research program, which NSF leads, requires the coordination of many Federal agencies and nations. University access to the facilities of many of the national laboratories has been facilitated through interagency agreements. There are a number of models for effective interagency coordination, such as committees and subcommittees of the White House-led NSTC.

In the fields of high-energy and nuclear physics, NSF and DoE have developed an effective scheme that facilitates interagency coordination while simultaneously obtaining outside expert advice. The High Energy Physics Advisory Panel (HEPAP), supported by NSF and DoE, gives advice to the agencies on research priorities, funding levels, and balance, and provides a forum for DoE-NSF joint strategic planning. This scheme has facilitated joint DoE-NSF infrastructure projects. For example, the HEPAP-backed plan for U.S. participation in the European Large Hadron Collider has been credited with making that arrangement succeed.[27]

Partnerships have also played an important role in developing the genomics infrastructure. For example, the Human Genome Project, the Arabidopsis Genome Project, and the International Rice Sequencing Project have made vast amounts of genomic information available to researchers in the life sciences and other fields. Each of these projects was accomplished through a strong network of interagency and international partners.

[27] Committee on the Organization and Management of Research in Astronomy and Astrophysics, National Research Council, *U.S. Astronomy and Astrophysics: Managing an Integrated Program*, August 2001.

COLLIDING PARTICLES

The Large Hadron Collider, which is under construction at CERN, is expected to begin operating in 2005. NSF contributed to the construction of two high-energy particle accelerators: a large angle spectrometer and the compact muon solenoid. There is preliminary experimental evidence that the Higgs particle, the key to understanding mass, can be detected with the collider. CREDIT: Large Hadron Collider, European Organization for Nuclear Research (CERN)

Partnerships with the private sector also play an important role in facilitating the construction and operation of S&E infrastructure. For example, industrial firms have funded much of the equipment available in the Engineering Research Centers and the National Nanofabrication Users Network (NNUN). Public-private sector partnerships have also helped to enable the Internet, the Partnerships for Advanced Computational Infrastructure (PACI), and the TeraGrid Project.

THE NEXT DIMENSION

While there have been many significant breakthroughs in infrastructure development over the last decade, nothing has come close to matching the impact of IT and microelectronics. The rapid advances in IT have dramatically changed the way S&E information is gathered, stored, analyzed, presented, and communicated. These changes have led to a qualitative, as well as quantitative, change in the way research is performed. Instead of just doing the “old things” cheaper and faster, innovations in information, sensing, and communications are creating new, unanticipated activities, analysis, and knowledge. For example:

- Simulation of detailed physical phenomena - from subatomic to galactic and all levels in between - is possible; these simulations reveal new understanding of the world, e.g. protein folding and shape, weather, and galaxy formation. Databases and simulations also permit social and behavioral processes research to be conducted in new ways with greater objectivity and finer granularity than ever before.

- Researchers used to collect and analyze data from their own experiments and laboratories. Now, they can access results in shared archives, such as the protein data bank, and conduct research that utilizes information from vast networked data resources.

- Automated data analysis procedures of various kinds have been critical to the rapid development of genomics, climate research, astronomy, and other areas and will certainly play an even greater role with accumulation of ever-larger databases.

- Low-cost sensors, nano-sensors, and high-resolution imaging enable new, detailed data acquisition and analysis across the sciences and engineering - for environmental research, genomics, applications for health, and many other areas.

- The development of advanced robotics, including autonomous underwater vehicles and robotic aircraft, allows data collection from otherwise inaccessible locations, such as under polar ice. Advanced instrumentation makes it possible to adapt and revise a measuring protocol depending on the data being collected.

Research tools and facilities increasingly include digital computing capabilities. For example, telescopes now produce bits from control panels rather than photographs. Particle accelerators, gene sequencers, seismic sensors, and many other modern S&E tools also produce information bits. As with IT systems generally, these tools depend heavily on hardware and software.

The exponential growth in computing power, communication bandwidth, and data storage capacity will continue for the next decade. Currently, the U.S. Accelerated Strategic Computing Initiative (ASCI) has as its target the development of machines with 100 teraflop/second capabilities[28] by 2005. Soon many researchers will be able to work in the "peta" (10^{15}) range.[29] IT drivers - smaller, cheaper, and faster - will enable researchers in the near future to:

- Establish shared virtual and augmented reality environments independent of geographical distances between participants and the supporting data and computing systems.

- Integrate massive data sets, digital libraries, models, and analytical tools from many sources.

- Visualize, simulate, and model complex systems such as living cells and organisms, geological phenomena, and social structures.

With the advent of networking, information, computing, and communications technologies, the time is approaching when the entire scientific community will have access to these frontier instruments and infrastructure. Many applications

[28] A teraflop is a measure of a computer's speed and can be expressed as a trillion floating-point operations per second.
[29] UK Office of Science and Technology, *Large Facilities Strategic Road Map*, 2001.

have been and are being developed that take advantage of network infrastructure, such as research collaboratories, interactive distributed simulations, virtual reality platforms, control of remote instruments, field work and experiments, access to and visualization of large data sets,[30] and distance learning (via connection to infrastructure sites).[31]

Advances in computational techniques have already radically altered the research landscape in many S&E communities. For example, the biological sciences are undergoing a profound revolution, based largely on the enormous amount of data resulting from the determination of complete genomes. Genomics is now pervading all of biology and is helping to catalyze an integration of biology with other scientific and engineering fields. In order to fully understand the vast amount of genomic information available and apply it to improve the environment, nutritional quality of food, and human and animal health and welfare, new and improved computational and analytical tools and techniques must be developed, and the next generation of scientists and engineers must be trained to use them. Central to genomic sequencing and analysis is access to high-speed computers to store and analyze the enormous amount of data. Automated methods for model search, classification, structure matching, and model estimation and evaluation already have an essential role in genomics and in other complex, data-intensive domains, and should come to play a larger role in the future.

The Nation's IT capability has acted like adrenaline to all of S&E. The next step is to build the most advanced research computing infrastructure while simultaneously broadening its accessibility. NSF is presently working toward enabling such a distributed, leading-edge computational capability. Extraordinary advances in the capacity for visualization, simulation, data analysis and interpretation, and robust handling of enormous sets of data are already underway in the first decade of the 21st century. Computational resources, both hardware and software, must be sufficiently large, sufficiently available, and, especially, sufficiently flexible to accommodate unanticipated scientific and engineering demands and applications over the next few decades.

[30] Examples of large data sets include large genomic databases, data gathered from global observations systems, seismic networks, automated physical science instruments, and social science databases.
[31] R.H. Rich, *The Role of the National Science Foundation in Supporting Advanced Network Infrastructure: Views of the Research Community,* American Association for the Advancement of Science, Washington, D.C., July 26, 1999.

CHAPTER THREE

THE ROLE OF THE NATIONAL SCIENCE FOUNDATION

NSF LEADERSHIP ROLE

Among Federal agencies, NSF is a leader in providing the academic research community with access to forefront instrumentation and facilities. Its history and mission confer this role upon it. NSF is the only agency charged to broadly "promote the progress of science; to advance the National health, prosperity, and welfare; to secure the National defense; and for other purposes."[32] While other agencies support S&E infrastructure needed to accomplish their specific missions, only NSF has the broad responsibility to see that the academic research community continues to have access to forefront instrumentation and facilities, to provide the needed research support to utilize them effectively, and to provide timely upgrades to this infrastructure.

Because of its unique responsibilities and mission, NSF must address issues and adopt strategies that are different from those of other agencies. For example, application mission agencies, such as DoD and DoE, focus primarily on what is enabled by a facility. NSF's infrastructure investments must also consider other issues, such as the educational impacts of the facility on designers, operators, researchers, and students; the balance of support across disciplines and fields; and the development of next-generation instruments. This broad, integrated strategy is reflected in NSF's three strategic goals, expressed here as outcomes:

People - A diverse, internationally competitive and globally engaged workforce of scientists, engineers, and well-prepared citizens

Ideas - Discovery across the frontiers of S&E, connected to learning, innovation, and service to society

Tools - Broadly accessible, state-of-the-art and shared research and education tools

These goals are mutually supportive and each is essential to ensure the health of the U.S. S&E enterprise. For example, advances in infrastructure go hand-in-hand with scientific progress and workforce development. Research discoveries

[32] National Science Foundation Act of 1950 (Public Law 81-507).

create the need for new infrastructure and underpin the development of new infrastructure technologies. In turn, infrastructure developments open up new research vistas and help to sustain S&E at the cutting edge. The development of new infrastructure also has an enormous impact on the education of students who will be the next generation of leaders in S&E.

Except for the South Pole Station and the other Antarctic Program facilities, NSF does not directly construct or operate the facilities it supports. Typically, NSF makes awards to external entities, primarily universities, consortia of universities, or nonprofit organizations, to undertake construction, management, and operation of facilities. All infrastructure projects are selected for funding through a competitive and transparent merit review process. NSF retains responsibility for overseeing the development, management and successful performance of the projects. This approach provides the flexibility to adjust to changes in science and technology while providing accountability through efficient and cost-effective management and oversight. An essential added benefit of NSF's model is the opportunity to train young scientists and engineers by engaging them directly in planning, construction, and operation of major facilities and large-scale instrumentation.

Throughout its 50-year history, NSF has enjoyed an extraordinarily successful track record in providing state-of-the-art facilities for S&E research and education. NSF management and oversight have not only enabled the establishment of unique national assets, but have also ensured that they serve the S&E communities and the discovery process as intended. Some of the areas where NSF plays a major Federal funding role are:

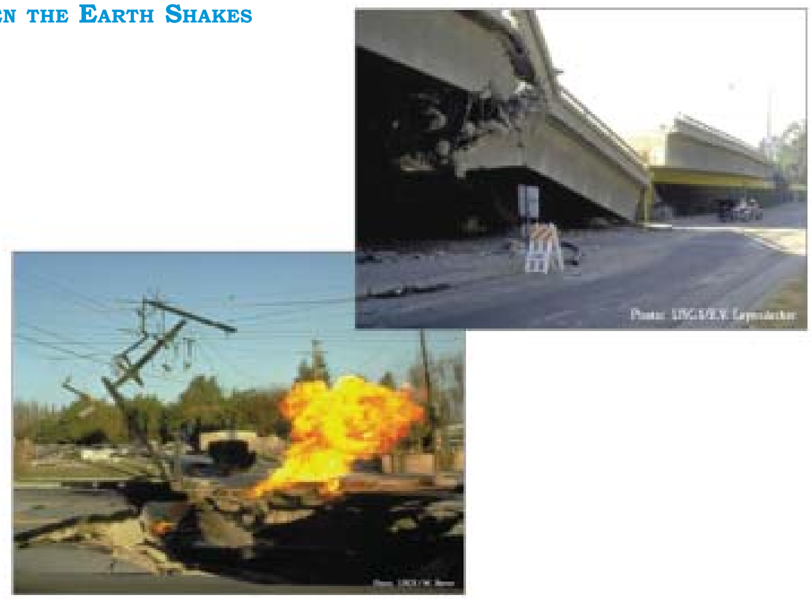
- Atmospheric and climate change research
- Digital libraries for S&E
- Biocomplexity and biodiversity research
- Exploration of the Earth's mantle
- Gravitational physics
- High-performance computing and advanced networking
- Machine learning and statistics
- Cognitive psychology
- Ground-based astronomy
- Materials research
- Oceanography
- Plant genomics
- Polar research
- Seismology and earthquake engineering

Establishing Priorities for Large Projects

In identifying new facility construction projects, the S&E community, in consultation with NSF, develops ideas, considers alternatives, explores partnerships, and develops cost and timeline estimates. By the time a proposal is submitted to NSF, these issues have been thoroughly examined.

Upon receipt by NSF, large facility proposals are first subjected to rigorous external peer review, focusing on the criteria of intellectual merit and the broad (probable) impacts of the project. Only the highest rated proposals - i.e. those that are rated outstanding on both criteria - survive this process and are recommended to a high-level review panel composed of the Assistant Directors and office heads, serving as stewards for their fields and chosen for their breadth of understanding, and chaired by the Deputy Director.

When the Earth Shakes



The George E. Brown, Jr. Network for Earthquake Engineering Simulation is a new model for scientific research that will radically change engineering to minimize earthquake damage, such as the damage pictured here. This Web-interface technology will allow researchers anywhere in the world to operate the equipment and observe experiments of earthquake simulations and related effects. The first test used a shake table to vibrate a model bridge with 100 sensors attached that streamed video and data to engineers. CREDIT: U.S. Geological Survey

The review panel uses a two-stage process. First, it selects the new start projects it will recommend to the Director for future NSF support, based on a discussion of the merits of the science within the context of all sciences that NSF supports. Second, it places these recommended new-start projects in priority order.

In selecting projects for future support, the panel considers the following criteria:

- Significance of the opportunity to enable frontier research and education.
- Degree of support within the relevant S&E communities.
- Readiness of project, in terms of feasibility, engineering cost-effectiveness, interagency and international partnerships, and management.

Using these criteria, projects that are not highly rated are returned to the initiating directorates and may be reconsidered at a future time. Highly rated projects are then placed in priority order by the panel. This process is conducted in consultation with the NSF Director. The review panel and the Director use the following criteria to determine the priority order of the projects:

- How "transformative" is the project? Will it change the way research is conducted or change fundamental S&E concepts/research frontiers?

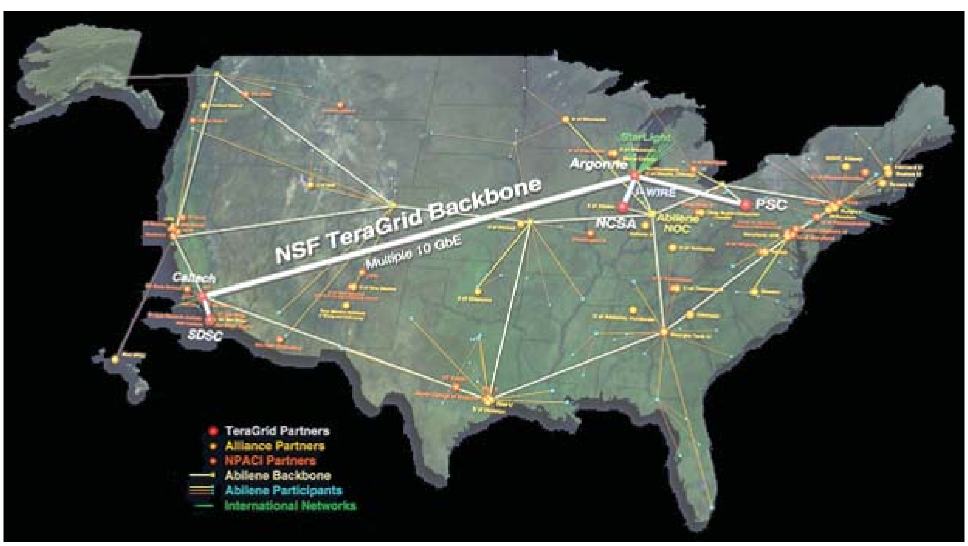
- How great are the benefits of the project? How many researchers, educators and students will it enable? Does it broadly serve many disciplines?

- How pressing is the need? Is there a window of opportunity? Are there interagency and international commitments that must be met?

These criteria are not assigned relative weights because each project has its own unique attributes and circumstances. For example, timeliness may be crucial for one project and relatively unimportant for another. Additionally, the Director must weigh the impact of a proposed facility on the balance between scientific fields, the importance of the project with respect to national priorities, and possible societal benefits.

After considering the strength and substance of the panel's recommendations, the balance among various fields and disciplines, and other factors, the Director selects the candidate projects to bring before the NSB for consideration. The NSB reviews individual projects on their merits and authorizes the Foundation

MATRIX OF THE FUTURE



The Extensible Terascale Facility is a scalable, distributed, heterogeneous grid computing-communication-information system. Scheduled for commissioning in the fall of 2004, the facility will provide for the seamless integration of high-end computing platforms, large archival science and engineering data resources, cutting-edge visualization facilities, and research-enabling instruments and sensors. CREDIT: Donna Cox, National Center for Computing Applications to pursue the inclusion of selected projects in future budget requests. In August the Director presents the priorities, including a discussion of the rationale for the priority order, to the NSB, as part of the budget process. The NSB reviews the list and either approves or argues the order of priority. As part of its budget submission, NSF presents this rank-ordered list of projects to OMB. Finally, NSF submits a prioritized list of projects to Congress as part of its budget submission.

CURRENT PROGRAMS AND STRATEGIES

Table 4 indicates that the FY 2003 budget estimate for facilities and other Tools totaled $1,122 million, representing about 22.3 percent of the overall NSF budget request. Over the past few years this number has ranged from 22 percent to 27 percent. The FY 2004 budget request for Tools is $1,340 million, which is about 24.5 percent of the total.

In the category of Research Resources, a range of activities are supported, including multiuser instrumentation; the development of instruments with new capabilities, improved resolution or sensitivity; upgrades to field stations and marine laboratories; support of living stock collections; facility-related instrument development and operation; and the support and development of databases and informatics tools and techniques. Not included in Table 4 are more than 300 NSF-supported research centers receiving a total of $372 million in NSF support and leveraging additional external support of $319 million (mostly university and industrial matching).[33]

UNDERSTANDING CELL BIOLOGICAL PROCESSES

An undergraduate at the University of Georgia uses cryo-transmission electron microscopy to obtain atomic-level structural information about the complex macromolecular assemblies that govern fundamental cell biological processes. CREDIT: Mark A. Farmer, Director, Center for Ultrastructural Research, University of Georgia

[33] Although NSF research centers are part People, part Ideas and part Tools, for budget convenience they are classified in the Ideas category.

Table 4.
NSF Investment in Tools, FY 2002-2004

(Dollars in Millions)

	FY 2002 Actual	FY 2003 Estimate	FY 2004 Estimate	Change FY 2004/2003 Amount	Change FY 2004/2003 Percent
Facilities					
Academic Research Fleet	61.90	62.00	65.00	3.00	4.8%
Antarctic Facilities and Operations	123.38	128.70	144.29	15.59	12.1%
Cornell Electron Storage Ring	19.49	19.49	21.00	1.51	7.7%
Gemini	12.50	12.60	14.20	1.60	12.7%
Incorporated Research Institutions for Seismology	12.93	13.10	14.10	1.00	7.6%
Laser Interferometer Gravitational Wave Observatory	24.00	29.50	29.00	-0.50	-1.7%
Major Research Equipment & Facilities Construction[1]	122.41	136.28	226.33	90.05	66.1%
National Astronomy Facilities	88.36	84.33	93.43	9.10	10.8%
National Center for Atmospheric Research	77.59	74.87	80.09	5.22	7.0%
National High Magnetic Field Laboratory	24.97	24.00	24.50	0.50	2.1%
National Superconducting Cyclotron Laboratory	14.81	14.70	15.20	0.50	3.4%
Ocean Drilling Program/Integrated Ocean Drilling Program	31.50	30.00	15.40	-14.60	-48.7%
Partnerships for Advanced Computational Infrastructure	75.27	71.49	76.49	5.00	7.0%
Other Facilities[2]	42.43	63.54	87.29	23.75	37.4%
Other Tools					
Advanced Networking Infrastructure	47.60	46.62	46.42	-0.20	-0.40%
Cyberinfrastructure	0.00	0.00	20.00	20.00	N/A
Major Research Instrumentation	75.89	54.00	90.00	36.00	66.7%
National High Field Mass Spectrometry Facility[3]	1.06	0.99	0.00	-0.99	100.0%
National STEM Digital Library	27.07	27.50	23.80	-3.70	-13.5%
Polar Logistics	97.85	94.07	97.07	3.00	3.2%
Research Resources	111.23	106.36	128.85	22.49	21.1%
Science Resources Statistics	16.18	23.36	24.47	1.11	4.8%
Science and Technology Policy Institute	3.99	4.00	4.00	0.00	0.0%
Total, Tools Support	**$1,112.41**	**$1,121.50**	**$1,340.93**	**$219.43**	**19.6%**

[1] Funding levels for MREFC projects in this table include initial support for operations and maintenance funded through R&RA as well as construction, acquisition and commissioning costs funded through MREFC.

[2] Other Facilities includes support for the National Nanofabrication Users Network through FY 2003, the National Nanotechnology Infrastructure Network in FY 2004, and other physics, materials research, ocean sciences, atmospheric sciences, and Earth sciences facilities.

[3] Support for the National High Field Mass Spectrometry Facility will be integrated into the National High Magnetic Field Laboratory in FY 2004.

NSF centers have been outstanding catalysts for the acquisition and deployment of major infrastructure investments. For example, many of the Engineering Research Centers and Materials Research Science and Engineering Centers acquire, maintain and update extensive shared facilities and testbeds, often with major equipment donations from industry partners. These facilities often serve as shared campus-wide, statewide, or regional facilities.

Table 5 contains data on NSF's investment in Tools by major activity: the seven NSF directorates, the OPP, Integrative Activities (IA), and the Major Research Equipment and Facilities Construction (MREFC) Account.

TABLE 5.
NSF TOOLS EXPENDITURES BY MAJOR ACTIVITY, FY 1998-2002

(Dollars in Millions)

Budget Activity	FY 1998 Tools	FY 2002 Tools	Change 2002/1998	FY 2002 Total Budget	Tools as % of Total
BIO[a]	50	51	2%	510	10%
CISE	104	142	37%	515	28%
ENG	4	6	50%	471	1%
GEO	176	217	23%	610	36%
MPS	146	223	53%	920	24%
SBE	9	33	267%	184	18%
OPP	163	221	36%	301	73%
IA	53	80	51%	106	75%
EHR	0	24	NA	866	3%
MREFC	78	115	47%	115	100%
OTHER[b]	0	0	0	185	0%
NSF TOTAL[c]	$783	$1,112	46%	$4,783	23%

[a] BIO = Biological Sciences; CISE = Computer and Information Science and Engineering; ENG = Engineering; GEO = Geosciences; MPS = Mathematical and Physical Sciences; SBE = Social, Behavioral, and Economic Sciences; OPP = Office of Polar Programs; IA = Integrative Activities; EHR = Education and Human Resources.

[b] Other budget items include Salaries and Office of Inspector General.

[c] Numbers may not add due to rounding.

BIO invests about 10 percent of its annual budget in the Tools category. Heretofore, the typical infrastructure investments have been in small- to medium-size instrumentation, such as mass spectrometers, electron microscopes, and genomic sequencers, and in stock centers, natural history collections, and searchable biological databases. The biological sciences are undergoing a profound revolution, based largely on the use of genomics data and IT advances. Hence, there are indications that BIO's future infrastructure requirements will increase substantially. (The future needs and opportunities of each directorate are discussed in the next section of the report.)

CISE supplies the critical infrastructure needs not only for computer S&E research, but also for other sciences and engineering that require high-end computational and communications capabilities. Its infrastructure investment is large - 28 percent of its budget - and growing rapidly. Much of the infrastructure budget provides support for two major projects: the Terascale Computing Systems (TCS) and the Partnerships for Advanced Computational

Infrastructure (PACI). Additionally, CISE currently provides support for small- to medium-end activities for more than 200 research universities. Resources range over the breadth of the cyberinfrastructure and include computational resources, networking testbeds, software and data repositories, and instruments.

ENG direct investment in Tools is small - only 1 percent of its budget - largely composed of support for the NNUN. However, this direct investment is augmented by ENG's equipment investment through research grants and at NSF-supported centers, such as the Engineering Research Centers and the Earthquake Engineering Research Centers. These centers also attract a considerable investment in industry matching funds. ENG also supports the Network for Earthquake Engineering Simulation (NEES), which is funded from the MREFC Account.

EHR's current infrastructure consists of the people, computing equipment and networks, physical facilities, instrumentation, and other components that drive educational excellence and support the integration of research with education. In FY 2002, EHR will invest nearly $25 million in the National Science, Technology, Engineering, and Mathematics Education Digital Library (NSDL), a national resource that will aid researchers and educators in the development and dissemination of teaching and learning resources.

Flying Laboratories

Representative research aircraft platforms operated by several agencies, including a Naval Research Laboratory P-3 that carries an NSF-supported tail-mounted Doppler radar, the NSF C-130 flying laboratory, two National Oceanic and Atmospheric Administration P-3 hurricane surveillance and research aircraft, a Department of Energy Citation used for terrestrial remote sensing, and a National Aeronautics and Space Administration ER-2 high-altitude research aircraft. CREDIT: Cheryl Yubas, Suborbital Program Manager, Code YS, NASA

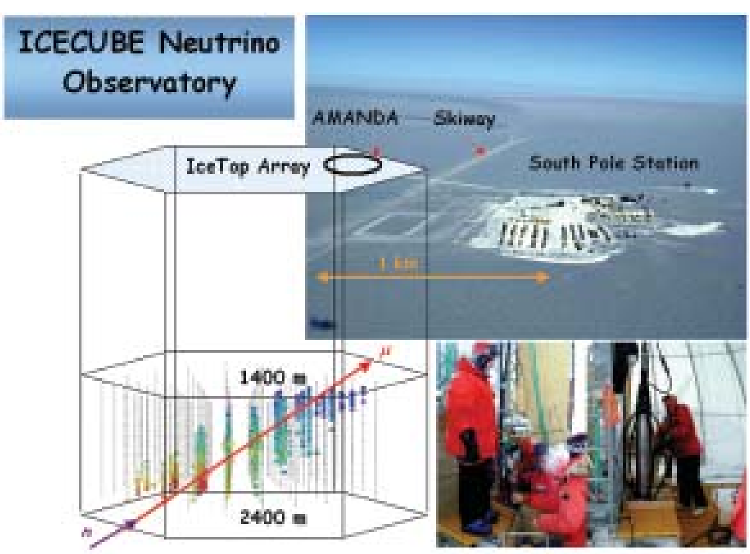
GEO spends approximately 36 percent of its total budget on infrastructure and also relies heavily on the MREFC Account. Because of its inherently observational nature, cutting-edge research in the geosciences requires a vast range of capabilities and diverse instrumentation, including ships and aircraft, ground-based observatories, laboratory and experimental analysis instruments, computing capabilities, and real-time data and communication systems.

MPS currently invests about 24 percent of its overall budget annually in the Tools category, most of which goes to the larger facilities. Like GEO, the disciplines represented by MPS require extensive observational facilities and other infrastructure. In addition, MPS facilities rely heavily on support from the NSF-wide MREFC Account.

SBE invests about 18 percent of its budget in infrastructure, composed chiefly of distributed facilities that do not require large construction. This infrastructure includes new data collections that serve a broad range of scholars; digital libraries, including data archives; shared facilities that enable new data to be collected; and centers that promote the development of new approaches in a field.

OPP supports research across all disciplines in the two polar regions, ranging from archaeology and astrophysics to biology and space weather. OPP invests 73 percent of its budget in Tools and supports large scientific instruments; laboratories; facilities for housing, health and safety, food service, and sanitation; satellite communications; transportation (including fixed-wing aircraft, helicopters, and research ships); and data and database management, all requiring significant investment in ongoing maintenance and operations in an unforgiving climate. This infrastructure is provided for the benefit of all the research programs supported by NSF's directorates, as well as the Federal mission agencies and other institutional partners.

DETECTING WITH ICECUBE

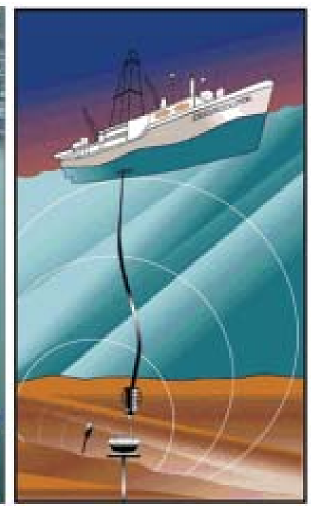


The IceCube project will be a neutrino observatory that uses one cubic kilometer of the Antarctic ice sheet as a detector. It will provide a hitherto unseen view of the most active and energetic astrophysical objects. CREDIT: University of Wisconsin (Madison) IceCube Project Office

NSF-wide Infrastructure Programs

Major Research Equipment and Facilities Construction (MREFC) Account: NSF established the MREFC Account in 1995 to better manage the funding of large facility projects, such as accelerators, telescopes, research vessels, and aircraft, all of which require peak funding over a relatively short period of time. Previously, such projects were supported within NSF's Research and Related Activities (R&RA) Account. The MREFC Account supports facility projects that provide unique research and education capabilities at the cutting edge of S&E, with costs ranging from several tens to hundreds of millions of dollars. It provides funding for *acquisition, construction, and commissioning* in contrast to other activities, such as *planning, design and development, and operations and maintenance,* which are funded from the R&RA Account.

DRILLING BENEATH THE SEA



The Ocean Drilling Program is an international partnership of scientists and research institutions organized to explore the evolution and structure of Earth as recorded in the ocean basins. The JOIDES Resolution is the drill ship used to collect geologic samples from the floor of the deep ocean basins through rotary coring and hydraulic piston coring. Undergraduate and graduate students participate in drilling expeditions with some of the world's leading scientists. CREDIT: Ocean Drilling Program, www-odp.tamu.edu/resolutn.html

Table 6 indicates the projects supported by the MREFC Account since its inception. Included are several projects approved by the NSB but still awaiting funding.

Table 6.
Projects Supported by the Major Research Equipment and Facilities Construction (MREFC) Account

Completed Projects:

- Gemini Observatory
- Laser Interferometer Gravitational Wave Observatory (LIGO)
- Polar Support Aircraft Upgrades

Currently Being Funded

- Atacama Large Millimeter Array/Millimeter Array (ALMA/MMA)
- EarthScope
- High-performance Instrumented Airborne Platform for Environmental Research (HIAPER)
- IceCube Neutrino Detector
- Large Hadron Collider (LHC)
- Network for Earthquake Engineering Simulation (NEES)
- South Pole Station: Safety Project and Modernization
- Terascale Computing Systems

NSB Approved but Not Yet Funded

- National Ecological Observatory Network (NEON)
- Ocean Observatories
- Rare Symmetry Violating Processes (RSVP)
- Scientific Ocean Drilling

While the MREFC model has served NSF well, there are a number of issues that NSF is currently examining in its effort to provide the best support for large facility projects, such as:

- How large should a project be before it can be considered for MREFC funding?
- When should large infrastructure projects be supported within directorate budgets versus the MREFC Account?
- What costs should be charged to the MREFC Account versus the R&RA Account?
- How should budget priorities be established across different fields and disciplines?
- How should these large projects be managed?

Major Research Instrumentation (MRI): The MRI program supports instrumentation having a total cost ranging from $100,000 to $2 million. It seeks to improve the quality and expand the scope of research and foster the integration of research and education by providing instrumentation for research-intensive learning environments. In FY 2004 NSF has requested $90 million for this program to support the acquisition and development of research instrumentation for academic institutions.[34] This amount falls short of meeting the real needs and opportunities, based on the survey of directorate needs and the amount of MRI proposals received in FY 2002.

Small Instrumentation in Research Grants: In the past decade, NSF's strong support for individual investigator (and small groups of investigators) research has held steady. However, equipment within a research grant has declined from 6.9 percent to 4.4 percent of the total grant budget. This decline is partly because the average size of NSF research grants has not kept pace with inflation. Other issues include the increasing cost of new instruments, the need to replace large bulky instruments with smaller and faster instruments, and most of all, the need for computers and interfaces for the acquisition of large data sets from midrange or larger centers or sites. The potential for remote access to and operation of instruments at larger centers or sites is a key aspect of future investments at this level. In addition to increased funding for special programs, such as MRI, increasing the average size of an NSF research grant will help address the need for more attention to small-scale infrastructure.

FUTURE NEEDS AND OPPORTUNITIES

Table 7 summarizes the 10-year projection of future S&E infrastructure requirements identified in reports provided by each of the NSF directorates and OPP. The degree of specificity employed in identifying the requirements ranged from listing specific facilities and instrumentation to providing rough estimates for broad categories of infrastructure needs. Hence, the $18.9 billion estimate of funding needed over the next 10 years must be viewed as a rough indication of need, and not one that has been assessed and formally endorsed by the NSB. In order to view the commonalities and differences between scientific fields, a summary of the infrastructure needs of each directorate and office is presented below.

TABLE 7.
NSF FUTURE INFRASTRUCTURE NEEDS, FY 2003-12

Range of Project Cost	TOTAL	%
$1M - $10M	3,950	20
$11M - $50M	5,400	29
$51M - $250M	6,800	37
$251M - $500M	1,700	9
> $500M	1,000	5
Total (Millions of Dollars)	$18,850	100

[34] The amount appropriated by Congress in FY 2003 was $84 million.

BIO: The use of information technology and the development of numerous new techniques have catalyzed explosive research growth and productivity. However, infrastructure investments have not kept up with the expanding needs and opportunities. For example, there is an increasing need to develop, maintain and explore huge interoperable databases that result from the determination of complete genomes. In order to thrive in the future, biological researchers will need new large concentrated laboratories where a variety of experts meet and work on a daily basis. They will also need major distributed research platforms, such as the National Ecological Observatory Network (NEON), that link together ecological sites, observational platforms, laboratories, databases, researchers and students from around the globe. An essential and neglected aspect of support for biological research is the provision of resources to make automated data analysis and interpretation procedures publicly accessible and easily usable by all investigators. Increasingly, published results are derived from intensive automated data analysis and modeling and cannot be reproduced or checked by other researchers without access to the software, which was often developed for a specific research project.

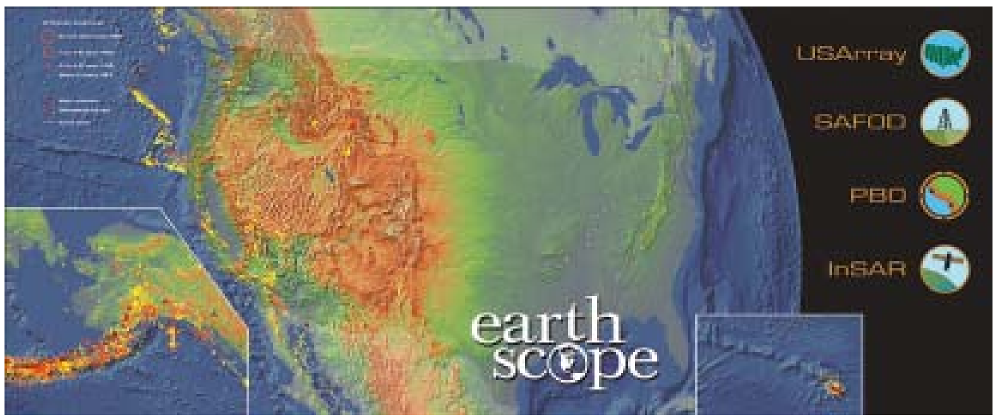
CISE: In the future, substantial investments must be made in providing increasingly powerful computational infrastructure necessary to support the increasing demands of modeling, data analysis and interpretation, management, and research. CISE researchers will require testbeds to develop and prove experimental technologies. CISE must also expand the availability of high-performance computing and networking resources to the broader research and education community. Effective utilization of advanced computational resources will require more user-friendly software and better software integration. Funding for highly skilled technical support staff is essential to encouraging broader participation by the community in the evolving cyberinfrastructure.

EHR: The directorate's future needs include electronic collaboratory spaces in support of research and instruction; centers for disseminating and validating successful educational materials and practices at all levels; increased computational capacity for needs in modeling and simulation in systems research and in learning settings; and databases of international and domestic student learning indicators.

ENG: The rapid pace of technological change will require ENG to invest significantly more funds for research instrumentation and instrumentation development, multiuser equipment centers, and major networked experimental facilities, such as the National Nanotechnology Infrastructure Network, and the NEES. Needs for research tools are diverse, ranging from high-speed, high-resolution imaging technology to study gene development and expression to a suite of complex instruments that enables the simulation, design, and fabrication of novel nano- and micro-scale structures and systems. In addition, substantial investment is needed to enable engineering participation in grid activities, to facilitate collaborations between engineering and computer science researchers, and to develop tools (including improved teleoperation and visualization tools, integrated analytical tools to support real-time analysis of processes, multiscale modeling, and protocols for shared analytical codes and data sets).

GEO: In the future, the geosciences research community will require new state-of-the-art observing facilities and research platforms. Many of these facilities must be mobile and/or distributed over wide geographic locations. The increased need for distributed, interdependent observing systems will require better networking technologies, faster access to data bases and models, real-time access to data from observing platforms, and remote control of complex instruments. The increased demands for climate and environmental modeling will require high-end computational capabilities (petaflop) and new visualization tools. An essential element in future advances is the ability to integrate data from multiple observatories into models and data sets. The necessity of support, noted above for biology, for publicly accessible and usable data analysis and interpretation software applies equally here.

A New View of Earth



This map of the United States shows the structure and physiographic features that will be imaged and studied with EarthScope, a distributed, multi-purpose geophysical instrument array. The three components are the USArray, the San Andreas Fault Observatory at Depth (SAFOD), and the Plate Boundary Observatory (PBO). Combined with new satellite and Global Positioning Systems, EarthScope will provide a dynamic picture of forces and processes that shape the Earth, including those that control earthquakes and volcanic eruptions. CREDIT: EarthScope Working Group, 2001 (information provided by David Simpson of the Incorporated Research Institutions for Seismology)

MPS: Mathematical and physical sciences researchers seek answers to fundamental science questions that have the potential to revolutionize how we think about nature (e.g. the origin of mass, the origin of the matter-antimatter asymmetry of the universe, the nature of the accelerating universe, and the structure of new materials). Such research increasingly requires more expensive and sophisticated instruments that range from the relatively small to the very large, such as radio observatories, neutron scattering, x-ray synchrotron radiation, high magnetic fields, neutrino detectors, and linear colliders. In addition, increased investments are needed in cyberinfrastructure to facilitate the conduct of science in the rapidly changing environment surrounding the massive petabyte data sets from astronomy and physics facilities.[35] Investments

[35] For example, the amount of data that will be produced by the Large Hadron Collider at the European Organization for Nuclear Research (CERN) will be colossal and require major advances in grid network technology to fully exploit it.

include high-speed communication links, access to teraflop computing resources, and electronic communications and publishing.

OPP: With the growing realization that the polar regions offer unique opportunities for research - in fields as disparate as neutrino-based astrophysics and evolutionary biology at the genetic level - comes the need for increasingly sophisticated and diverse new instrumentation. Progress in areas such as climate change research will hinge on the development of distributed observing systems adapted to function in the harsh polar environment with minimum on-site maintenance and power requirements. Automated, intelligent underwater and airborne robotic systems will be essential in providing safe and effective access to sub-ice and atmospheric environments. High-speed connectivity to the South Pole Station must be improved to enable scientists to control instruments from stateside laboratories and to analyze incoming data in real time. Finally, the basic infrastructure that enables scientists to survive in polar regions, especially in Antarctica, must be maintained and improved.

SBE: Research in the social, behavioral and economic sciences is increasingly a capital-intensive activity. Social science research, for example, is increasingly dependent on the accumulation and processing of large data sets, requiring large computer facilities, access to state-of-the-art information technologies, and employment of trained, permanent staffs. Advances in computational techniques are radically altering the research landscape in many research communities. Examples include automated model search aids, sophisticated statistical methods, modeling, access to shared databases of enormous size, new statistical approaches to the analysis of large databases (data mining), Web-based collaboratories, virtual reality techniques for studying social behavior and interaction, and the use of computers for online experimentation.

Areas of Particular Priority

The demand for new S&E infrastructure is driven by scientific opportunity and the needs of researchers; hence, it is *field dependent*. However, it is not the purpose of this report to provide a detailed examination of the opportunities and needs for each scientific discipline and field. There are many discipline-specific surveys, studies and reports that do this quite well. Rather, in examining the range of need and opportunities identified in the NSF directorate reports, it is useful to consider the needs and issues they have in common. For example, the directorates identified the following areas as having particular priority:

Cyberinfrastructure: Advances in computational and communications technology are radically altering the research landscape for scientists and engineers in many disciplines. In the future, these researchers must be prepared to develop, manage and exploit an even more rapid evolution in the tools and infrastructure that empower them. Virtually all of the directorates and offices cited cyberinfrastructure as a top investment priority. The following were noted as pressing needs:

- Accessing the next generation of information systems including grid computing, digital libraries and other knowledge repositories, virtual reality/telepresence, and high-performance computing and networking and middleware applications.

- Expanding the availability of high-performance computing and networking resources to the broader research and education community. As more extensive connection across the S&E community is supported, the utility of the resources to current users must also be sustained. Collaboration and coordination with State and local infrastructure efforts will also be essential. The overall goal is to provide resources and build capacity for smaller institutions while continuously enabling new research directions at the high end of computing performance.

- Providing computational infrastructure necessary to support the increasing demands of modeling, data analysis and management, and research. Computational resources at all levels, from desktop systems to supercomputing, are needed to sustain progress in S&E. The challenge is to provide scalable access to a pyramid of computing resources from the high-performance workstations needed by most scientists to the teraflop-and-beyond capability critically needed for solving the grand-challenge problems.

- Increasing the ability to integrate data sets from multiple observatories into models and physically consistent data sets. Development of techniques and systems to assimilate information from diverse sources into rational, accessible, and digital formats is needed. Envisioned is a Web-accessible hierarchical network of data/information and knowledge nodes that will allow the close coupling of data acquisition and analysis to improve understanding of the uncertainties associated with observations. The system must include analysis, visualization, and modeling tools.

- Improved modeling and prediction techniques adequate for data analysis under modern conditions, which include enormous data sets with large numbers of variables, intricate feedback systems, distributed databases with related but non-identical variable sets, and hierarchically related variables. Academic groups, despite inadequate interfaces and support, now implement many of the most advanced techniques as freeware.

- Maintaining the longevity and interoperability of a growing multitude of databases and data collections.

Large Facility Projects: Over half of the needs identified by the directorates fell in the category of “large” infrastructure; i.e., projects with a total cost of $75 million or more. The reality is that many important needs identified 5 to 10 years ago have not been funded and the scientific justifications for those facilities have grown. In the past couple of years, the number of large projects approved for funding by the National Science Board, but not yet funded, has grown. The FY 2003 appropriation for the MREFC Account is about $148 million. It will require an annual investment of at least $350 million for several years to address the backlog of research facilities construction projects.

Midsize Infrastructure: Many of the NSF directorates identified a "midsize infrastructure" funding gap. While there is no precise definition of midsize infrastructure, for the purposes of this report it is assumed to have a total construction/installation cost ranging from millions to tens of millions of dollars. Examples of infrastructure needs that have long been identified as very high priorities but that have not been realized include acquisition of an incoherent scatter radar to fill critical atmospheric science observational gaps; replacement of an Arctic regional research vessel; replacement or upgrade of submersibles; beam line instrumentation for neutron science; and major upgrades of computational capability. In many cases the midsize instruments that are needed to advance an important scientific project are research projects in their own right, projects that advance the state-of-the-art or that invent completely new instruments. These projects are not suitable for funding with the MREFC account owing to their mix of research and instrument construction, but they are essential if NSF is to continue to be the agency whose work leads to developments like MRI and laser eye surgery - developments that had their roots in research on advanced instrumentation.

Maintaining and Upgrading Existing Infrastructure: Obtaining the money to maintain and upgrade existing research facilities, platforms, databases, and specimen collections is a difficult challenge for universities. IT adds a new layer of complexity to already complex science and engineering instruments. The design and build time for large instruments can be two to four generations of IT, while IT must be "planned in" - it cannot be designed in afterwards. Instruments with long lifetimes must consider upgrade paths for IT systems that will enable enhanced sensors, data rates or other improved capabilities. The challenge to NSF is how to maintain and upgrade existing infrastructure while simultaneously advancing the state-of-the-art.

DOPPLER ON WHEELS

The Doppler on Wheels Project has created three mobile Doppler weather radars mounted on trucks that have explored rare, short-lived and small-scale phenomena, permitting the first-ever mappings of tornado winds, hurricane wind streaks, and resolution of detailed tornado structure and evolution at scales well below 100 meters. CREDIT: Ling Chan, Doppler on Wheels Project, Center for Severe Weather Research

Instrumentation Research: Increased support for research in areas that can lead to advances in instruments, in terms of cost and function, is critically important. Such an investment will be cost effective because skipping even one generation of a big instrument may save hundreds of millions of dollars. Also, totally new instruments can open doors to new research vistas. In addition, industry is rapidly transforming the tools developed in support of basic research into the tools and technologies of industry. At the same time, industry is relying on NSF-sponsored fundamental research programs in universities for the initial development of such tools.

NNUN is a network of five university user facilities that offer advanced nano- and micro-fabrication capabilities to researchers in all fields. NNUN has served more than 1,000 users and has given many graduate and undergraduate students an opportunity to work in a state-of-the-art facility.

Multidisciplinary Infrastructure Platforms: As the academic disciplines become intertwined, there is an increasing need for sites where multidisciplinary teams can interact and have access to cutting-edge tools. Such facilities must be shared among a number of researchers much as a telescope is shared among a number of astronomers. The sharing of such facilities, in turn, requires investigators to become more collaborative and work in new ways. This approach will require increased attention to multidisciplinary training. Open technological platforms offer high-quality instrumentation and technological services to researchers and institutions that could not otherwise afford them. Networks can help guide users, provide services, and encourage interaction between different communities.

Polar Regions Research: NSF infrastructure in the polar regions enables research supported not only by OPP and most other NSF Directorates, but also by the Nation's mission agencies, notably NASA, the Department of Interior (DoI), DoE, and the Department of Commerce (DoC). The new South Pole Station will enable this research; however, improved transportation to the station will be needed as will continuous high-bandwidth capability for data transfer and connectivity to the cyberinfrastructure. In addition, NSF infrastructure at McMurdo Station, the base for South Pole and remote field operations, needs to be maintained at a faster pace than has occurred in recent years. Finally, many fields of science require access to polar regions during the winter months, a capability that currently can be supported only to a very limited extent.

Integration of research and education is an integral part of both the infrastructure and research activities supported by BIO. For example, The Arabidopsis Information Resources (TAIR) site maintains and curates the fundamental databases used by all Arabidopsis researchers, as well as supporting a wide range of educational activities for students and teachers. Some BIO-supported infrastructure supports more students than faculty. For example, at many biological field stations and marine laboratories the ratio of student to faculty users is at least 20 to 1.

Education and Training: Investments that expand the educational opportunities at research facilities have already had an enormous impact on students. Many of these investments can be further leveraged by new activities that reach out to K-12 students and influence the teaching of science and mathematics. Similarly, the public's direct participation in advanced visualization access to national research facilities can open a much-needed avenue for public involvement in the excitement of scientific discovery and the creative process of engineering.

Infrastructure Security: The events of September 11, 2001, increased awareness of important security issues with respect to protecting the Nation's S&E infrastructure. Examples include:

- Preventing attacks on S&E infrastructure to destroy valuable national resources and disrupt U.S. science and technology.

- Preventing use of S&E infrastructure, such as shared research Web sites, for destructive purposes.
- Ensuring security, confidence, and trust in S&E databases.

The increasingly distributed and networked nature of S&E infrastructure means that problems can propagate widely and rapidly. Infrastructure security requires innovations in IT to monitor and analyze threats in new settings of global communications and commerce, asymmetric threats, and threats emanating from groups with unfamiliar cultures and languages. The U.S. and its international partners face unprecedented challenges for ensuring the security, reliability and dependability of IT-based infrastructure systems. For example, the major barriers to realizing the promise of the Internet are security and privacy issues - research issues requiring further study - and the need for ubiquitous access to broadband service. Current middleware and strategic technology efforts are attempting to address these problems, but a significantly greater investment is needed to do so successfully.

CHAPTER FOUR
FINDINGS AND RECOMMENDATIONS

Over the past decade, the funding for academic research infrastructure has not kept pace with rapidly changing technology, expanding research opportunities, and increasing numbers of users. Information technology and other technologies have enabled the development of many new S&E tools and made others more powerful, remotely usable, and connectable. The new tools being developed make researchers more productive and able to do more complex and different tasks than they could in the past. An increasing number of researchers and educators, working as individuals and in groups, need to be connected to a sophisticated array of facilities, instruments, databases, technical literature and data. Hence, there is an urgent need to increase Federal investments to provide access for scientists and engineers to the latest and best S&E infrastructure, as well as to update infrastructure currently in place.

To address these concerns, the Board makes the following five recommendations:[36]

RECOMMENDATION 1:

Increase the share of the NSF budget devoted to S&E infrastructure in order to provide individual investigators and groups of investigators with the tools they need to work at the frontier.

The current 22 percent of the NSF budget devoted to infrastructure is too low to provide adequate small- and medium-scale infrastructure, and needed investment in cyberinfrastructure. A share closer to the higher end of the historic range (22–27 percent) is desirable. It is hoped that significant additional resources for infrastructure will be provided through future growth of the NSF budget.

[36] The NSB will periodically assess the implementation of these recommendations.

RECOMMENDATION 2:

Give special emphasis to the following four categories of infrastructure needs:[37]

- **Increase research to advance instrument technology and build next-generation observational, communications, data analysis and interpretation, and other computational tools.**

Instrumentation research is often difficult and risky, requiring the successful integration of theoretical knowledge, engineering and software design, and information technology. In contrast to most other infrastructure technologies, commercially available data analysis and data interpretation software typically lags well behind university-developed software, which is often not funded or underfunded, limiting its use and accessibility. This research will accelerate the development of instrument technology to ensure that future research instruments and tools are as efficient and effective as possible.

- **Address the increased need for midsize infrastructure.**

While there are special NSF programs for addressing "small" and "large" infrastructure needs, none exist for infrastructure projects costing between millions and tens of millions of dollars. This report cites numerous examples of unfunded midsize infrastructure needs that have long been identified as high priorities. NSF should increase the level of funding for midsize infrastructure, as well as develop new funding mechanisms, as appropriate, to support midsize projects.

- **Increase support for large facility projects.**

Several large facility projects have been approved for funding by the NSB but have not been funded. At present, an annual investment of at least $350 million is needed over several years to address the backlog of facility projects construction. Postponing this investment now will not only increase the future cost of these projects but also result in the loss of U.S. leadership in key research fields.

- **Develop and deploy an advanced cyberinfrastructure to enable new S&E in the 21st century.**

This investment should address leading-edge computation as well as visualization facilities, data analysis and interpretation toolkits and workbenches, data archives and libraries, and networks of much greater power and in substantially greater quantity. Providing access to moderate-cost computation, storage, analysis, visualization, and communication for every researcher will lead to an even more productive national research enterprise. Design of these new technologies and capabilities must be guided by the needs of a variety of potential users, including scientists and engineers from many disciplines. This important undertaking requires a significant investment in

[37] The order of presentation does not imply a priority ranking.

software and technical staff, as well as hardware. This new infrastructure will play a critical role in creating tomorrow's research vistas.

RECOMMENDATION 3:

Expand education and training opportunities at new and existing research facilities.

Investment in S&E infrastructure is critical to developing a 21st century S&E workforce. Education, training and outreach activities should be vital elements of all major research facility programs. Educating people to understand how S&E instruments and facilities work and how they uniquely contribute to knowledge in their targeted disciplines is critical. Outreach should span many diverse communities, including: existing researchers and educators who may become new users, undergraduate and graduate students who may design and use future instruments, and kindergarten through grade twelve (K-12) students, who may be motivated to become scientists and engineers. There are also opportunities to expand access to state-of-the-art S&E infrastructure to faculty and students at primarily undergraduate colleges and universities.

RECOMMENDATION 4:

Strengthen the infrastructure planning and budgeting process through the following actions:

- Foster systematic assessments of U.S. academic research infrastructure needs for both disciplinary and cross-disciplinary fields of research. Re-assess current surveys of infrastructure needs to determine if they fully measure and are responsive to current requirements.

- Develop specific criteria and indicators to assist in establishing priorities and balancing infrastructure investments across S&E disciplines and fields.

- Develop and implement budgets for infrastructure projects that include the total costs to be incurred over the entire life-cycle of the project, including research, planning, design, construction, commissioning, maintenance, operations, and, to the extent possible, research funding.

- Conduct an assessment to determine the most effective NSF budget structure for supporting S&E infrastructure projects throughout their life-cycles, including the early research and development that is often difficult and risky.

Because of the need for the Federal Government to act holistically in addressing the requirements of the Nation's science and engineering enterprise, the Board developed a fifth recommendation, aimed principally at the Office of Management and Budget (OMB), the Office of Science and Technology Policy (OSTP), and the National Science and Technology Council (NSTC).

RECOMMENDATION 5:

Develop interagency plans and strategies to do the following:

- Work with the relevant Federal agencies and the S&E community to establish interagency infrastructure priorities that rely on competitive merit review to select S&E infrastructure projects.

- Stimulate the development and deployment of new infrastructure technologies to foster a new decade of infrastructure innovation.

- Develop the next generation of the high-end high-performance computing and networking infrastructure needed to enable a broadly based S&E community to work at the research frontier.

- Facilitate international partnerships to enable the mutual support and use of research facilities across national boundaries.

- Protect the Nation's massive investment in S&E infrastructure against accidental or malicious attacks and misuse.

CHAPTER FIVE
CONCLUSION

Rapidly changing infrastructure technology has simultaneously created a challenge and an opportunity for the U.S. S&E enterprise. The challenge is how to maintain and revitalize an academic research infrastructure that has eroded over many years due to obsolescence and chronic underinvestment. The opportunity is to build a new infrastructure that will create future research frontiers and enable a broader segment of the S&E community. The challenge and opportunity must be addressed by an integrated strategy. As current infrastructure is replaced and upgraded, the next-generation infrastructure must be created. The young people who are trained using state-of-the-art instruments and facilities are the ones who will demand and create the new tools and make the breakthroughs that will extend the science and technology envelope. Training these young people will ensure that the U.S. maintains international leadership in the key scientific and engineering fields that are vital for a strong economy, social order, and national security.

Appendix A

The Charge to the Task Force on Science and Engineering Infrastructure

NSB-00-181
September 28, 2000

CHARGE
COMMITTEE ON PROGRAMS AND PLANS
TASK FORCE ON SCIENCE AND ENGINEERING INFRASTRUCTURE

The quality and adequacy of the infrastructure for science and engineering (S&E) are critical to maintaining the leadership of the United States on the frontiers of discovery and for insuring their continuous contribution to the strength of the national economy and to quality of life. Since the last major assessments were conducted over a decade ago, that infrastructure has grown and changed, and the needs of science and engineering communities have evolved. The National Science Board, which has a responsibility for monitoring the health of the national research and education enterprise, has determined the need for an assessment of the current status of the national infrastructure for fundamental science and engineering, to ensure its quality and availability to the broad S&E community in the future.

Several trends contribute to the need for a new assessment:

- The impact of new technologies on research facilities and equipment;
- Changing infrastructure needs in the context of new discoveries, intellectual challenges, and opportunities;
- The impact of new tools and capabilities, such as information technology and large data bases;
- Rapidly escalating cost of research facilities;
- Changes in the university environment affecting support for S&E infrastructure development and operation; and
- The need for new strategies for partnering and collaboration.

The Task Force on Science and Engineering Infrastructure (INF), reporting to the Committee on Programs and Plans (CPP), is established to undertake and guide an assessment of the fundamental science and engineering infrastructure in the United States. The task force will develop terms of reference and a workplan with the aim of informing the national dialogue on S&E infrastructure, highlighting the role of NSF and the larger resource and management strategies of interest to Federal policymakers in both the executive and legislative branches.

The workplan should enable an assessment of the current status of the national S&E infrastructure, the changing needs of science and engineering, and the requirements for a capability of appropriate quality and size to insure continuing U.S. leadership. It should describe the scope and character of the assessment and a process for including appropriate stakeholders, such as other Federal agencies, and representatives of the private sector and the science and engineering communities. The workplan should include consideration of the following issues:

- Appropriate strategies for sharing the costs of the infrastructure with respect to both development and operations among different sectors, communities, and nations;
- Partnering and use arrangements conducive to insuring the most effective use of limited resources and the advancement of discovery;
- The balance between maintaining the quality of existing facilities and creation of new ones; and
- The process for establishing priorities for investment in infrastructure across fields, sectors, and Federal agencies.

The INF Task Force should present its workplan and timetable to the CPP and the full Board for approval at the December 2000 meeting.

Eamon M. Kelly
Chairman

APPENDIX B
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APPENDIX C

SOURCES OF PUBLIC COMMENT

The draft report was posted on the NSF website from December 11, 2002, through January 15, 2003. A response form was provided to facilitate suggestions and reactions. An email address was also available. In addition, NSF solicited comments through press coverage and direct contacts. The NSB received 45 substantive responses (91 pages) commenting on the draft report, all of them submitted by email. Most responses were received from individuals but a few were submitted in the name of several people or an entire association. These responses by no means represent a random or representative sample of the research and education communities NSF serves. Most of the respondents provided specific comments that aided in preparing the final draft of the report.

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Appendix D

Selected Acronyms and Abbreviations

A&M	Agricultural & Mechanical
ALMA	Atacama Large Millimeter Array
ALMA/MMA	ALMA/Millimeter Array
AMS	American Mathematical Society
ASCI	Accelerated Strategic Computing Initiative
BIO	Biological Sciences Directorate
CERN	European Organization for Nuclear Research
CESR	Cornell Electron Storage Ring
CISE	Computer & Information Science & Engineering Directorate
CPP	Committee on Programs and Plans
DoC	U.S. Department of Commerce
DoD	U.S. Department of Defense
DoE	U.S. Department of Energy
DoI	U.S. Department of the Interior
EHR	Education and Human Resources Directorate
ENG	Engineering Directorate
EU	European Union
F&A	facilities and administration
FY	fiscal year
GAO	U.S. General Accounting Office
GEO	Geosciences Directorate
HEPAP	High Energy Physics Advisory Panel
HIAPER	High-Performance Instrumented Airborne Platform for Environmental Research
IA	Integrative Activities
INF	Task Force on Science and Engineering Infrastructure
IT	information technology
K-12	kindergarten through grade 12
LHC	Large Hadron Collider
LIGO	Laser Interferometer Gravitational Wave Observatory
MPS	Mathematical and Physical Sciences Directorate
MREFC	Major Research Equipment and Facilities Construction
MRI	Major Research Instrumentation
MSU	Michigan State University
NAS	National Academy of Sciences
NASA	National Aeronautics and Space Administration
NASF	net assignable square feet
NEES	Network for Earthquake Engineering Simulation
NEON	National Ecological Observatory Network
NHMFL	National High Magnetic Field Laboratory
NIH	National Institutes of Health
NNUN	National Nanofabrication Users Network
NRC	National Research Council
NSB	National Science Board
NSDL	National Science, Technology, Engineering, and Mathematics Education Digital Library
NSF	National Science Foundation
NSTC	National Science and Technology Council
OMB	Office of Management and Budget
OPP	Office of Polar Programs
OSTP	Office of Science and Technology Policy
PACI	Partnerships for Advanced Computational Infrastructure
R&D	research and development
R&RA	Research and Related Activities
RSVP	Rare Symmetry Violating Processes
S&E	science and engineering
S&T	science and technology
SBE	Social, Behavioral, and Economic Sciences Directorate

SMETE	science, mathematics, engineering, and technology education
SPARC	Space and Aeronomy Collaboratory
SRS	Science Resources Statistics
STPI	Science and Technology Policy Institute
TAIR	The Arabidopsis Information Resources
TCS	Terascale Computing Systems
UCLA	University of California at Los Angeles
UK	United Kingdom
U.S.	United States