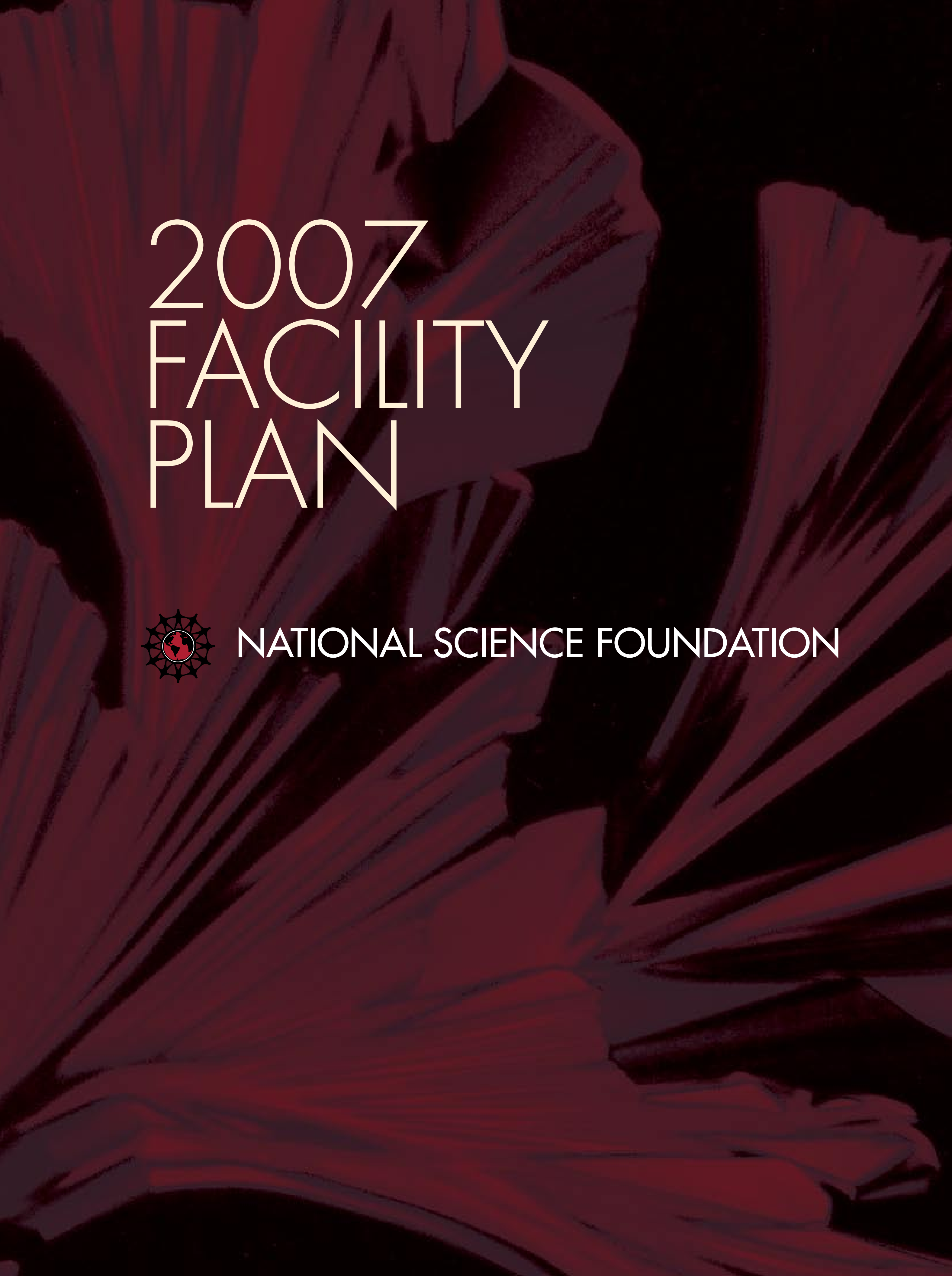
NATIONAL SCIENCE FOUNDATION

NSF 07-22

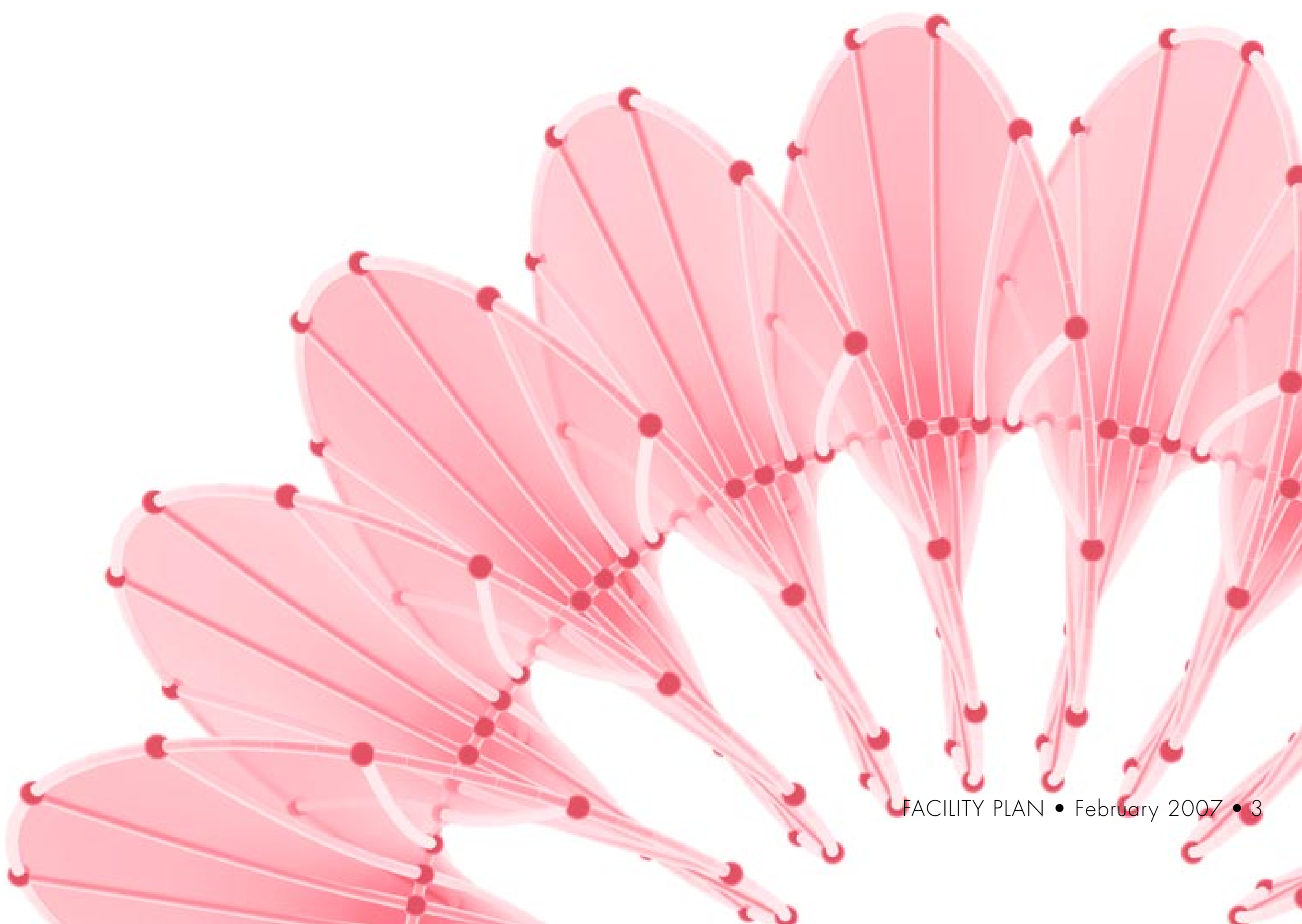
4201 WILSON BLVD
ARLINGTON, VA 22230

2007 FACILITY PLAN



NATIONAL SCIENCE FOUNDATION

TABLE OF CONTENTS



Following the release of the National Academies report, *Setting Priorities for Large Research Facility Projects Supported by the National Science Foundation*[1], the National Science Foundation (NSF) committed to develop and annually update the 2005 *National Science Foundation Facility Plan*[2].

As mandated in a joint management report by the National Science Board (NSB) and the NSF Director, *Setting Priorities for Large Research Facility Projects Supported by the National Science Foundation*[3], the Facility Plan combines into a single document:

INTRODUCTION

- a description of the frontier science and engineering goals and opportunities that provide context and demonstrate a compelling need for major facilities (Chapter 1);
- a status report on major facilities under construction and in various stages of development (Chapter 2 and Appendix I); and
- the process for selection of Major Research Equipment and Facilities Construction (MREFC) projects (Appendix I).

The Facility Plan supports and advances the *National Science Board* 2020 *Vision for the National Science Foundation*[4]. Specifically, the NSB vision directs NSF to "drive the cutting edge of fundamental and transformative research" and "provide the bright minds in our research institutions with the tools and instruments needed to probe the frontiers of knowledge and develop ideas that can transform our understanding of the world." To achieve this, NSB directs NSF, as a strategic priority, to "build the Nation's basic research capacity through critical investments in infrastructure, including advanced instrumentation, facilities, cyberinfrastructure and cutting-edge experimental capabilities."

The new NSF Strategic Plan, *Investing in America's Future, FY 2006-2011*[5], reflects the priorities of the NSB 2020 vision document and includes as a long-term investment priority the support of new capabilities, technologies and instrumentation needed for the next generation of major research equipment and facilities. Next-generation facilities will broaden opportunities for U.S. researchers, educators and students, and enable transformative research and education.

Identifying and funding the kind of tools that will truly transform research in science and engineering is an essential part of NSF's mission. As in all NSF endeavors, inquiry involves everyone—from the research communities to program staff—to identify the most promising and exciting opportunities and the most important equipment needed to explore them. NSF then assists the communities in refining their insights, forming a consensus, and focusing on paramount objectives and their corresponding hardware requirements. At that point, if a project clearly offers revolutionary potential, it may qualify for further consideration in a rigorous and deliberative process designed to select only the best of the best as candidates for substantial program funds or MREFC support.

As in any sort of exploration, the horizon keeps moving. Every year new opportunities will arise and new priorities will assert themselves. As a result, no roster of potential projects is ever final. Responsible stewardship of public funds demands that all candidate efforts be evaluated and reevaluated constantly in the context of the latest, most pressing research goals and the most profoundly important unanswered questions. To that end, the NSF/NSB report cited above, *Setting Priorities*[3], defines the process for developing, reviewing, approving and prioritizing large-scale research facility projects.

This process of identification and selection is, and must be, continuously repeated. Despite the stunning pace of research progress in the 21st century, the future success of entire fields critically depends upon development of new and powerful tools. Such projects are increasingly large and complex, with highly sophisticated Information Technology components, including distributed sensor networks and vast data-storage and transmission capabilities.

Costs of construction now typically extend to

---

1 Washington, DC.: National Academies Press. Available on-line at: http://www.nap.edu/catalog/10895.html

2 NSF 05-058, National Science Foundation. Available on-line at: http://www.nsf.gov/pubs/2005/nsf05058/nsf05058.pdf

3 NSB-05-77, National Science Foundation, September 2005. Available on-line at: http://www.nsf.gov/pubs/2005/nsb0577/index.jsp

4 NSB-NSF 05-142, National Science Foundation, December, 2005. Available on-line at: http://www.nsf.gov/pubs/2006/nsb05142/nsb05142.pdf

5 NSF 06-048, National Science Foundation, September 2006. Available on-line at: http:// www.nsf.gov/strategicplan

tens or hundreds of millions of dollars, with millions more required annually for decades of operation, maintenance, upgrades and retooling.

So great is the potential effect of these expenses that in 1995, Congress created a special, separate MREFC account to support the acquisition, construction and commissioning of major research facilities and equipment. It is intended to prevent such large expenditures from disrupting the budgets of NSF directorates and threatening NSF's traditional support of "core" research programs, which are funded from the Research and Related Activities (R&RA) Account, for which NSF has requested $5.13 billion in FY 2008. Typically, the threshold for MREFC projects is 10 percent of the annual budget of the proposing directorate or office. Most projects total much more.

But cost is by no means the sole criterion. Each MREFC candidate project must represent an outstanding opportunity for research and innovation, as well as education and broader impacts. Each should offer the possibility of transformative knowledge and the potential to shift existing paradigms in scientific understanding, engineering processes, and/or infrastructure technology over the lifetime of a project.

Moreover, each must serve an urgent contemporary research need that will persist throughout the often lengthy process of planning and development, and that will merit continued support during the Operations and Maintenance phase of the project.

The cumulative costs of operational support over the lifetime of a project are often larger than the initial MREFC construction costs. Those operation and maintenance expenditures cannot be funded from the MREFC account, but must be budgeted through the R&RA account. So it is essential that both NSF and the research community that benefits from an MREFC project agree that each project represents, and will continue to represent, the best use of resources in that research area for years, and often decades, to come.

The ensemble of facilities included in this Plan—those under construction or proposed, as well as future projects expected to result from current investments in planning and assessment—will enable the United States to maintain its position at the forefront of discovery and innovation, promote learning and training of researchers in science and engineering, and generate knowledge that enriches the nation.

The Facility Plan includes a discussion of the frontiers of science and engineering and the associated opportunities that provide compelling arguments for the need for new major facilities. It also includes status reports that describe progress on individual large facility projects currently in various stages of development, as well as a discussion of long-range opportunities that may or may not ultimately result in the construction of a new facility.

The first NSF Facility Plan was released in September 2005. Entirely new versions will be produced every three years, in concert with NSF's strategic planning cycle. Yearly revisions, such as this one, are released at the same time as NSF's annual budget request to Congress. This document generally preserves the format of the original Facility Plan, but also contains some new information:

- Chapter 1, a discussion of research objectives and opportunities, has been retained largely unchanged from the 2005 Facility Plan, because the factors shaping the context and criteria for future facilities have changed little in the intervening period.
- Chapter 2 contains updated descriptions of facilities under construction or planned in the near-term. These descriptions have been updated to reflect their progress since publication of the initial Facility Plan, and the narratives have been focused to avoid duplication with material already available in the NSF FY 2008 Budget Request to Congress.

Three minor changes have been made to the original Facility Plan:

- Chapter 2 now includes only sections on NSB-approved New Starts, and Readiness Stage Projects.
- Appendix I, Horizon Projects, is a fresh update of the material previously found in the section of Chapter 2 in the original plan entitled "Projects Under Exploration." Many long-range opportunities in which NSF invests planning support may never result in a proposal to construct a facility, or those investments may yield serendipitous results quite unanticipated at present. In view of these considerations, the emphasis within Appendix I has been shifted to describe NSF's current view of possible future facility opportunities. The Appendix no longer refers by name to any specific facility project.
- A summary of the criteria that proponents of a specific project or facility must satisfy in order to advance the project to the Readiness Stage of development has been added at the beginning of Appendix I.

CHAPTER ONE

RESEARCH OBJECTIVES AND OPPORTUNITIES AT THE FRONTIERS OF SCIENCE AND ENGINEERING

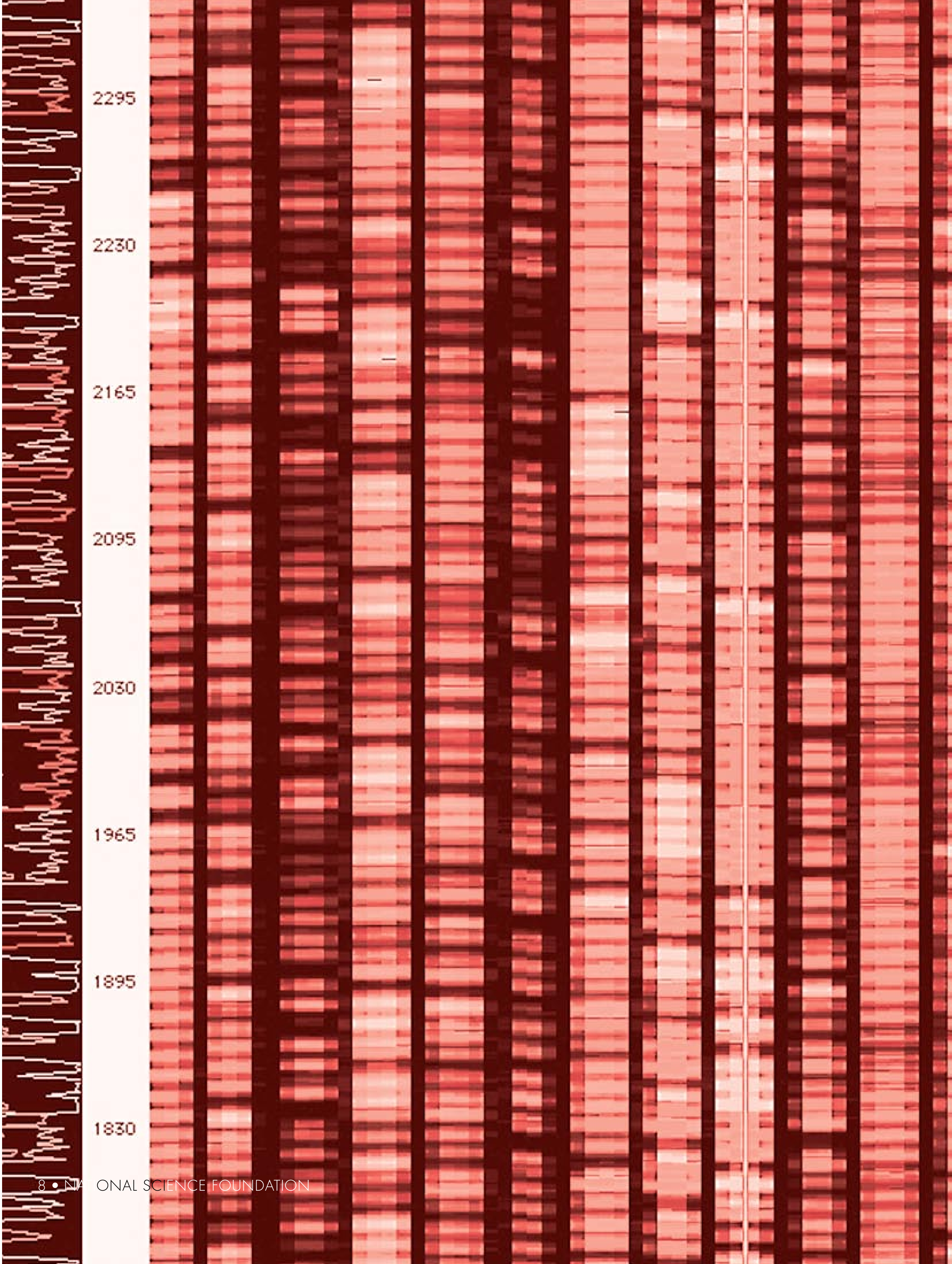
Research explorations operate at many frontiers simultaneously. One useful way to distinguish them is by physical scale of inquiry. There are fundamental questions to be answered across more than 50 orders of magnitude in space and time, ranging from the subatomic to the cosmic, and from quintillionths of a second to billions of years. Each scale presents special challenges—and special opportunities—for revolutionary facilities and the work they can make possible.

However, answering many of the most profound questions often will involve combining insights from two or more scales, and from radically different kinds of equipment. For example, progress in cosmology will demand dramatically improved understanding of particle physics, just as a complete understanding of gravity—the dominant force at astronomical distances—will entail reconciling it with quantum mechanics, the rules that govern matter and energy at the very smallest dimensions. Similarly, understanding global climate will entail integration of macro- and micro-scale surface and satellite data collection, combined with information from oceanography, atmospheric chemistry, social sciences and ecology, to name only a few.

The sections in this chapter address scientific goals and challenges according to their major physical scale range, including the multi-scale domain, and indicate how these goals and challenges give rise to compelling cases for the construction of new research facilities.

Many such challenges will also require a new generation of computing, communication, analysis and information technologies. These resources, some of which are now in development, are collectively known as cyberinfrastructure. They will enable researchers to conduct detailed experiments on computer models and to investigate phenomena that are inherently difficult to visualize. They also will serve one of NSF's major goals: to make possible information and resource sharing on an unprecedented scale, including instantaneous access to data repositories and tools for collaboration and analysis.

NSF's Office of Cyberinfrastructure (OCI) was created in 2005 to support the strategic development and deployment of cyberinfrastructure common to many science and engineering disciplines, to promote cyberinfrastructure interoperability in the United States, and to facilitate cyberinfrastructure investments in major research activities in fields ranging from high-energy physics to oceanography to ecology. Through coordinated planning and investments, OCI provides economies of scale and scope, ensuring that the agency's aggregated cyberinfrastructure investment is greater than the sum of its parts.


2295
2230
2165
2095
2030
1965
1895
1830

MESOSCALE 1

From Millimeters to Hundreds of Kilometers

Although this size range encompasses the familiar world in which we live—and in which most traditional science and engineering work has been done—it will never exhaust its mysteries. Indeed, entire new horizons of research have appeared in the past few years, thanks to developments made possible by the convergence of fresh insight and powerful new technologies.

Fundamental questions in a host of mesoscale fields can be answered satisfactorily only by using the next generation of tools.

THE BIOSPHERE

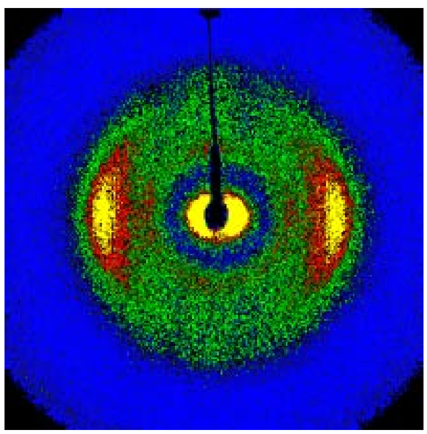
How can we detect, model and predict the ways in which coupled natural and human systems respond to different kinds of stresses and modifications? Such models must include the consequences of the interplay among air, water, land and biota, and predict the effects of altering one variable (e.g., a particular pollutant, precipitation or invasive species) on one or more other variables. Those effects, it now appears, can be hugely complicated and are frequently nonlinear. Understanding them will require novel collaborations of researchers and collation of data taken simultaneously in many ways at many physical and temporal scales.

It also will require researchers to view holistically different kinds of interrelated phenomena that never have been regarded as systems. For example: How do population trends, land use, and industrial and urban processes affect hydrological systems and water quality in rivers, lakes and estuaries? How can research about human and social behavior at all levels, from small groups to communities to regions—especially in response to crises or destabilizing events—lead to effective engineering approaches for managing these dynamic systems?

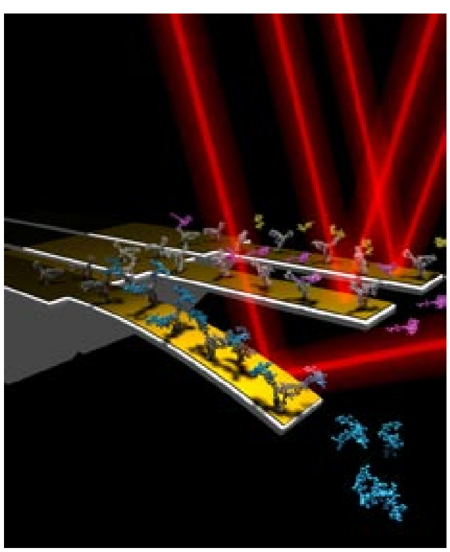
Such efforts will require new kinds of ecological observatories, enabling collection and integration of data from a number of different kinds of distributed sensors, both for empirical research and for creation of effective models. The results can profoundly affect our ability to understand the spread of infectious diseases, quality of water supplies in critical regions, stability of essential ecosystems, optimal engineering solutions to complex problems, and many other issues.

ENERGY AND WASTE

What are the essential power sources and industrial processes of the future? To a large extent, 21st century civilization is still running on 19th century technologies—most notably, combustion of fossil fuels. And humanity is still practicing a social paradigm unchanged in 100,000 years—burying or burning its copious wastes. Finding alternatives to those situations is one of the most pressing goals facing engineers, biologists, chemists and physicists. Fuel cells, photovoltaic devices, biologically produced fuels, and superconducting materials are only in preliminary stages of development, and they are merely the first generation of their kind. Fundamental research is needed to improve performance and identify new methods of storing and transporting energy. At the same time, investigators must devise much more efficient and benign forms of manufacturing, recycling and disposal, while discovering or creating new materials that blur the distinction between organic and inorganic, combining the characteristics of metals, films, polymers and ceramics.



This image shows the X-ray scattering pattern of a stretched DuPont fuel cell membrane, funded in part by an NSF EPSCoR grant.



This image illustrates cantilevers specifically modified for a biochemo-optomechanical chip being developed for high-throughput multiplexed biomolecular analysis.

INDIVIDUAL AND SOCIAL DYNAMICS

How can we understand the totality and complexity of human and organizational behavior? The integration of vast computing power, massive data sets, large complex models, and new analytical tools will be necessary to enable researchers to comprehend, simulate, visualize and predict such behavior. Among the many outstanding questions:

- How do organizational and collective behaviors differ from the behavior of the individuals within them?
- What forces shape the various subsystems of societies, such as the economy, the polity, and the legal system? What determines creativity and innovation at the individual and organizational levels?
- How do social and biological factors combine to shape human preference?
- How do emotions and cognition combine to influence human choices?
- How do people, organizations and social systems respond to sudden shocks and extreme events such as market collapses, ethnic violence, floods, earthquakes, tsunamis and terrorist assaults?

These questions cannot be answered without integrating information collected across a wide range of scales, from individuals and peer groups to regional and ethnic clusters, and throughout diverse disciplines from psychology and anthropology to economics and law. Ensuring the statistical validity of such unprecedented data sets presents a separate and equally formidable challenge to current understanding.

SENSORS AND SENSOR SYSTEMS

How can we detect subtle but potentially crucial changes in materials or the environment, and combine sensor signals into a coherent picture? Numerous scientific and technical problems—from making sense of collisions at a particle accelerator to monitoring the security of facilities to tracking alterations in brain activity or blood chemistry—require steady progress in two areas: developing ever more sensitive and ever smaller sensors, and devising robust systems of assembling multiple signals into useful information. Those objectives will require basic research that brings together specialties as diverse as surface chemistry, microelectronics, biophysics, photonics, information theory and mathematics.

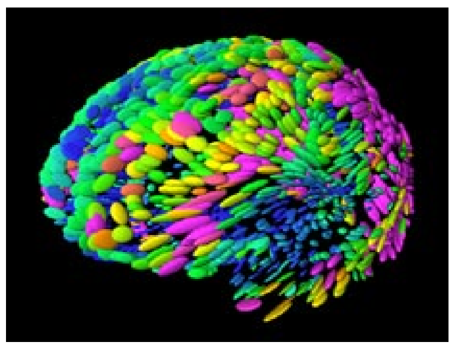
NEUROSCIENCE, COGNITIVE AND BEHAVIORAL SCIENCES

How are brain functions at the molecular, cellular, physiological and neural-network levels related to human functions such as memory, learning, and decision-making? Within the past two years, both invasive and non-invasive sensing technologies have expanded rapidly. It now is possible to design experiments that simultaneously measure brain function in large numbers of experimental subjects and/or interacting individuals. Indeed, we soon may be on the verge of characterizing at the neuronal level how people learn – that is, how the brain acquires, organizes, and retains knowledge and skills.

The goal is to better understand the biological underpinnings of behavior, as well as the ways in which behavior feeds back into neural activity. The implications of such research for educational theory and practice—as well as potential applications to various neural disabilities and other deficits—are extraordinary.

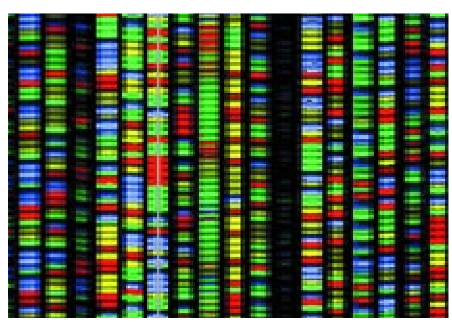
GENETIC AND OTHER DATA SETS

Across the stupendous spectrum of living things, what are the most significant similarities and differences? One of the most promising answers to that question entails the creation of comprehensive genome databases. At present, only a few organisms have been fully sequenced, and those sequences are still incompletely understood. Furthermore, broader and faster research is needed to answer basic, enduring questions such as: What is the minimal biological "tool kit" of living things? What biochemical and physiological processes are conserved across kingdoms and 3.5 billion years of evolution, and what major forms do variations take? What genes are responsible for human cognitive capabilities? And what are the origins and development of the human species and the nature of human adaptation processes over the last five to six million years?



Researchers have created virtual template brains that can assist in the study of anatomical differences related to aging and disease. The variation in color and shape of the spheres indicates the magnitude and principal directions of the anatomical differences across subjects.

Moreover, the current successes of genomic research have revealed new opportunities. No counterpart to GenBank, the public DNA sequence database maintained by the National Center for Biotechnology Information (NCBI), exists for other kinds of biological data (e.g., morphology, anatomy, ecology, behaviors or ontogenies). Serious efforts are needed to systematize the vast hoard of biological information.



The DNA sequencing process makes it possible for researchers to discover the amino-acid sequence in a substance.

MESOSCALE 2

Thousands of Kilometers

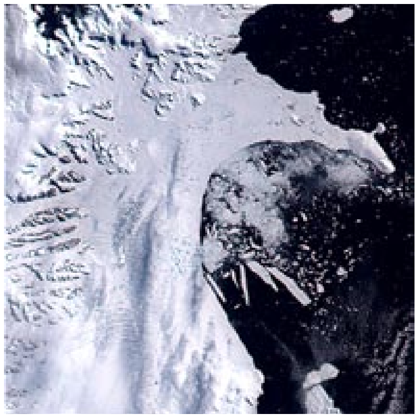
Thanks to a growing network of global sensors and data repositories, and a new awareness of relationships and "teleconnections" among disparate variables, it is increasingly possible to understand natural (and anthropogenic) phenomena on a planet-wide scale. Investigators are finally poised to expand understanding and predictability of the complex, interactive processes that determine variability in the past, present and future states of the Earth. These processes control the origin and current status of the forms of life on the planet, and affect the interdependencies of society and planetary processes.

GLOBAL ENERGY BUDGET AND PLANETARY "METABOLISM"

How can we better understand the links between physical and chemical processes by focusing on the exchanges of energy within and among the components of the Sun-Earth systems, including the oceans and atmosphere? Among other goals, progress is necessary to improve the accuracy and projective power of global climate models, and to understand how ocean circulation—and therefore climate—responds to global temperature changes. In addition, comprehending the present and future state of the planet demands improved and more detailed understanding of the links and feedbacks among physical, chemical, geological, biological and social systems; how these systems have evolved; and how they affect biocomplexity in the environment.

PLANETARY STRUCTURE

How do the shape and composition of Earth's components change over time, from the inner core to the upper atmosphere? Answering that question entails the detection of motion of the Earth's surface on the scale of millimeters per year, the deformation resulting from the buildup



One of a series of satellite images of the Antarctic Peninsula that recorded the catastrophic break-up of a massive portion of the Larsen B ice shelf—an area larger than Rhode Island—in 2002. NSF is responsible for managing all U.S. research activities in the Antarctic as a single, integrated program.

of stress by tectonic processes that lead to earthquakes, the deformation of volcanoes preceding eruption, and the movement of ice sheets and glaciers.

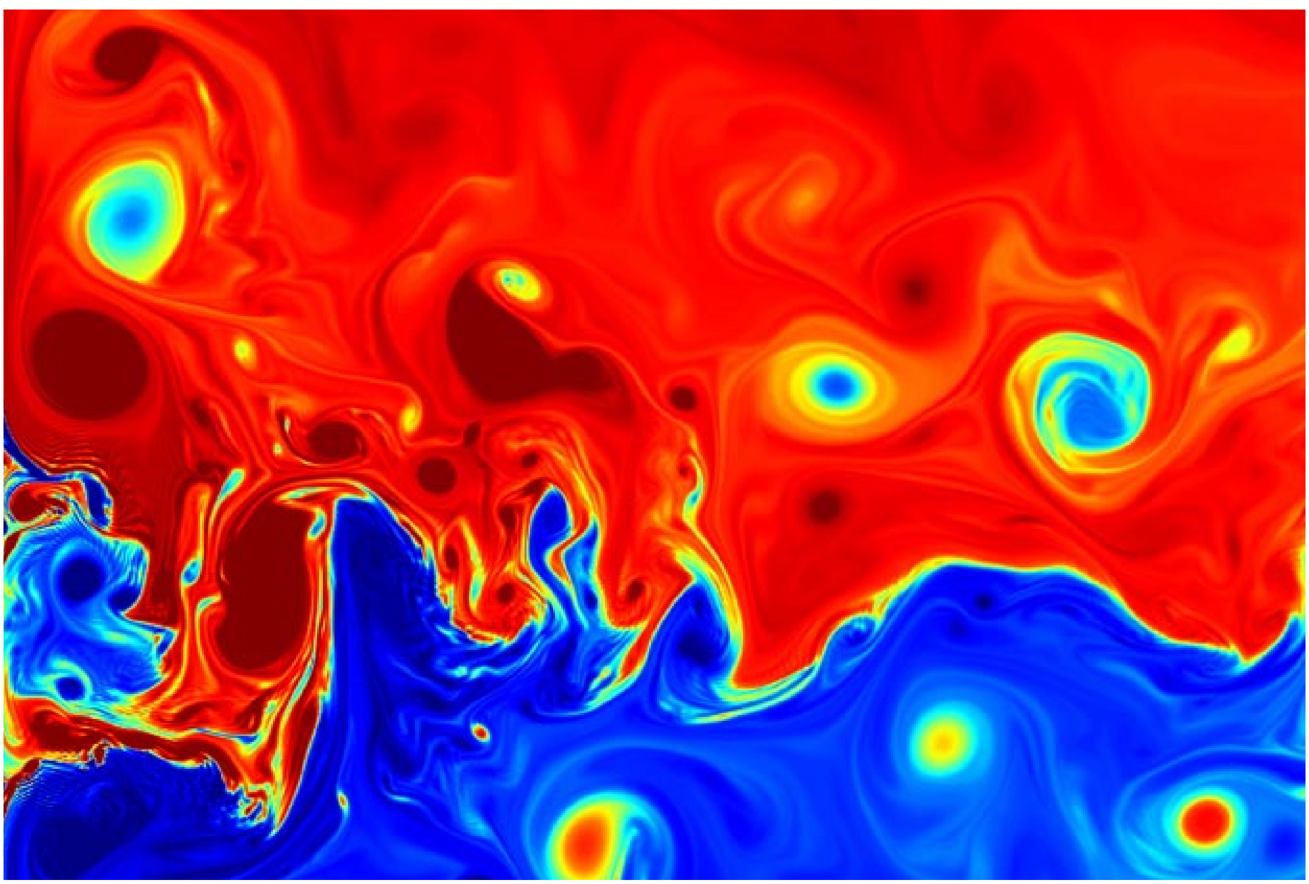
CHEMICAL BALANCE AND FUNDAMENTAL CYCLES

What processes determine the ways in which carbon, nitrogen, sulfur and other key elements cycle through the Earth's biological, geological and ocean systems? For example, what factors govern the amount of carbon sequestered in seawater and biomass, and what are the variables, parameters and limits of those processes? How much buffering, regulating or offsetting chemical action do natural systems offer to increased concentrations of man-made compounds, and what are the likely points at which irreversible changes may occur in chemical regimes?

WHOLE-EARTH MODELS OF BIOLOGICAL SYSTEMS

The dynamic simulation of biological systems at a global scale has, to date, been a major gap in large-scale simulations of global processes. A major integrated hardware and software effort could elucidate some of the most vexing questions in life sciences, such as: What is the biological "carrying capacity" of the Earth, and what are the effects of different variables on it? What is the optimal global spatial allocation of crops and livestock for sustainable production? How do alleles, genes and genotypes move dynamically through populations, organisms and ecosystems? What factors will allow us to predict accurately the occurrence of new species and the imminent extinction of others?

This image from a numerical simulation of an idealized wind-driven ocean basin, was produced on massive parallel computers at the San Diego Supercomputer Center.



MICROSCALE 1

Micrometers to Nanometers

In recent years, imaging, manipulation and testing of objects has become possible at smaller and smaller sizes and time scales. This has resulted in an explosion of progress across dozens of fields and holds the promise of truly transformational understanding of matter and energy. With today's equipment, even students can pick up and move a single atom on a surface. Researchers have learned how tiny modifications in the assembly, composition or placement of atoms and molecules produce strikingly different behaviors that can be customized for particular effects.

One of the most intriguing and valuable discoveries is the fact that the properties of matter can change dramatically as dimensions approach a nanometer (1 billionth of a meter, or about 10 atomic diameters).

Many devices already are exploiting these characteristics. For example, a structure called a "quantum dot" can hold just one electron, making it a "single electron transistor" hundreds of times smaller than those in today's most sophisticated microchips. Even mechanical systems such as gears, turbines, levers and fluid channels now can be constructed on the scale of a few microns (millionths of a meter—or about one fiftieth the width of a human hair), enabling investigators to create microchips for rapid analysis of blood or genetic material.

At the same time, miniaturization and growing sophistication of "photonic" devices, which generate and control light just as electronic devices generate and control electrons, are transforming communications and signal processing. Because light can move through matter much faster than electrons, and can carry many superimposed data streams at different wavelengths, photonics research promises spectacular changes in the speed of computing and information transfer.

Finally, research is now approaching another long-sought goal: to view chemical reactions in fine detail and in small time increments. Just as fast camera shutter speeds can "stop" even rapid motion, the advent of lasers with pulses as short as 1 millionth of a billionth of a second are making it possible to create "slow motion" images of chemical reactions, vastly increasing our understanding of the ways atoms combine or break apart.

Continuing fundamental research at the micro- and nanoscales will have a major impact on our comprehension of many important phenomena, including those described below.

MOLECULAR UNDERSTANDING OF LIFE PROCESSES

Our recently acquired ability to investigate fundamental biological functions at the molecular scale has revealed the marvelous complexity of microscale cellular processes—and in the process raised a host of truly profound questions, such as: How do proteins fold and bind, producing many of the essential biochemical reactions of life? How do membranes work to permit selective entry and exit of molecules and ions, enabling cells to interact with their surroundings? What are the molecular origins of the emergent behavior that underlies life processes from heartbeats and circadian rhythms to neurological activity? How do biological systems assemble themselves? How did the first biologically relevant molecules form and how did they organize into self-replicating cells? How does a single fertilized cell become a multi-cellular organism? And how does a common set of genes give rise to a wide range of morphologically and ecologically distinct organisms?

Medical researchers seek to apply those insights to treatments, and engineers require them for innovation in fields such as bioengineering and nanotechnology.

Biologists need to answer these questions to understand how organisms operate and evolve at the most fundamental level. It has been accepted for many years that everything in a living cell is connected to everything else; but mapping out the networks has been an extraordinarily difficult task.

Understanding gene expression, for example, involves thousands of genes and their products, many of which combine, cooperate, antagonize, and/or collaborate to regulate the expression of thousands of other genes at multiple levels. Modeling this enormously complex system will demand large amounts of new knowledge that microscale science promises.

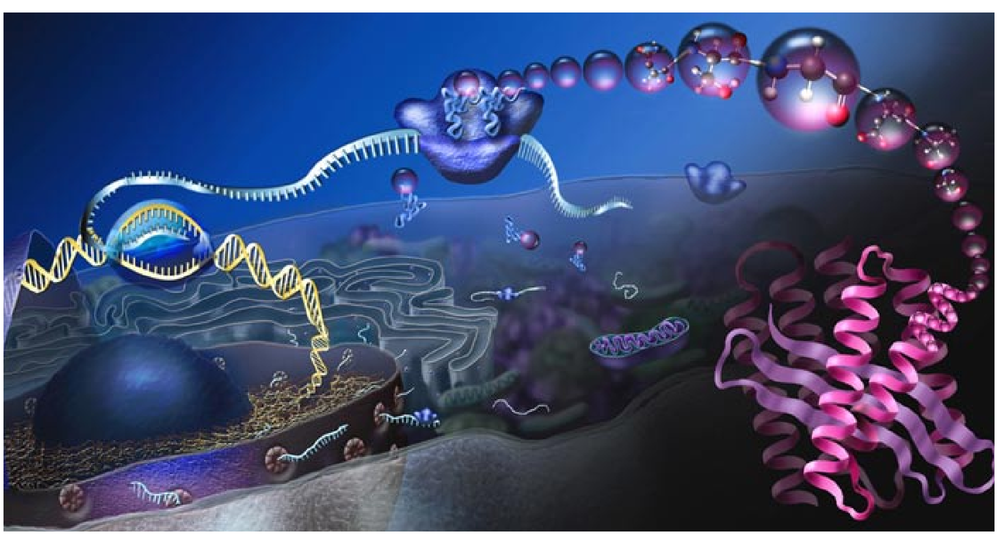
MOLECULES AND MATERIALS BY DESIGN

Among its "grand challenges" for chemistry and chemical engineering, a recent National Academies report urges researchers to "learn how to synthesize and manufacture any new substance that can have scientific or practical interest, using compact and safe synthetic schemes and processes with high selectivity for the desired product, and with low energy consumption and benign environmental effects in the process."

That will require knowledge of how to design and produce functional molecules, devices and systems from first principles, atom by atom, and will demand the ability to image and control individual atoms and molecules in three dimensions.

Investigators will

This artist's rendition of a cell shows the translation of DNA into RNA, and then the final protein product.



have to learn how to design and produce new material structures, nanoscale devices, and system architectures with properties that can be predicted, tailored and tuned before production.

In particular, that effort will include the understanding and exploitation of self-assembly.

Part of the challenge will be finding ways to mimic and modify the creation of natural substances as different as silk and seashells. Part will consist of creating entirely new compounds and structures that do not occur naturally. And part will combine both into hybrid materials with specific desired properties.

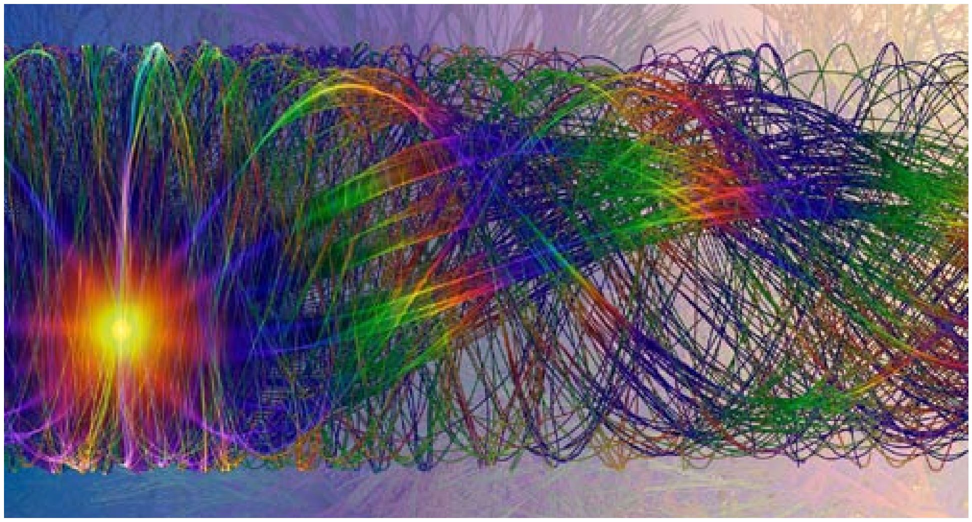
The results will prompt revolutionary scientific advances and engineering innovations in such areas as individualized pharmaceuticals, new drug delivery systems, more resilient materials and fabrics, catalysts for industry, and much faster computer chips, among others.

EFFICIENT MANUFACTURING AT THE NANOSCALE

New kinds of fabrication will require widely available instruments, metrics and positioning equipment that permit standardization and dimensional control on a scale much smaller than most existing facilities provide.

In order to advance new concepts for high-rate synthesis and processing of nanostructures and nanosystems, NSF's FY 2008 Budget Request for the National Nanotechnology Initiative calls for enabling scaled-up, reliable and cost-effective nanomanufacturing that integrates ultraminiaturized top-down processes and bottom-up or self-assembly processes.

A special focus will be on creating active nanostructures and complex nanosystems. Major research facilities will support this activity through the National Nanotechnology Infrastructure Network, Network for Computational Nanotechnology, and four Nanoscale Science and Engineering Centers focused on manufacturing.



This image illustrates electron paths in a nanowire, including imperfections in the wire. NSF has been a pioneer among federal agencies in fostering the development of nanoscale science, engineering and technology.

ELECTRONICS BEYOND SILICON

Since the arrival of the first miniaturized integrated circuits more than 30 years ago, the number of transistors that can be packed onto a microchip has increased exponentially, doubling approximately every 18 months. But this progression, known as "Moore's Law," cannot continue unless individual components are made much smaller—and engineers are reaching the physical limits of traditional semiconductor and metal devices. The next generation of microprocessors will rely on molecular-scale electronics.

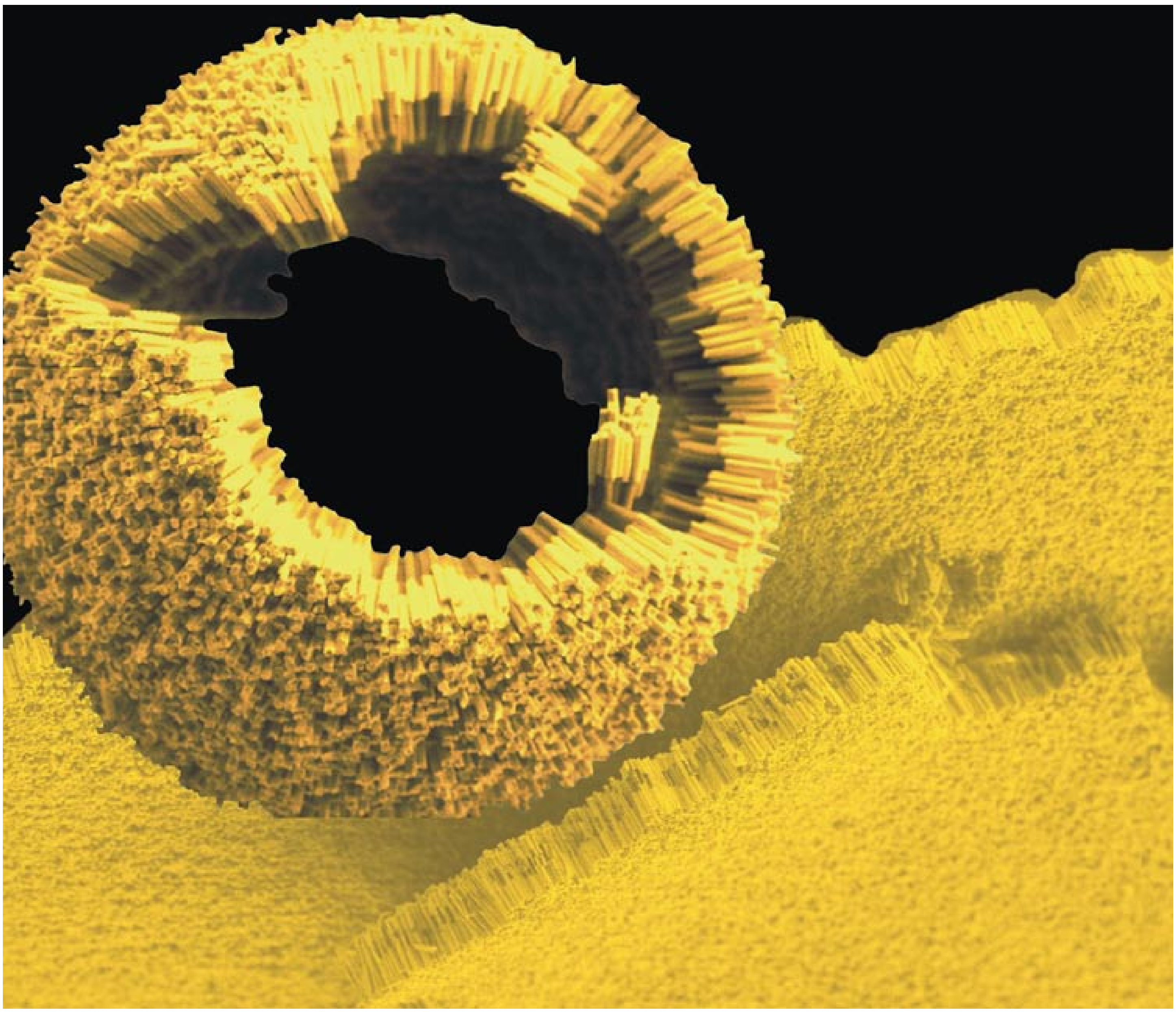
Making and controlling such nanostructures demands entirely new areas of knowledge and expertise. For example, among dozens of other problems, researchers will have to create novel architectures to accommodate drastically smaller voltages and currents, and find ways to make the processing elements synchronize with each other directly rather than follow a central clock.

At the same time, scientists and engineers will be struggling to construct useful "quantum computers" in which units of information—instead of existing only in one of two states (zero or one, on or off, as in conventional binary computers)—can be in a "superposition" of multiple states simultaneously. This condition, made possible by the often counterintuitive laws of quantum mechanics, can permit a variety of calculations to be made at once—potentially reducing the timetable for solving certain problems from years to hours.

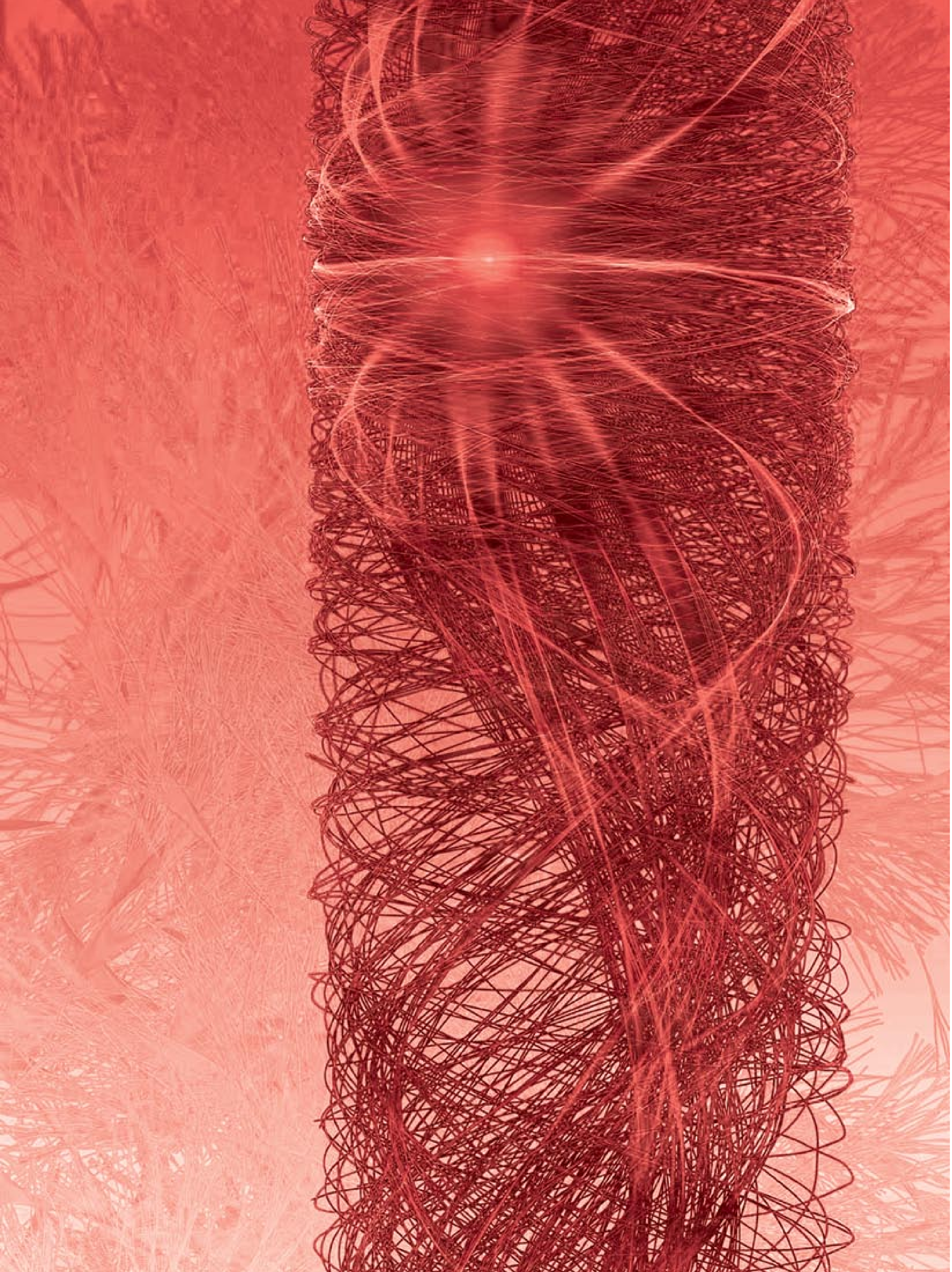
However, the same quantum uncertainty that makes the superposition possible also makes it intensely difficult to keep such a machine in a steady state and to read out information accurately. The obstacles to quantum computing are daunting and call for the utmost ingenuity in creating new instruments and devices.

NEW STATES AND BEHAVIORS OF MATTER

As recently as 10 years ago, physics recognized only four states of matter: solids, liquids, gases and plasmas. Then researchers devised equipment and techniques that made it possible to create an entirely new state—predicted by theory and called a Bose-Einstein condensate—in which multiple atoms coalesce into a single condition equivalent to one "super atom" at extremely low temperatures. This is only one of the peculiar phenomena that occur in such conditions, along with superconductivity and superfluidity, the flow of fluid without viscosity or resistance. Continuing research in the field of cryogenics, where work is done as close to absolute zero as possible, is expected to prompt the emergence of even more unusual properties.



Inspired by the molecular assembly techniques used in living cells, chemist Chad Mirkin and his colleagues at Northwestern University have created a new class of nanometer-scale building blocks that can spontaneously assemble themselves into ultra-tiny spheres, tubes and curved sheets.



MICROSCALE 2

Subatomic

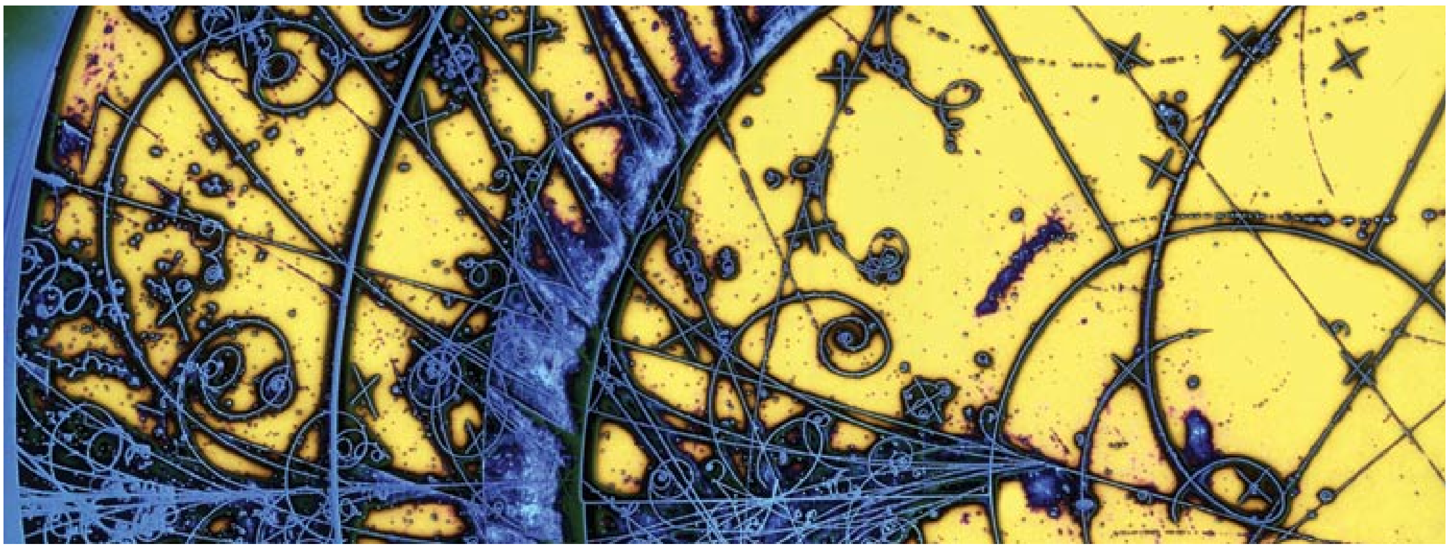
Over the past 100 years, research has revealed the structure of the atom, the substructure of its neutrons and protons, the existence of antimatter, and the behavior of particles that carry three of the four fundamental forces. This collective knowledge, embodied in the consensus theory of particles and interactions known as the "standard model," is one of the grand triumphs in the history of science, making predictions that can be confirmed by observation to 10 decimal places. But it is incomplete.

Among other problems, the standard model does not explain why the elementary particles have such a remarkable variety of masses, nor how the property of mass itself arises. It cannot account for certain inconsistencies, or "asymmetries," in the behavior of particles and their antiparticles. So both theorists and experimentalists are working to expand, refine or replace the model. In the process, they are asking the most fundamental questions possible. Among them: What is the full set of nature's building blocks? Have we detected them all, or are there a few—or dozens—more? How many space-time dimensions are there and did they emerge from something more fundamental? Is there a single, unified force that underlies electromagnetism, the weak and strong forces, and gravity? If so, how is it described?

Some of the answers, if they arrive, will be found on Earth at high-energy accelerators that smash particles into their antiparticles, creating brief showers of very exotic material. Physicists use exquisitely sensitive detectors to examine the results, in search of new particles and processes. Over the next decade, the Large Hadron Collider (LHC) at the European Organization for Nuclear Research (CERN) is expected to reveal—or possibly rule out—the existence of particles beyond the standard model. But many high-energy devices around the world will be required to conduct complementary and confirmatory research. And researchers will be watching those results closely to see if they provide support for "string theory," which posits that what we regard as different kinds of particles actually are simply different vibration modes of infinitesimal string-like entities comprising 10, 11, or more dimensions.

At the same time, particle physicists are teaming with astronomers and astrophysicists to use the awesome variety of extreme conditions detectable in space as "laboratory specimens" for new theories of matter and force. Many experts now believe that any complete revision of the standard model will have to combine ground-based and astronomical observations into a comprehensive understanding.

Some of the most interesting phenomena, and many of the most potentially revolutionary theories, span spatial scales from the smallest to the largest. To cite only two: What is the connection between elementary particles and the dark matter and dark energy that make up 95 percent of the universe? And how do the properties of individual atoms and molecules interact to create the properties of bulk materials?



(Top) This artistically enhanced picture shows particle tracks in the Big European Bubble Chamber.

(Bottom) NSF's contribution to the international LHC project includes support for the construction of two detectors, ATLAS and CMS. The ATLAS tile calorimeter will collect the energy released in the LHC's proton-proton collisions. Special plastic manufacturing techniques have been adapted to mass-produce the ATLAS elements.

MACROSCALE 1

Millions of Kilometers to Thousands of Light Years

In science, new answers always bring even newer questions. That clearly has been the case during the past quarter century, which constitutes a golden age of discovery in astronomy and cosmology. Through powerful tools and ideas, astronomers and physicists have extended our vision further out in space and our understanding further back in time. They also have uncovered new puzzles, unexplained phenomena, and areas of interest. The list is long, and begins close to home.

LIVING WITH THE SUN

A deep understanding of our local star, the Sun, is enormously important for many practical reasons – including the need to anticipate solar events, to protect against their effects on communications, and to discern the Sun's stability and its role in Earth's climate and evolution. Comprehending solar phenomena also will provide a wealth of information about millions of similar stars in the universe, and particularly about the activity and variability of solar-type stars.

Specific research questions regarding solar/terrestrial connections include: What are the processes that cause solar variability? What are the mechanisms responsible for powerful solar activity such as solar flares and coronal mass ejections? What is the impact of solar activity on terrestrial communications and power systems? What is the connection between solar activity and space weather? What is the origin of the Sun's 22-year solar cycle, and why is it manifested in the number and location of sunspots? How does the solar dynamo work to create the star's titanic magnetic field? What powers the solar corona, which is hundreds of times hotter than the surface of the Sun?

Star trails surrounding the South Celestial Pole appear to spin over the Gemini South dome. Digital images obtained every minute for a period of about 4.5 hours were combined to create this image.

Answering these questions fully will require new and very sophisticated devices and telescopes, both Earth-based and space-based. It also will demand instruments that can discern fine structure in the magnetic fields and trajectories of solar plasma, whether in "active regions" in and around sunspots or within ejected material in prominences, flares and coronal mass ejections.

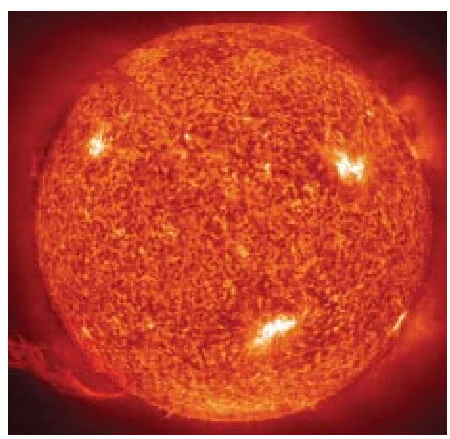
OUR GALAXY AND ITS NEIGHBORS

It has been decades since the presence of "dark matter"—the invisible material that makes up much of the mass of the universe—was first inferred from the rotation of spiral galaxies. Yet its nature is still a mystery. Further understanding will combine astrophysical observations with Earth-based efforts at detection, several of which are already under way. Those activities, in turn, will have to be tempered by and reconciled with discoveries in particle physics from existing and future accelerators and other facilities.

Conversely, it was only a few years ago that astronomers produced the first evidence of planets around stars besides our Sun. Now about 150 are known. But it is still unclear how planets form, what mechanisms determine their composition, and whether there are habitable analogues to Earth in nearby space. Much higher telescopic resolution, and new sensor suites, will be needed to begin to probe these mysteries.

Different science will be required to explain many ultrahigh-energy phenomena observed recently, from gamma-ray "bursters" to superenergetic cosmic ray particles whose method of acceleration is unknown but may indicate new phases of matter.

Finally, the sky is full of stars—there are about 100 billion in our galaxy alone. Yet there still is insufficient understanding of how stars form, what factors determine their ultimate qualities, how long they live, and how they die. There is evidence of stars in our region of space that are nearly as old as the universe itself. And there may be stellar phenomena that we have not yet observed.



Millions of miles away, coronal mass ejections from the Sun blast billions of tons of plasma toward Earth's magnetosphere with the potential to disturb space systems, power grids and communications.

MACROSCALE 2

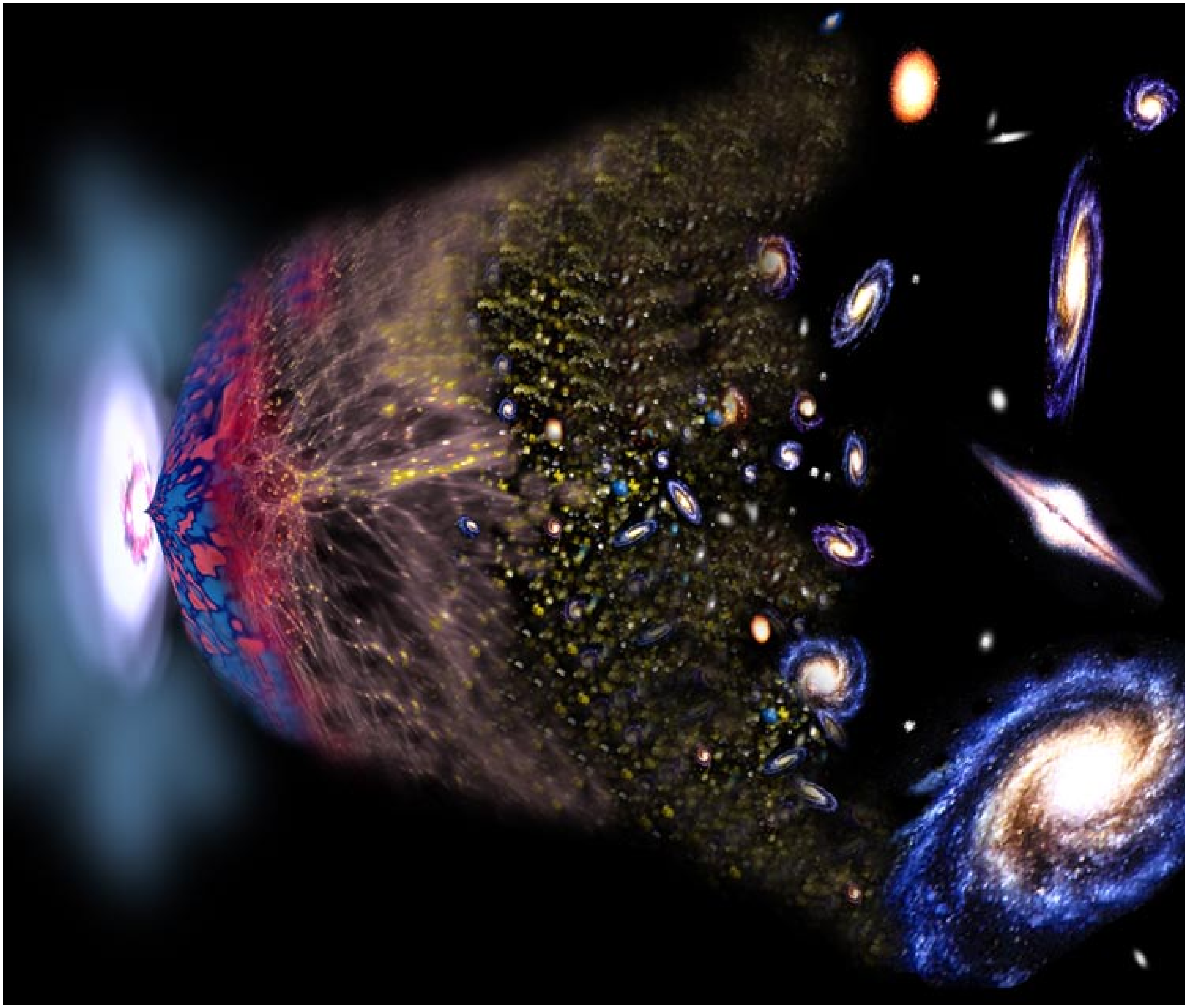
Millions to Billions of Light Years

Some recent discoveries have shaken conventional ideas so fundamentally that they are obliging researchers to rethink some of their most familiar notions. For example, our understanding of cosmology was challenged less than a decade ago when researchers produced evidence that the expansion of the universe—known since the early 20th century and presumed to be relatively constant—was in fact speeding up.

What currently undetectable "dark energy" could be fueling that expansion? What does it mean for the destiny of our universe? What are the components of the 95 percent of the cosmos that is not made up of ordinary matter? And what do the new revelations portend for our comprehension of elemental forces?

Gravity is perhaps the most spectacular example. It was the first fundamental force to be understood scientifically, when Newton united the heavens and the Earth through his equations. Maxwell's equations then united the forces of electricity and magnetism in the theory of electromagnetism, and a century later electrodynamics was explained on the quantum scale. The strong and weak forces were characterized with varying degrees of success. By the end of the 20th century, it appeared to many observers that nature's fundamental interactions were, at last, comprehensible, requiring only some refinements and calibrations.

That was by no means the case. Einstein's Theory of General Relativity revealed much about the force of gravity on the cosmic scale. But if it is to be part of a truly cohesive and complete description of what shapes the universe, gravity must be made consistent with quantum mechanics, the rules that govern interactions



at the smallest spatial scales. So far, the two theories are incompatible. Researchers expect that current and future gravitational wave observatories will add abundant insight by detecting space-time perturbations that occur when two neutron stars or two black holes collide.

Attempts to reconcile gravity and quantum theory also will have to take place in the context of other large questions about the origin and evolution of the cosmos, including: What was the "Big Bang" that produced the universe some 13.7 billion years ago? Did the cosmos experience a split-second period of "inflation" that expanded it? How and where did the chemical elements form, and how has the composition of the universe evolved? How did galaxies form, and how are they evolving?

This artist's conception illustrates the history of the cosmos, from the Big Bang and the recombination epoch that created the microwave background, through the formation of galactic superclusters and galaxies themselves. The flaring emphasizes that the universe's expansion currently is speeding up.

This image of the Pelican Nebula was produced by the National Optical Astronomy Observatories survey program.

MULTI-SCALE
or Scale-Independent Objectives

Finally, some of the most ambitious research objectives transcend scale, and achieving them will have repercussions across numerous disciplines and dimensions.

COMPUTER SCIENCE

What is computable? What computable functions can machines perform in bounded, practical amounts of time? What are the principles of organization and the structures of software that will permit increasingly large collections of machines to work together effectively on a common problem? How can collections of machines communicate with each other effectively? What principles underlie the activities of humans (perhaps aided by other machines) in the task of designing hardware and software?

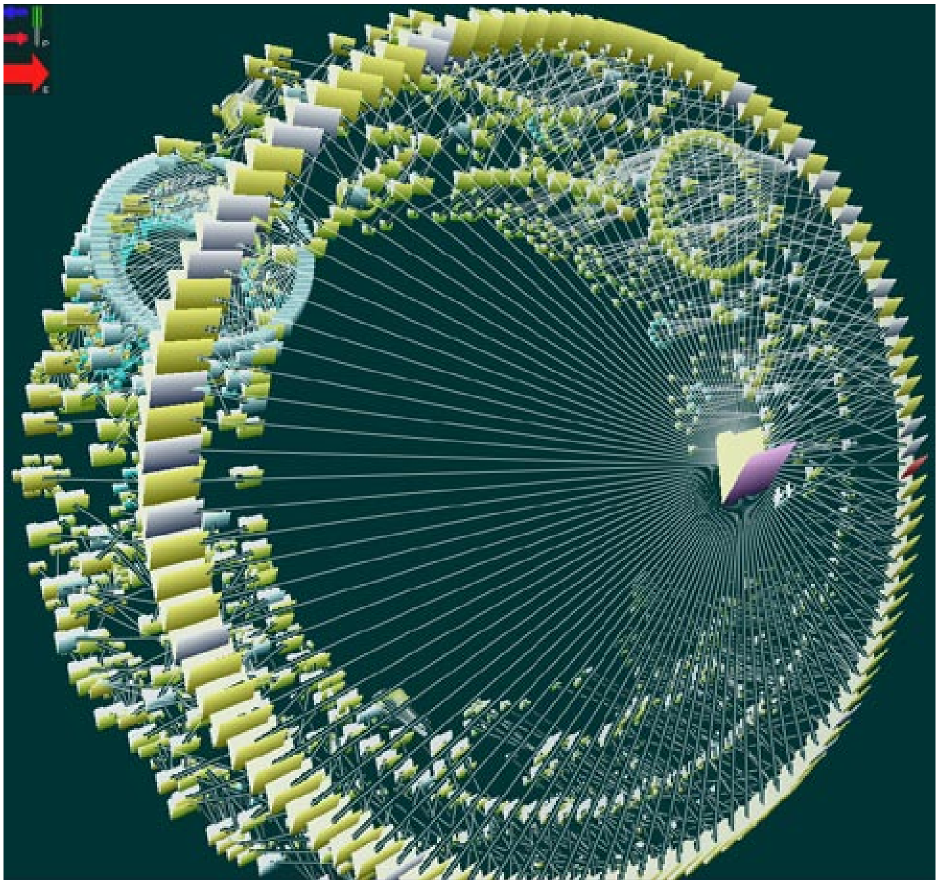
How can interlocking systems, or "networks of networks," be made secure, fault-tolerant, and robust to the greatest degree possible? How can those systems be integrated with social and cultural norms so as to provide the greatest utility to populations in times of crisis? How can vast databases be organized so that they can be queried rapidly?

What are the limits of artificial intelligence, and how can they be approached to expand human cognitive capabilities? Can heuristic or probabilistic decision schemes be maximized in machine intelligence? What are the possibilities of computerized learning? How can we manage and oversee the structure of complex computer systems with millions or billions of components? And how can systems with different characteristics and/or architectures communicate—especially in searching for patterns in enormously large data sets?

MATHEMATICS

How can uncertainty be quantified and controlled? Which mathematical structures best describe multi-scale phenomena? How can large data sets be mined for information? How fast can large numbers be factored? And how can data be archived so as to be accessible decades from now?

How can we best model complexity, self-organization and "chaotic" or nonlinear phenomena? How can patterns of data—including "unvisualizable" situations such as geometries in more than four dimensions, or sensor data streams from diverse instruments—be assembled into shapes and structures that have explanatory meaning? What rules govern complicated natural processes from the differentiation of cells and the expression of genes to the folding of proteins or the self-arrangement of crystalline nano-

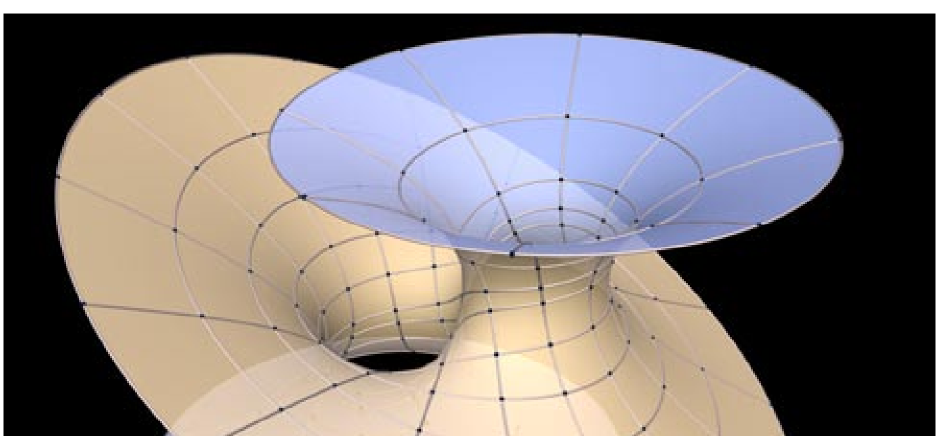


This Ferris wheel-like arrangement may be the next elegant solution for managing unwieldy amounts of information. The three-dimensional interface organizes computer contents by their relationships rather than their physical position on a hard drive. The program displays relationships that would not be clear in a normal, two-dimensional file tree and could be applied to any sort of hierarchical database.

structures? What sorts of algorithms are suitable to test systems—such as multibillion-transistor computer chips or 100-billion-neuron human brains—whose total possible data routes are astronomically large?

What sorts of mathematical forms best achieve different kinds of optimization, from efficient transportation and manufacturing networks to maximum return on financial portfolios to deployment of armies and materiel? How can rare events of interest be extracted from huge data sets? How can significant patterns be discerned from the inherent "noise" and stochastic artifacts that arise in such large collections? Similarly, how can one identify, record and analyze the complicated interplay of many covariables in large systems—whether ecological, social, neurological or geophysical?

So profound are the foregoing questions, and so uncertain the approaches to answering them, that the requisite instruments and facilities can barely be imagined at present. They will test the limits of science and engineering, and the power of human ingenuity.



This surface illustrates the failed attempt to construct a complete, properly embedded, minimal surface with three ends and without a handle. No matter what one does, the three ends cannot all be horizontal simultaneously, and thus eventually will intersect.

CHAPTER TWO

MAJOR RESEARCH EQUIPMENT AND FACILITIES CONSTRUCTION PROJECTS

MREFC-funded construction projects proceed through a progressive sequence of increasingly detailed development and assessment steps prior to approval for construction funding. Initially, NSF reacts to opportunities articulated and advocated by the research community during the Horizon process. These ideas are subjected to external merit review, and those ideas or concepts of exceptional merit are further developed into conceptual designs that define the key research questions the proposed facility is designed to answer. Ideas and concepts in this category are defined to be Horizon Projects. For the most promising projects, NSF directs proponents to include within their conceptual designs a description of the functional requirements of the major subsystems of the proposed facility that flow down from the key research questions, accompanied by: a top-down budget estimate; a risk assessment and the corresponding contingency budget needed for risk mitigation; and a projection of future partnerships possible during further development, construction or operation. Concurrently, NSF develops an Internal Management Plan that defines its strategy for conducting oversight during more intensive pre-construction planning, and also for funding this activity and laying out off-ramps should project development not progress as planned. NSF then conducts a Conceptual Design Review (CDR). If the project is determined to meet Readiness Stage requirements, NSF requests proponents to provide a Project Development Plan (PDP) that details the scope, schedule and budget needed to develop the project's Preliminary Design. At this point, if NSF approves the PDP, this activity is carried out in the Readiness Stage.

The goal of the Readiness Stage is to identify and quantify all of the key cost drivers associated with the proposed project into a Preliminary Design, providing detailed descriptions of all major facility subsystems and their interconnections, a bottom-up cost estimate with substantiation for the basis of estimate, a detailed risk assessment and algorithmically based contingency estimate, and a resource-loaded schedule. The project also assembles key members of the team that will build the proposed project if it is funded for construction. NSF, utilizing external experts having the requisite skills to assess all of the major elements of the construction plan, reviews it in a Preliminary Design Review (PDR). If NSF approves the Preliminary Design, it requests NSB to approve the project's inclusion in a future NSF Budget Request to Congress. Should the NSB approve, the project is classified as a Possible New Start.

While in this stage, the project continues to refine cost estimates, recruit additional construction staff, and finalize partnership commitments. A final pre-construction design is prepared and reviewed by NSF, using the same rigor as the PDR. If successful, NSB is requested to authorize NSF to obligate funds to the proponents to commence construction. Projects in this category are in the Construction Stage.

This chapter provides brief status reports on MREFC-funded projects currently under construction, along with those proposed by NSF as New Starts in FY 2007 or later. Also included is a status report on the project currently in the Readiness Stage.

These status reports provide descriptions of the science opportunities and specific facility research objectives that motivate construction, in the context of each project's respective research community needs. Where applicable, the status of interagency, international, or industrial partnerships, agreements and co-funding is also described. Furthermore, NSF's role as described in its oversight plan, along with recent oversight activities and assessments planned within the next two years or so, are also included, as well as additional project-specific issues.

For many major research facilities, there is substantial overlap of the construction and operations stages, with initial operations beginning well before construction is complete, and ramping up to full operation as the construction and commissioning activities conclude. Estimates for operations and maintenance budgets are provided.

Within each project description, references are provided for additional information available on external Web sites. There is also additional detail on each project in the annual NSF Budget Request to Congress that has not been duplicated here, but which is available within the MREFC and Facilities chapters of the NSF FY 2008 Budget Request, accessible at http://www.nsf.gov/about/budget/fy2008/.

The status reports follow in the order shown in the table on page 32, which displays financial data from NSF's FY 2008 Budget Request to Congress and lists all projects that are under construction or are Construction Ready, along with their anticipated construction budget profiles. Project budgets have been updated since the last Facility Plan was written.

The major horizontal headings within the table reflect the chronological progress towards completion for the various projects. Both the High Performance Instrumented Airborne Platform for Environmental Research (HIAPER) and the South Pole Station Modernization Project (SPSM) are largely complete and in operational use, although some construction work remains.

There are four ongoing construction projects: the Atacama Large Millimeter Array (ALMA), EarthScope, IceCube, and the Scientific Ocean Drilling Vessel (SODV), which will complete their construction on different time scales. In the case of ALMA, the budget has been substantially augmented to reflect re-baselined budget estimates for antenna procurement, added costs resulting from unanticipated complexities of the international partnership arrangements, and the changing Chilean business environment.

MREFC funds were requested for commencement of construction for three projects in FY 2007: Alaska Regional Research Vessel (ARRV), National Ecological Observatory Network (NEON), and Ocean Observatories Initiative (OOI). In each case, a Final Design Review, utilizing an external panel of experts in the various disciplines and skills necessary to construct the project, will scrutinize the project budget, scope, schedule, and management plan. The results are evaluated by NSF prior to requesting NSB approval to obligate construction funds. In the case of NEON and OOI—for which approval by the NSB to request congressional appropriation of MREFC funds significantly predates NSF's Guidelines for Planning and Managing the MREFC Account[1]—CDRs and PDRs will also be conducted. This may result in alterations to the present budget magnitude and spending profile as these planning and assessment activities progress. In every case, NSB will be informed of the results of this oversight and assessment activity. Should NSF operate under a full-year Continuing Resolution, commencement of construction activities would be deferred until MREFC funds are appropriated.

One project, Advanced Laser Interfero-meter Gravitational Wave Observatory (Adv LIGO), is described as a possible new start in FY 2008. This project has completed a PDR to vet the project scope, budget, schedule, risks and partnerships, and has had annual cost updates to make sure that the budget information reflects current understanding of likely costs. Another cost update is planned for 2007.

One project, Advanced Technology Solar Telescope (ATST), is in the Readiness Stage, where its total budget and an obligation profile are being developed. For that reason, it is not listed in the table on the following page.

1 See http://www.nsf.gov/bfa/docs/mrefcguidelines1206.pdf

MREFC ACCOUNT STATUS

(Dollars in Millions)

	FY 2005 and Prior Actual	FY 2006 Actual	FY 2007 Request	FY 2008 Estimate	FY 2009 Estimate	FY 2010 Estimate	FY 2011 Estimate	FY 2012 Estimate	FY 2013 Estimate
PROJECTS IN PROCESS OF COMPLETION									
High Performance Instrumentation Airborne Platform for Environmental Research (HIAPER)	81.50								
South Pole Station Modernization (SPSM)[1]	120.41	13.07	9.13	6.55					
PROJECTS UNDER CONSTRUCTION									
Atacama Large Millimeter Array (ALMA)[2]	143.31	48.66	64.27	102.07	74.75	42.76	21.44	3.00	
EarthScope	117.85	49.62	27.40						
IceCube	122.33	56.44	28.65	22.38	11.33	0.95			
Scientific Ocean Drilling Vessel (SODV)	6.08	66.03	42.88						
NEW STARTS IN FY 2007									
Alaskan Regional Research Vessel (ARRV)[3]			56.00	42.00	25.00				
National Ecological Observatory Network (NEON)[4]			4.00	8.00	20.00	30.00	26.00	12.00	
Ocean Observatories Initiative (OOI)[5]			5.12	30.99	80.00	90.00	95.00	30.00	
POSSIBLE NEW START IN FY 2008									
Advanced Laser Interferometer Gravitational Wave Observatory (AdvLIGO)[6]				32.75	51.43	46.30	15.21	23.73	15.50
TOTALS		$233.81	$237.45	$244.74	$262.51	$210.01	$157.65	$68.73	$15.50

Note: Table may not add due to rounding.

[1] The SPSM cost to complete was updated in August 2006. The revised work plan, schedule and estimate were reviewed in detail by an external panel in September 2006. The FY 2008 estimate reflects the cost to complete the remaining scope of the project in accordance with the revised schedule.

[2] ALMA increased by $16.38 million in FY 2007, and the total project cost increased from $344 million to $499 million following FY 2006 re-baselining. In FY 2007, NEON and OOI are reduced by $8 million and $8.38 million respectively to cover ALMA's increase.

[3] The ARRV funding profile includes an additional $25 million in FY 2009 to cover increases identified in the November 2006 independent cost estimate.

[4] NEON's revised baseline is expected in May 2007 following a Preliminary Design Review (PDR). The reduced funding in FY 2007 and FY 2008 is restored in FY 2012.

[5] NSF plans to conduct a PDR of OOI in December 2007 that will review the future year funding estimates shown here.

[6] The AdvLIGO estimate reflects the formal project baseline reviewed by the external panel convened by NSF in June 2006.

STATUS REPORTS

PROJECTS IN THE PROCESS OF COMPLETION

HIGH-PERFORMANCE INSTRUMENTED AIRBORNE PLATFORM FOR ENVIRONMENTAL RESEARCH (HIAPER)

Facility Objectives: A medium-altitude, long-duration jet has been a requirement of the science community since the 1980s. Scientists and program managers from several agencies—NSF, National Aeronautics and Space Administration (NASA), National Oceanic and Atmospheric Administration (NOAA), and Department of Energy (DOE), along with the university community—collaborated to determine the specific requirements for the research platform (duration, range, payload and altitude) that will satisfy many of the requirements of the broad environmental research community. A Gulfstream V was selected as the platform of choice (one of two aircraft certified to meet the altitude requirement). Over a period of several years, modifications to the airframe were made; in October 2005, the Federal Aviation Administration certified the modifications and the aircraft was ready to begin its initial science missions.

The expected operational lifetime of the HIAPER aircraft is 25 years.

Status: The aircraft was constructed, modified and delivered on schedule and within budget. A total of 15 research instruments that will be installed on the airframe are currently under development, with a delivery schedule that extends until early 2009.

The facility completed its first major scientific project, the Terrain-Induced Rotor Experiment (T-REX), in 2006. T-REX was an interagency and international research program that also included the University of Wyoming's King Air (an NSF-supported facility) and the UK's BAe 146 research aircraft.

Partnerships: NASA, NOAA, private industry and the university community are active participants in the development of HIAPER instrumentation. Germany's Aerospace Research Center and Space Agency has acquired a Gulfstream 550 aircraft, and its modifications are consistent with those on HIAPER, thus facilitating commonality of instrument use and operations.

NSF's Role: NSF's HIAPER program officer provides oversight to the HIAPER Project Office at the National Center for Atmospheric Research (NCAR), which maintains and operates NSF's aircraft. All documents (e.g., Implementation Plan, Risk Management Plan) were approved by the NCAR Director and the NSF HIAPER program officer.

NSF's annual support for aircraft operations is estimated at $5 million through the R&RA account of NSF's Directorate for Geosciences (GEO), Division of Atmospheric Sciences (ATM).

Additional information

on HAIPER can be found at http://www.hiaper.ucar.edu/ and http://www.atd.ucar.edu/raf/HIAPER_P_HAIS_I_Availability.html.

SOUTH POLE STATION MODERNIZATION PROJECT (SPSM)

Facility Objectives: The SPSM project provides a new station to replace the current U.S. South Pole station, built three decades ago and now inadequate in terms of capacity, efficiency and safety. The new station is an elevated complex with two connected buildings, designed to support 150 people in the summer and 50 people in the winter. The station was designed to support research that can only be conducted at the South Pole. Features include a "quiet sector" to support monitoring of the Earth's seismicity, a "clean air sector" for research in atmospheric chemistry, and a "dark sector" to support astronomy and astrophysics. The expected lifetime of the modernized station is 24 years, through 2031.

Aurora Australis, the Southern lights, appear over NSF's Amundsen-Scott South Pole Station. This image shows the atmospheric phenomenon over a wing of the new station.

Status: Construction of the new South Pole Station is approximately 90 percent complete and on a newly revised schedule to finish the remaining work by FY 2010. All eight wings of the elevated station became operational on or before February 2006. The remaining work includes completing installation of siding on the station and construction of the cargo/warehousing facility. The project schedule is being extended to FY 2010 to allow redirection of much of the tightly constrained South Pole construction resources to installation of the IceCube neutrino detector and the South Pole Telescope during 2007 and 2008.

The construction budget has evolved from its original estimate of $127.90 million in FY 1997. Funds for a change in project scope to increase the station capacity from 110 to 150 people and for a schedule extension due to weather-induced delays were provided in FY 2003, increasing the budget to $133.51 million. As a result of an updated project cost and schedule review completed shortly after the end of the 2004/2005 operating season, the estimated total cost of SPSM rose to $142.71 million. An external review in September 2006 led to an updated total estimated cost at completion of $149.3 million, due to increases in logistical support costs, labor rate adjustments, and allowances that mitigate risks due to weather delays and other variable factors such as the ability to hire sufficient numbers of skilled personnel.

No SPSM MREFC construction funds were requested for FY 2006; $9.13 million was requested for FY 2007, and $6.55 million is requested in FY 2008.

The FY 2008 budget request provides resources to complete construction activities on a revised schedule that will allow for final acceptance of all SPSM scope on or before FY 2010 .

Partnerships: In the 1990s, NSF and the Office of Science and Technology Policy agreed that the SPSM should be a U.S. project. This was echoed in a recommendation made in the *Report of the U.S. Antarctic Program External Panel*: International cooperation in scientific research and logistics support should be encouraged, but permanent facilities and infrastructure at permanent U.S. sites in Antarctica should be provided by and maintained by the United States. The geopolitical significance of the South Pole Station, sitting at the apex of the territorial claims of seven nations, was a major factor in this decision not to seek international partnerships for SPSM construction. An additional factor was that relying on a multinational air support system was believed to increase safety risks.

NSF's Role: NSF's Office of

Polar Programs (OPP) has the overall management responsibility for SPSM. Logistics and construction are handled by OPP's prime support contractor, Raytheon Polar Services Company. Architectural and engineering design and construction inspection are provided through a Memorandum of Agreement with Naval Facilities Command, as well as an engineering team of consultants on contract to OPP.

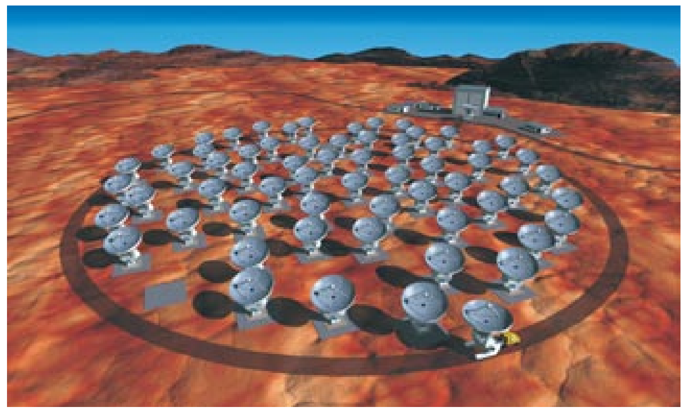
A steady state of operations and maintenance support is anticipated at $15 million per year from the OPP R&RA account—slightly higher than the current annual operational costs. Along with direct operations and maintenance support for South Pole Station, NSF will support science and engineering research through ongoing research and education programs. FY 2007 support for such activities is budgeted at $8 million from the OPP R&RA account. In FY08 it is expected to increase to $9.5 million.

Additional information on SPSM can be found at http://www.nsf.gov/od/opp/support/southp.jsp.

PROJECTS UNDER CONSTRUCTION

ATACAMA LARGE MILLIMETER ARRAY (ALMA)

Facility Objectives: This international project will be an aperture-synthesis radio telescope operating in the wavelength range from 0.4 to 3.0 mm. ALMA will be the world's most sensitive, highest-resolution millimeter-wavelength telescope, combining sub-arc second angular resolution with sensitivity equivalent to a single antenna nearly 100 meters in diameter. The array will provide observations to test theories of planet formation, star birth and stellar evolution, galaxy formation and evolution, and the evolution of the universe itself. ALMA also will play a central role in the education and training of U.S. astronomy and engineering students; in fact, at least 15 percent of ALMA's approximately 2,000 yearly users are expected to be students. The array will be located at a 5,000-meter altitude near San Pedro de Atacama in the Second Region of Chile, the ALMA host country.



This artist's conception shows the ALMA array in Compact Configuration. When construction is finished in 2011, ALMA will be the world's largest and most powerful radio telescope, operating at millimeter and sub-millimeter wavelengths.

ALMA instrumentation will push gallium arsenide and indium phosphide transistor amplifier technology to high frequencies; will challenge production of high-density, high-speed integrated circuits for computational uses; and is expected to stimulate commercial device and communication technologies development.

The expected operational lifetime of ALMA is at least 30 years.

Status: ALMA construction is currently more than 28 percent complete. Antenna fabrication is now underway, and initial fabrication and test of prototype receiver and signal processing electronics is in progress. Civil construction is also underway on the ALMA site, where access roads, an antenna test facility, support buildings, and other site infrastructure have been erected or are in progress.

The ALMA budget has grown significantly. The U.S. share of the ALMA construction cost was originally set at $344 million. Cost escalations arising from the prices of the production antennas, civil construction in Chile, and the unanticipated managerial and technical complexity of the international project led to a series of re-baselining reviews conducted by the ALMA Board and NSF in late 2005 and early 2006. These culminated in a reduction of the core array from 64 to 50 antennas, extension of the schedule for NSF-funded construction activities into FY 2012, and a revised budget estimate for a total project cost estimate of $499 million. The new baseline was approved and authorized by NSB in May 2006, following external review that confirmed ALMA will still be capable of achieving its essential scientific objectives using a 50-antenna array.

The first antennas and electronics will be delivered to the ALMA site for integration and testing in 2007. A three-element array will begin commissioning in 2008, and a six-element array will start science certification in 2009. The facility operations plan will be reviewed in 2007, and early science operations are expected to commence in 2010.

Partnerships: Originally referred to as the Millimeter Array (MMA) in the United States, the alliance was named ALMA when North America and Europe became equal partners. Japan joined ALMA as a third major partner in September 2004, and will deliver a number of enhancements to the baseline instrument.

The North American side of the project, consisting of the United States and Canada, is led by Associated Universities Inc (AUI) through the National Radio Astronomy Observatory (NRAO). Funding and execution of the project in Europe is carried out through the European Southern Observatory (ESO). Funding of the project in Japan is carried out through the National Institutes of Natural Sciences of Japan, and project execution is the responsibility of the National Astronomical Observatory of Japan.

NSF's Role: Program oversight is the responsibility of the ALMA staff associate in the Division of Astronomical Sciences (AST) within NSF's Directorate for Mathematical and Physical Science (MPS). AST's external MMA Oversight Committee has been advising NSF on the project since early 1998, and comprises half of the International ALMA Management Advisory Committee. Management of the NRAO effort on ALMA is carried out under cooperative agreement with AUI. U.S. construction was initiated in FY 2002, and in Europe in FY 2003.

Revised estimates for MPS/AST steady-state operations and maintenance costs, which will be fully attained in 2013, are about $30 million annually and will be provided through the R&RA account. Along with direct operations and maintenance support for ALMA, NSF will support research performed at the facility through ongoing research and education programs. The annual support for such activities is estimated to be about $10 million once the facility reaches full operations.

Additional information on ALMA can be found at http://www.alma.nrao.edu/.

EARTHSCOPE

Facility Objectives: The EarthScope facility is a distributed, multipurpose geophysical-instrument array that is supporting major advances in our knowledge and understanding of the structure and dynamics of the North American continent. It is a unique, downward-looking "telescope" combining three elements:

- Plate Boundary Observatory (PBO)—continuously recording Global Positioning System (GPS) and borehole strain systems that form a high-accuracy, state-of-the-art array to record crustal deformation;
- San Andreas Fault Observatory at Depth (SAFOD)—a 3.1 km-deep borehole that provides access for the first time to a major seismogenic fault at depth to explore fault conditions and study nucleation and rupture processes of earthquakes;
- USArray—a dense array of high-capability seismometers that is being deployed in a step-wise fashion across the United States to greatly improve resolution of the subsurface structure.

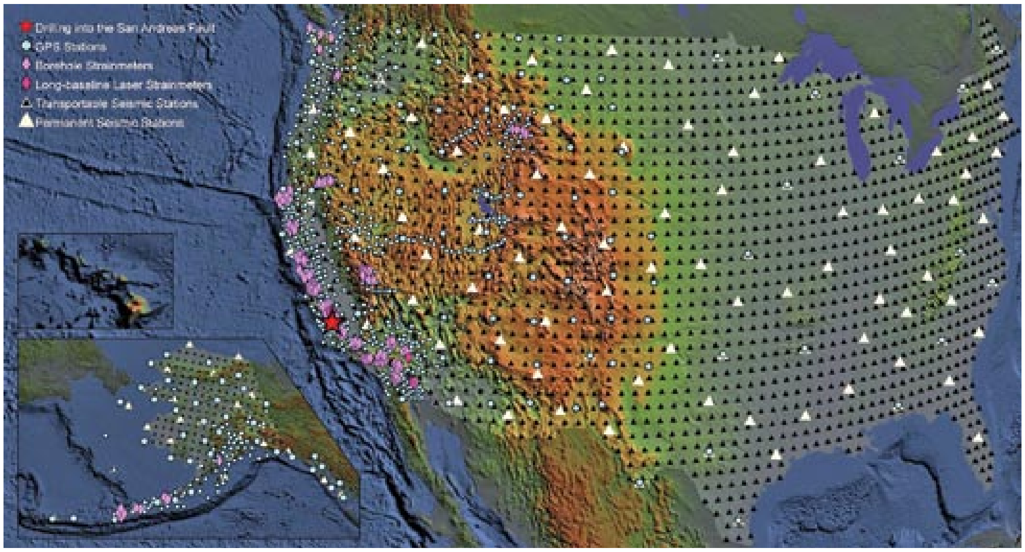
EarthScope data and research are enhancing understanding of the North American continent, earthquakes and seismic hazards, magmatic systems and volcanic hazards, lithospheric dynamics, regional tectonics, and fluids in the crust. Data and data products from EarthScope are freely and openly available via the Internet and have already been used in published earthquake studies, earthquake responses, public and professional meeting presentations, and in university and other educational settings. EarthScope also engages science and non-science students in geosciences discovery through the use of data and technology in real time or retrospectively through integrated research and education. The expected operational lifetime of EarthScope is 15 years.

Status: EarthScope is more than 60 percent complete, and approximately on budget and schedule. The PBO has installed more than 500 permanent geodetic stations. PBO instrumentation has recorded two volcanic eruptive sequences, one in Cascadia and one in the Aleutians. More than 300 of the first 400 stations of the USArray are deployed and the remaining installations are scheduled for completion by October 2007.

Drilling at the SAFOD intersected the main trace of the San Andreas Fault in August 2005. Passive recording instrumentation has been installed in the drill hole to help determine the locations of the multilateral holes that will be drilled through San Andreas Fault traces in the summer of 2007. Rock, fluid and gas samples are being used in scientific investigations in the United States and Europe.

Partnerships: The U.S. Geological Survey (USGS), NASA, DOE and the International Continental Scientific Drilling

Programme are funding partners, with USGS and NASA as operating partners. EarthScope partners may also include state and local governments, geological and engineering firms, and Canadian and Mexican agen-



This map shows the complete EarthScope footprint. One thousand and six hundred of the transportable sites (moving west to east) and all 2,400 campaign stations will continue to be deployed after the conclusion of the MREFC project. Locations of the stations will be determined through the annual proposal review process. Many of these sites likely will change annually.

cies. Over 3,000 Earth scientists and students are expected to use the facility annually. Geotechnical and engineering firms directly use EarthScope data and models. Instrumentation firms collaborate on development of state-of-the-art seismic systems, down-hole instrumentation, and high-precision GPS antenna designs.

NSF's Role: Programmatic oversight is the responsibility of the EarthScope program director, located in the Earth Sciences Division (EAR) in GEO. Site visits, annual reviews, and consultations with external advisory committees are conducted regularly to ensure coordination of facility construction and operation, science, education and outreach, and information technology efforts.

Conceptual planning for EarthScope developed over the past decade. NSF funded planning, design and the implementation of a five-year period of acquisition, facility construction and commissioning in FY 2003. While the final obligation of funds is in FY 2007, U.S.-funded construction activities are scheduled to continue through 2008, with project completion and full operation beginning in late 2008. NSF support for annual operations and maintenance is estimated at $24 million through the GEO/EAR R&RA account. NSF is also supporting ongoing research and education programs.

Additional information on EarthScope can be found at http://www.earthscope.gov and http://www.earthscope.org.

ICECUBE NEUTRINO OBSERVATORY

Facility Objectives: IceCube will be the world's first high-energy neutrino observatory and is being constructed deep in the ice at the South Pole to address frontier questions in astrophysics. It represents a new window on the universe that provides unique data on: the engines that power active galactic nuclei, the origin of high-energy cosmic rays, the nature of gamma ray bursters, the activities surrounding super-massive black holes, and more. (See the recent National Academies reports: *Connecting Quarks with the Cosmos—Eleven Science Questions for the New Century*; and *Neutrinos and Beyond—New Windows on Nature*.) IceCube will record the energy and arrival direction of high-energy neutrinos ranging in energy from 100 GeV (10^{11} electron Volts [eV]) to 10 PeV (10^{16} eV), with sensitivity that extends to 10^{18} eV.

One cubic kilometer of ice is being instrumented with photomultiplier (PM) tubes to detect charged reaction products from high-energy neutrino interactions in the ice within or near the fiducial volume. An array of Digital Optical Modules (DOMs), each containing a PM and associated electronics, will be distributed uniformly from 1.5 km to 2.5 km beneath the surface of the South Pole ice cap in highly transparent, bubble-free ice. The IceCube design comprises 70 strings of DOMs and 140 surface cosmic ray air shower detector modules at completion. The operational lifetime of IceCube is 25 years after construction is complete.

Status: IceCube is more than 65 percent complete and approximately on budget and schedule. A significant portion of the overall project is represented by the specialized hot-water drill and the large amount of support equipment that have been designed, built, tested and deployed to the South Pole. Additionally, more than 1500

DOMs have been produced and tested, and more than 19 of the 70 planned 60-DOM strings have been deployed deep within the Antarctic ice, including seven so far during FY 2007. Thirty-two surface modules were deployed during the FY 2005 and FY 2006 austral summer seasons, and 20 more are planned during FY 2007.

Custom data acquisition and analysis hardware and software have been developed and are now being used to collect and study the signals coming from the deployed DOMs.

Limited operations and early science are planned for spring 2007, while construction activities are scheduled to continue through 2011. If project cost performance is good, up to 10 strings and 20 surface modules may be added.

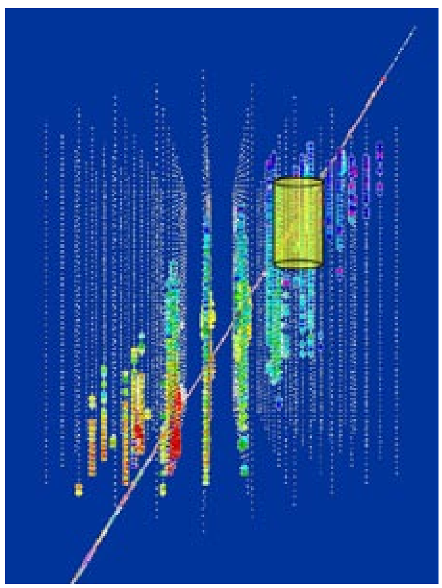
Partnerships: NSF provides funding to the University of Wisconsin, which leads construction of IceCube. The project is an international partnership with construction co-funding from Belgium, Germany and Sweden, which provide $29.70 million of the total project cost of $271.77 million.

At the April 2006 meeting of the International Oversight and Finance Group (IOFG), a pro rata cost-sharing plan was developed to jointly support operations.

NSF's Role: Oversight of IceCube construction is the responsibility of OPP. The project was baselined by NSF in 2004. Comprehensive annual external progress reviews were held in May 2005 and 2006, and will be held each subsequent spring throughout construction.

The annual external reviews are interspersed with monthly progress reports and quarterly reports, site visits, weekly teleconferences and frequent internal NSF project oversight and management meetings.

NSF conducted a review of IceCube operations in August 2006, followed by an IOFG meeting in September to assess results of the review and provide feedback to the IceCube Collaboration, which is now in the process of developing a cost-effective operations plan.



Side by side detectors: The prototype AMANDA neutrino telescope (represented as a yellow cylinder, upper right) provided the first precision map of high-energy neutrinos detected in Antarctic ice. The new IceCube instrument (consisting of more than 4,200 sensors deployed in long vertical strings) is expected to record far more neutrino events because it will be much larger and reach deeper than AMANDA.

NSF support for IceCube operations and maintenance is estimated to be approximately $3 million per year during full operation and will be shared between the R&RA accounts of OPP and the Division of Physics (PHY) in MPS. Support for research, education and outreach is also estimated at $3 million per year and will be equally shared between the same accounts.

Additional information on IceCube can be found at http://www.icecube.wisc.edu.

SCIENTIFIC OCEAN DRILLING VESSEL (SODV)

Facility Objectives: This project supports the contracting, conversion, outfitting and acceptance trials of a deep-sea drilling vessel for long-term use in the Integrated Ocean Drilling Program (IODP) inaugurated on Oct. 1, 2003. IODP will recover sediment and crustal rock from the seafloor and place observatories in drill holes to study the deep biosphere, the flow of fluids in sediments and the crust, the processes and effects of environmental change, and solid Earth cycles and geodynamics.

The vessel conversion will include installing new scientific laboratories that increase space and improve workflow, providing a modernized suite of scientific equipment, and modifying living spaces to accommodate a larger scientific complement and significantly improve habitability. The SODV will be prepared for year-round operations and made capable of operating in all ocean environments.

The SODV project scope was determined by the U.S. Science Advisory Committee for scientific ocean drilling and coordinated with the scientific community.

The refit of the SODV will extend its anticipated operational lifetime for at least 15 years.

Status: The SODV project is less than 10 percent complete, with engineering studies and project planning accounting for the bulk of that effort. Vessel conversion activity has not yet started. In 2003, NSF awarded a contract to Joint Oceanographic Institutions, Inc. (JOI) for IODP drilling operations, which included the planning and implementation of the SODV project. The subcontract to acquire, upgrade and operate a commercial vessel for scientific ocean drilling was awarded in December 2005 to Overseas Drilling Ltd., operator of the *JOIDES Resolution*. This ship had successfully served the predecessor Ocean Drilling Program since 1985.

After engineering design and science-related modifications are completed, the shipyard conversion contract will be awarded. Construction activities are scheduled to continue through 2007, with full operations beginning in FY 2008.

Partnerships: The IODP is co-led by NSF and the Ministry of Education, Culture, Sport, Science and Technology (MEXT) of Japan. MEXT will provide a heavy (riser) drillship

This aerial view shows the riserless ocean drilling vessel *JOIDES Resolution*.

for deep drilling objectives of the programs. NSF will provide the SODV: a light (riserless) drillship offering science support services for high-resolution studies of environmental and climate change, observation activities, and investigation of the deep biosphere. European and Asian nations are also participating in the program.

NSF's Role: The project is managed and overseen by a project manager in the Ocean Sciences (OCE) Division in GEO. GEO/OCE will provide about $57 million per year from the R&RA account to support IODP, beginning in early FY 2008, as the SODV vessel begins full operation. Along with funding direct operations and maintenance for IODP, NSF will support ongoing research and education programs at an estimated annual rate of $31 million through the GEO/OCE R&RA account.

Additional information on SODV can be found at http://www.joiscience.org/.

NEW STARTS IN FY 2007

ALASKA REGION RESEARCH VESSEL (ARRV)

Facility Objectives: The ARRV will provide greatly improved access to the Alaska region, enabling further exploration to address critical scientific issues. The construction of this ship will represent a major NSF contribution to the long-term research objectives of the International Polar Year (IPY), by providing the infrastructure necessary for future polar research. Research is urgently needed on topics ranging from climate change, ocean circulation, ecosystem studies and fisheries to natural hazards and cultural anthropology. Satellite observations have shown that the perennial ice in the Arctic is thinning at a rate of nine percent per decade, and recent research suggests the thinning is beginning to have major regional and global consequences.

The ARRV will replace the 40-year-old R/V *Alpha Helix*, and operate in the coastal and ocean waters (including in seasonal ice) in the Alaska region.

The anticipated operational lifetime of the ARRV is at least 30 years.

The Alaska Region Research Vessel (ARRV) will be 236 feet long, have a large heated deck, and create a clear channel, enabling effective handling of science packages near Alasko. The ARRV will replace the small, aging R/V *Alpha Helix*. The ice-strengthened ARRV, shown in this artist's rendition, will operate in the challenging seasonally ice-covered Alaskan waters, expanding current capabilities. In addition to providing a platform for training future scientists, researchers on the ship will link to students in distant classrooms through broadband satellite connectivity.

Status: The acquisition of the ARRV was approved by the NSB as a future MREFC project in August 2003. The design for the ARRV was completed in December 2004. The resulting manual of specifications and drawings forms the core document which will enable shipyards to develop construction bids.

ARRV anticipates commencing construction in FY 2007.

Two leading maritime international technology and business risk consultant companies provided independent design and cost matrices for the ARRV in November 2006. An updated cost estimate of $123 million based on these studies is reflected in NSF's FY 2008 Budget Request to Congress.

Partnerships: NSF will provide the funds for vessel construction. Operational funds will be divided proportionally among other federal agencies based on usage, in accordance with a long-standing Memorandum of Understanding.

NSF's Role: Programmatic oversight is the responsibility of the ARRV program director, located in GEO/OCE. In October 2006, NSF proceeded with a solicitation for a proposal to construct and operate the ship. An expert panel with a wide range of expertise (science, ship construction, project management, and ship operations) will be convened to review proposals. Following review and selection, a request for approval will be brought before the NSB in May 2007. A draft Internal Management Plan and solicitation for construction and maintenance have been prepared and are undergoing internal review and clearance. After the award is made, NSF will conduct a review of the awardee's Project Execution Plan (PEP) prior to any funds for construction being released. Following a 24-month period of construction and an additional six-month period for delivery, sea trials, ice trials, shipboard scientific equipment testing and any warranty adjustments, scientific operations are expected to begin in 2010.

Annual support for ship operation and maintenance is estimated at $7.5 million (in FY 2007 dollars) through the GEO/OCE R&RA account.

Additional information on ARRV can be found at http://www.nsf.gov/pubs/2007/nsf07515/nsf07515.txt.

NATIONAL ECOLOGICAL OBSERVATORY NETWORK (NEON)

Facility Objectives: NEON is conceived as a continent-wide research platform designed to extend the understanding of the biosphere to regional and continental scales. With NEON, investigators will, for the first time, conduct real-time studies at the scales required to address major ecological research objectives. These include understanding how changes in land use and climate affect ecosystems across a range of spatial and temporal extents, and how patterns and movement of genes and organisms across the continent influence biodiversity, invasive species and the spread of infectious diseases.

Through remote sensing, in situ observation, experimentation, synthesis and modeling, NEON will provide researchers with a unique capability to quantify the strong and weak forces regulating the biosphere and predict its response to climate and land-use change.

NEON will be a "shared-use" research platform of geographically distributed field and laboratory research infrastructure connected via cyberinfrastructure into a continental-scale research instrument. NEON infrastructure will include instrumented towers and sensor arrays, remote sensing capabilities, cutting-edge laboratory instrumentation, natural history archives, and facilities for data analysis, modeling, visualization, and forecasting—all networked onto a cyberinfrastructure backbone. Infrastructure will be deployed across the continental United States, Alaska, Hawaii and Puerto Rico using a statistically determined design.

The expected operational lifetime of NEON is 30 years after construction is completed in FY 2012.

Status: NEON continues to develop its construction and operations plan in anticipation of construction commencing in FY 2007. Significant accomplishments to date include the completion, and review by NSF, of NEON's Conceptual Design, Integrated Science and Education Plan, Networking and Informatics Plan, and the preliminary version of the PEP.

In FY 2007, NEON will proceed to develop a Preliminary Design, which will be externally reviewed. The NEON PEP will be finalized and Environmental Assessments initiated, while enabling R&D will be conducted to develop environmental sensors, promote network interoperability, and deliver tools for ecological modeling.

Pending NSB approval to obligate MREFC funds, NEON will build one instrumented multi-tower installation for the purpose of calibrating and validating the proposed instrumentation design.

Partnerships: NSF funds the NEON, Inc. collaboration to undertake pre-construction planning and eventual construction of the NEON facility. NSF-supported supercomputer centers are designing NEON's cyberinfrastructure and will participate in construction and commissioning of the facility.

Once NEON is in operation, it plans to share data with the USGS Earth Resources Observations Systems Data Center and NCAR. Data obtained from satellite remote sensing and NEON data will be combined to establish in situ verification of remote measurements. They will also assist with data archival. It is expected that partnerships with the USDA's Agricultural Research Service and with the U.S. Forest Service will provide opportunities to link understanding of fundamental biological processes and production systems.

NEON will function as a collaborative involving physical, computational, social, engineering and biological researchers.

Construction and operation of NEON are expected to provide significant R&D experiences that will benefit interagency and international programs or activities such as the U.S. Integrated Earth Observation System and the intergovernmental Group on Earth Observations, which is leading a worldwide effort to build a Global Earth Observation System of Systems (GEOSS).

This illustration depicts how infrastructure platforms that comprise the NEON sensing system will be deployed across the landscape in wildland, managed, and urban environments. BioSensor Towers, sensor networks, radar, mobile sensing, remote sensing, experimental facilities, education facilities, and forecasting facilities will be networked by leading-edge cyberinfrastructure into a national research platform.

NSF's Role: The Division of Biological Infrastructure (BIO/DBI) oversees NEON, coordinating oversight internally with the NSF Environmental Observing Networks Task Force, and with input from the BIO Advisory Committee.

In November 2006, NSF organized an external CDR of NEON. As a result of the recommendations stemming from this review, it is expected that the $100 million construction budget for NEON, shown in the table of MREFC account activity on page 32, will be revised as the project proceeds with the development of its Preliminary Design. This budget was developed in 2002, following initial workshops that examined NEON's scientific potential, technical requirements, and management structure. Since then, adoption by NSF of rigorous pre-construction planning guidelines—and corresponding efforts by the ecological community to respond to these guidelines and to the recommendations from the CDR—are resulting in improved definition of the project's intended scientific and technical scope, budget, and project implementation plans, including simultaneous deployment as one integrated national research platform, as recommended by the National Research Council (NRC) in 2004.

Prior to requesting NSB approval to obligate MREFC funds for construction, NSF will organize an external review of NEON's Preliminary Design, which will assess its scope, estimated project cost, risks, and schedule. This may result in a restatement of the total project cost and funding profile.

NSF intends to spend approximately $30 million from the BIO/DBI R&RA account to support concept and development activities through FY 2007. NEON's maintenance and operations will be funded through the BIO R&RA account at a level to be determined prior to the PDR.

Additional information on NEON can be found at http://www.NEONinc.org and http://research.esd.ornl.gov/~hnw/neon/withindomainrep.

OCEAN OBSERVATORIES INITIATIVE (OOI)

Facility Objectives: Sustained ocean-observing systems hold the promise of revolutionizing ocean science within this decade. The OOI will provide the capabilities needed to transform the way that ocean research is conducted and will address the following high-level themes, among other scientific objectives :

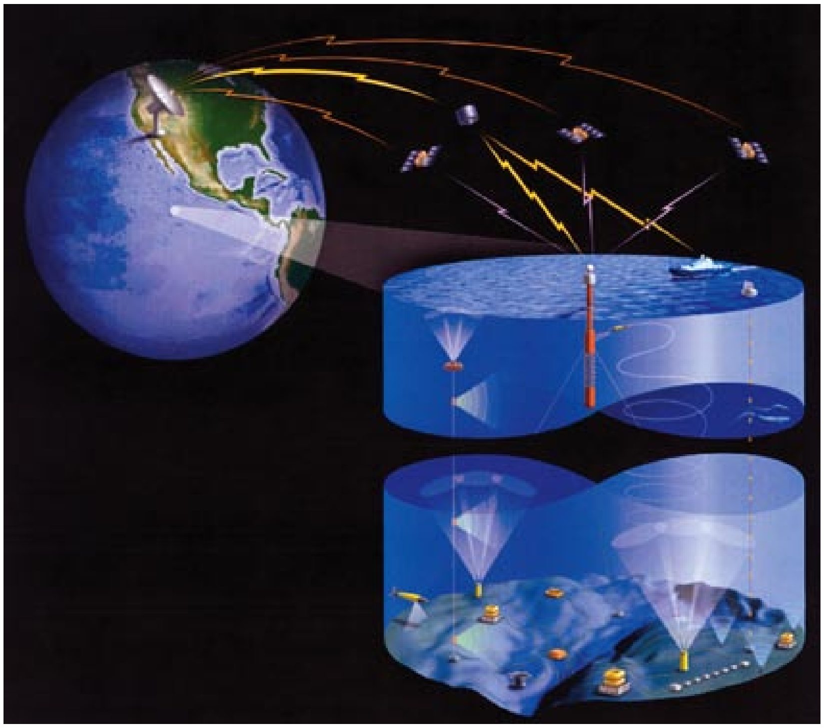
It will aid research on climate variability, ocean food webs, and biogeochemical cycles by providing a better understanding of the ocean's role in storing anthropogenic carbon and a clearer view of how long-term increases in atmospheric CO_2 may affect ocean chemistry and ecosystem structure and interactions.

It will advance the study of coastal ocean dynamics and ecosystems by tracking the ways in which climate change and human activity alter coastal ecosystems, habitats and living marine resources.

It will greatly clarify the impact of storms and other extreme events on exchanges of heat, gases and nutrients within the Earth-ocean-atmosphere system, including turbulent mixing and biophysical interactions.

It will expand understanding of fluid-rock interactions and the sub-seafloor biosphere, and help reveal the planetary significance and evolutionary importance of microbial activity in the ocean and in the newly discovered sub-seafloor biosphere.

It will improve understanding of global and plate-scale geodynamics, including the



The Ocean Observatories Initiative will provide an integrated array of communications devices and sensors placed on or below the sea floor and throughout the water column. A variety of instruments will transfer data, by cable or acoustic modem, to a buoy on the surface. The buoy's transmitter will then relay the information to the mainland by satellite.

processes that control the size and frequency of earthquakes at oceanic transform and subduction zone fault systems.

The anticipated operational lifetime of the OOI is 30 years.

Status: OOI is completing preconstruction planning activities. In February 2006, the Conceptual Network Design (CND) for the OOI was released. This document was developed from experimental plans, solicited from the research community, that were peer reviewed and binned according to scientific merit and feasibility. From this review, an advisory committee developed a network plan that was evaluated in draft form by approximately 300 members of the ocean science community at the Design and Implementation Workshop in March 2006. The CND, and associated detailed cost estimates for OOI network elements, form the core of the OOI PEP.

In 2007, NSF will assess the validity of the CND by conducting an external review. Later in the year, the project proponents will finalize development and submit to NSF a Preliminary Design report and a proposal for construction. These will also be externally reviewed to ascertain that project scope can be constructed, with high confidence, utilizing the plans developed and the budget requested.

Partnerships: With NSF funding, OOI is closely coordinating the design of its regional cabled observatory network with a similar effort underway by the Canadian NEPTUNE Project (now in its implementation phase) to establish a complementary and contiguous observatory network in the eastern Pacific in the area of the Juan de Fuca Plate. The selection of sites for the OOI global buoy array has been coordinated with input from NOAA's Global Climate Buoy Program and the international OceanSites Program.

Construction and operation of OOI are expected to provide significant R&D experiences that will benefit such interagency and international programs as the Integrated Ocean Observing System and GEOSS.

NSF's Role: Programmatic oversight is the responsibility of the OOI program director located in GEO/OCE. In 2006, NSF organized a "Blue Ribbon" review panel composed of senior, non-advocate members of the ocean science community, which confirmed that the ocean observing network proposed in the OOI CND will provide needed capabilities for ocean researchers to significantly advance the knowledge of high-priority research questions. The results of the panel's review were provided as input to an NSF-organized CDR, which assessed the infrastructure design scope and system-level development specifications for all major elements of design, implementation and management plans for the OOI, as well as for project risk assessment and budgeting. The CDR resulted in valuable guidance to the project, which is now being incorporated into OOI's Preliminary Design.

In August 2007, the OOI project office will prepare and submit a Construction Proposal that will include a detailed statement of the science requirements motivating the network design, along with management plans, budget, risk and schedule information comprising a Preliminary Design. NSF is planning to organize a two-tiered review of the preliminary design and proposed construction activity: a mail review that will focus on assessing the transformative nature and value of the science enabled by OOI, and a PDR that will broadly scrutinize the robustness of the planning for the proposed construction activity. Results of the mail review and the PDR will be submitted to NSB as part of the process to request approval to commence construction.

NSF support for annual operations and maintenance via the GEO/OCE R&RA account is estimated at $50 million beginning in FY 2012.

Additional information on OOI can be found at http://www.orionprogram.org.

POSSIBLE NEW START IN FY 2008

ADVANCED LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY (ADVLIGO)

Facility Objectives: The Laser Interferometer Gravitational-Wave Observatory (LIGO), one of the most advanced scientific instruments ever built, will measure extraordinarily small changes in its kilometer-scale optical arm lengths resulting from distortions of space-time caused by the passage of gravitational waves. The three initial LIGO interferometers have achieved their design sensitivity and are searching for gravitational waves generated by rare cataclysmic events involving supernovae, pulsars and neutron star and black hole collisions occurring as far away as 350 million light years. AdvLIGO is a major upgrade that will increase the volume of the universe within LIGO's reach, and its detection rate, by a factor of more than 1000. LIGO and AdvLIGO have the potential for making the first direct observation of gravitational waves, of making discoveries of new and unanticipated phenomena, and of ushering in a new era of gravitational-wave astronomy and astrophysics. LIGO has pioneered the field of gravitational wave measurement. A timely upgrade is necessary to maintain U.S. leadership in this area, as sensitivity enhancements comparable to that of AdvLIGO are also planned for competing instruments abroad.

The anticipated operational lifetime of AdvLIGO is 20 years.

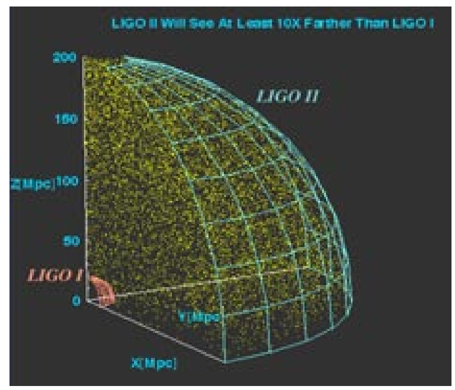
Status: AdvLIGO is completing its pre-construction planning activities. The LIGO Laboratory submitted a proposal for AdvLIGO in early 2003; a subsequent review judged the project to be scientifically sound and ready for construction. Since then, a continuing R&D program has enhanced readiness, solidified costs and schedule, and reduced risk. A 2006 baseline review panel concluded that AdvLIGO could be built to the project's submitted cost, schedule and execution plan.

AdvLIGO funding in FY 2008 would first allow the purchase and assembly of upgraded components. Continued operation during this initial period would allow tests of AdvLIGO components and would enhance LIGO's sensitivity. LIGO would be decommissioned in 2011, when the replacement of its components would begin, although some operations would continue. AdvLIGO is expected to begin full operation in 2014.

Partnerships: If construction is approved, NSF will fund Caltech, in partnership with MIT, to lead the efforts to build and commission AdvLIGO. Essential contributions will come from Britain and Germany. The University of Glasgow will develop AdvLIGO's suspension system, and Laser Zentrum Hannover is providing new higher power laser systems.

The LIGO program has strongly stimulated gravitational-wave research around the world, producing vigorous competing programs in other countries that also collaborate with LIGO to provide it with many necessary scientific advances. The LIGO Scientific Collaboration (LSC), which carries out LIGO's research program, consists of approximately 500 scientists from more than 40 institutions in nine countries.

NSF's Role: NSF oversight is coordinated internally by a program director in MPS/PHY. NSF conducts annual scientific and technical reviews, participates in LSC meetings, and makes site visits. During AdvLIGO's construction phase, NSF will exercise more intensive oversight through more frequent reporting requirements, stepped-up interaction with project personnel, scheduled reviews, and at least twice-yearly site visits.



The Advanced LIGO MREFC Project will improve the sensitivity of LIGO by more than a factor of 10, which will expand the volume of space LIGO will be able to "see" more than 1,000-fold.

NSF support for annual operations via the MPS/PHY R&RA account is estimated at $30 to 50 million.

Additional information on AdvLIGO can be found at http://www.ligo.caltech.edu/.

READINESS STAGE PROJECTS

The MREFC panel annually evaluates projects for admission to this category. Characteristics of facilities in this category, and their objectives for further development, are described in NSF's guidelines document[1]. The sponsoring Directorates and Offices bring candidates forward when those organizations consider the projects ready for MREFC funding consideration. At the time of preparation of the 2006 Facility Plan, the Advanced Technology Solar Telescope was the only project in this category.

This artist's rendition depicts an exterior view of the planned structure of ATST.

ADVANCED TECHNOLOGY SOLAR TELESCOPE (ATST)

Facility Objectives: The Advanced Technology Solar Telescope would contribute to the NSF science objective of understanding the Sun by enabling the study of magneto-hydrodynamic phenomena in the solar photosphere, chromosphere and corona. Understanding the role of magnetic fields in the outer regions of the Sun is crucial to understanding the solar dynamo, solar variability, and solar activity, including flares and mass ejections which can affect life on Earth.

Among the specific research subjects are: processes whereby cosmic magnetic fields are generated and how are they destroyed; the role played by cosmic magnetic fields in the organization of plasma structures and the impulsive releases of energy seen ubiquitously in the universe; mechanisms responsible for solar variability and its impact on climate; and the conditions responsible for solar activity, including solar flares and coronal mass ejections, which can impact terrestrial communications and power systems.

In addition, the telescope would contribute to improved understanding of space weather, which is critical to the safety of astronauts in space, or on the Moon. It would also enhance greatly our understanding of the activity and variability of solar-type stars.

The 4-meter, off-axis Gregorian (all reflective) telescope with integrated adaptive optics would have a field of view of 3 arc minutes, an angular resolution of < 0.03 arc seconds, and wavelength sensitivity from 0.3-28 microns (i.e., the entire visible and near-infrared regions of the electromagnetic spectrum). The ATST's light grasp would be a factor of 10 greater than the largest solar telescope in existence and adaptive correction would yield an increase in angular resolution of a factor of three to seven over the best adaptively corrected systems currently available. The ATST would allow researchers to observe the Sun with the requisite light grasp and angular resolution needed to observe the magnetic fields and turbulence on fundamental length scales (e.g. photon mean free path, pressure scale height). It would resolve features of about 30 km size on the Sun, as needed to test the current theories of solar magnetism and activity with direct observations. For comparison, the current best U.S. adaptive telescope is limited to a resolution of about 150 km on the surface of the Sun.

The expected operational lifetime of ATST is 50 years.

Status: ATST is ready to pursue advanced pre-construction planning activities. The ATST project conducted an extensive and successful conceptual design review in August 2003. A detailed cost review was held in March 2005 and a set of systems design reviews was conducted during 2005 and 2006. The project has selected Haleakala Peak on the island of Maui in Hawaii as its site and the environmental and cultural assessment processes are well advanced.

Partnerships: The ATST is a collaboration of 22 institutions. The project is managed by NSF's National Solar Observatory (NSO). NSO provides the world's forefront collection of solar telescopes for investigators supported by MPS/AST and GEO/ATM to study the "space weather" and atmospheric implications of solar activity. There are approximately 500 potential users in the United States, but as the preeminent facility for detailed ground-based studies of the Sun, ATST would draw from the world's entire community of solar physicists and astronomers.

The project enjoys strong support from the worldwide community. The European solar physics community is actively trying to raise funds to support the construction. Interagency partners include: the Air Force Office of Scientific Research, a long-standing partner in NSO; NASA Goddard Space Flight Center, which plans to provide a 12-micron Stokes polarimeter as a dedicated instrument for the ATST; and NASA Marshall Space Flight Center, which is

1 http://www.nsf.gov/bfa/docs/mrefcguidelines1206.pdf

contributing to the definition and design of the ATST imaging vector magnetograph.

As the first new large solar telescope constructed in nearly 30 years, and because of the new range of scientifically compelling questions that ATST can address, its construction is expected to rejuvenate the solar research community in U.S. universities. As a national facility, ATST would enable training of the next generation of solar physicists and instrument builders at the graduate and undergraduate levels. ATST is poised to become the world's flagship facility for the study of solar activity. Strong linkages have been established among a diverse set of collaborating institutions, including universities, industrial partners, NASA centers, and other Federally Funded Research and Development Centers. ATST could contribute to curriculum development and teacher training through ongoing NSO programs and to public outreach through the NSO Visitor Center, Web presence, and the like.

NSF's Role: Programmatic oversight is the responsibility of a program officer in MPS/AST, who works directly with the ATST project manager and project director, both at NSO. NSF currently supports design and development of the ATST project from MPS/AST and GEO/ATM.

NSF organized a PDR in October 2006, utilizing an external panel of scientific, technical, and managerial experts, to evaluate the robustness of the telescope and the facility's technical design, and the proposed budget, schedule, project execution plan, and risk management plan. The review determined that the design, budget and plans provide a firm basis for requesting future construction funding. The ATST could be presented to NSB as a possible new start for FY 2009 with full science operation beginning in 2015.

NSF support for annual operations and maintenance via the MPS/AST R&RA account, is estimated at $13 million.

Additional information on the ATST can be found at http://atst.nso.edu.

APPENDIX I. HORIZON PROJECTS

In addition to the facilities listed in Chapter 2, which are either under construction or in late-stage pre-construction planning, NSF invests in the development of new capabilities, technologies and instrumentation that will lead to the next generation of transformational infrastructure expected to be described in future NSF Facility Plans.

The selected high-priority areas must hold exceptional promise for accelerating science and engineering progress, advancing the frontiers of knowledge, and addressing national interests.

NSF has a long-established role in providing state-of-the-art infrastructure to meet major research challenges. NSF's strategy is to invest in tools that promise significant advances in a field of research and to make them widely available to a broad cross-section of investigators. NSF looks at investments that renew and increase the productivity of existing facilities; promote synergies between new and existing programs that create efficiencies and leverage financial investments and partnership opportunities; capitalize on intellectual payoffs from previous research; and offer bold, risk-taking opportunities to advance the frontiers of science and engineering.

Successful exploration—whether in uncharted wilderness or at the frontiers of knowledge—demands commitment, vision, daring and ingenuity. But those qualities alone are not always sufficient. Progress also requires the appropriate equipment. Often, new territory is accessible only with new tools. Discovery may require novel means for seeing, manipulating and analyzing natural phenomena.

Horizon Projects, listed here, reflect NSF's assessment of the landscape at the frontier of knowledge. They represent ideas and possible future opportunities for development of large-scale research infrastructure. They describe NSF's view as far into the future as it can see, typically a five- to 20-year look forward at the sorts of world-class project areas that may eventually bring forward candidates for construction funding from the MREFC account.

While many of these ideas may never mature, those that do are assessed through rigorous merit review. If and when these ideas and initiatives become sufficiently defined to motivate a concept for a future facility, the process culminates in a Conceptual Design Report and a CDR, as described in NSF's *Guidelines for Planning and Managing the MREFC Account*[1]. Projects satisfying conceptual design criteria, as defined in that document, advance into the Readiness Stage.

These criteria mandate that not only must the intellectual merit for a future facility be of the highest caliber, with compelling endorsement from the research community; but the project scope, budget and schedule must be properly scrutinized according to NSF's guidelines. Furthermore, the qualifications of the proposers to take on the work of comprehensive pre-construction planning must also be ascertained by NSF to be of the highest caliber before a project can advance to the Readiness Stage. NSF's plans for funding further pre-construction planning and development, conducting effective oversight, and managing the administrative risks that fall on it as the sponsoring agency, must also be documented and approved by the MREFC Panel with concurrence by the NSF Director. Finally, the scope of work and associated budget requirements necessary to complete pre-construction planning must be defined and vetted.

Since 1998, NSF has maintained a "Horizon" list of candidate large facility projects or research areas, identified by the research community, which might potentially result in a request for future MREFC construction funding. The number of projects on this list in any given year has

1 http://www.nsf.gov/bfa/docs/mrefcguidelines1206.pdf

ranged between 11 and 25. A total of about 50 different possible projects have been in this category. During that time, nine emerged to become part of MREFC budget requests. Each of those projects was typically in the Horizon category from three to five years. ATST is the most recent project to emerge, advancing into the Readiness category after FY 2005. Most projects in the Horizon category never develop the widespread base of support within their sponsoring communities, relative to competing opportunities, that is needed to obtain priority for resources for more detailed pre-construction development and planning.

This appendix describes those concepts and future opportunities viewed within the Horizon definition. These topics are segregated into two groups: those for which NSF would serve as the lead organization with responsibility for planning and development, and those projects in which NSF's role would be that of a partner with another federal agency. In the latter case, NSF might or might not contribute to future construction activity. Within each group, the sponsoring Directorates or Office is indicated, but with no implication with respect to relative prioritization.

AREAS WHERE NSF HAS PRIMARY RESPONSIBILITY

Basic Research in Networking and Distributed Systems (CISE)

The Directorate for Computing and Information Science and Engineering (CISE) is funding the investigation and planning of promising concepts for a major facility that would promote basic research in networking and distributed systems. The facility could comprise two parts: a national physical substrate including new classes of network routers and switches, a fiber-based backbone, sensors, and wireless edge devices and networks; and an integrating software management framework permitting researchers to assemble widely distributed sets of physical resources into multiple "virtual" networks and experiments simultaneously. It has been conceived in the context of a bold vision—the investigation of new networking and distributed system architectures that could lead to the development of a new Internet designed to meet the complex and compelling demands of the 21st century.

Human-stressed Water Systems (ENG and GEO)

The ENG and the GEO Directorates are funding environmental research on human-stressed water systems that may lead to development of a distributed research facility comprising interacting field sites, an integrating cyberinfrastructure, and an enabling management infrastructure. This effort could support data acquisition, data aggregation and curation, analytical tools for visualization and exploratory data mining, and predictive multi-scale modeling of dynamic water availability and quality. It would also enable forecasting of impacts of contemplated adaptive management strategies.

Coherent X-Ray Light Source (MPS)

The MPS Directorate is funding conceptual design and development studies for a next-generation coherent light source far brighter than present-day synchrotron-based facilities, with unique capabilities compared to competing technologies. The technology, if successful, would be adaptable to upgrade existing X-ray synchrotrons. It could open up exciting new scientific opportunities in fields ranging from condensed-matter and mesoscopic science to chemical dynamics, and from materials science and engineering to molecular biology and geophysics.

Deep Underground Science and Engineering Laboratory (MPS, GEO, ENG, BIO)

This is conceived as a new national laboratory able to exploit the unique features of the environment deep underground for frontier research. The scientific impact could be far-reaching and would embrace a broad range of disciplines, including nuclear physics, particle physics, biology, geology, engineering and defense. The MPS Directorate is currently supporting design and development activities related to possible experiments and potential sites.

Giant Segmented Mirror Telescope (MPS)

The Giant Segmented Mirror Telescope would be a general-purpose telescope of unprecedented size having unique capabilities for studying the evolution of galaxies and the formation of stars and planets. The telescope would utilize a number of smaller concave mirror segments, working together, to make up a primary mirror of 20- to 30-meter effective aperture, giving it from four to 10 times the collecting area of the largest telescopes in use. It would incorporate sophisticated adaptive optics systems to correct for the blurring effect of the Earth's atmosphere and realize resolving power at its diffraction limit. The combination of these two improvements would allow it to study galaxies in formation, probe proto-stellar disks, and perhaps image planets orbiting nearby stars. It was the highest priority recommendation in the NRC decadal survey *Astronomy and Astrophysics in the New Millennium*.[2]

Large Aperture Survey Telescope (MPS)

The Large Aperture Survey Telescope would be a special-purpose wide field optical telescope with an effective aperture in the six-meter class. It would take repeated images of the accessible sky several times per week with a camera employing more than a billion pixels, looking for transient and moving objects. Furthermore, the images could be combined to form the deepest images of the sky ever taken. The data could be crucial to refining our understanding of the nature of dark energy as well as discovering potentially hazardous, near-Earth asteroids. The telescope could provide a new mode of exploring the universe through "data mining" of huge archival data sets. Among the objectives to be addressed with such a resource are: a census of the solar system to unprecedented depth and completeness; a detailed proper motion survey of the stars in the solar neighborhood; the study of huge numbers of temporally variable objects from variable stars through active galaxies and quasars; and the characterization of hundreds of thousands of supernovae.

The construction of such an instrument was the third-ranked major initiative recommended by the astronomy and astrophysics decadal survey and was a recommendation of a number of more recent studies including *The Physics of the Universe—A Strategic Plan for Federal Research at the Intersection of Physics and Astronomy*[3].

Next Generation Meter/Centimeter Wavelength Radio Telescope (MPS)

The radio astronomical community in the United States is currently engaged in an exercise to define the next generation facility for meter/centimeter wavelength astronomy. All effort related to realizing a Phase II of the Expanded Very Large Array has now been subsumed into this community exercise. The community definition will feed into the next astronomy and astrophysics decadal survey, due to begin around 2008. The U.S. community exercise will be carried out in conjunction with an international effort that has as its goal realizing a radio astronomy facility with about 1 square kilometer of collecting area. The key science drivers for such a facility are: extreme tests of general relativity with pulsars and black holes; evolution of galaxies, cosmology, dark matter, and dark energy; probing the "Dark Ages"—the first black holes and stars; searching for extrasolar planets and life; and the origin and evolution of cosmic magnetism. Technology development for this possible facility was the third-ranked moderate initiative in the last astronomy and astrophysics decadal survey.

South Pole Station Future Communications and Power Needs (OPP)

Sophisticated experiments, not envisaged when South Pole Station was designed a decade ago, require increased communications capability and substan-

2 Washington, DC: National Academies Press. Available on-line at http://www.nap.edu/books/0309070317/html/

3 Washington, DC: Office of Science and Technology Policy. Available on-line at http://www.ostp.gov/html/physicsoftheuniverse2.pdf

tially increased electrical power. Filling those needs would entail an additional 500 to 750 kilowatt generating capability, together with fuel storage sufficient to run the new generators through the austral winter season. NSF is considering options to upgrade communications with the South Pole Station, from the current 10 hours per day provided by aging satellites, to continuous high-bandwidth connectivity, in order to fully realize the South Pole's research potential and to be able to respond to medical emergencies. The options under consideration include contracting with a private company, seeking a partnership with NASA for shared use of its next-generation satellite fleet, and constructing a high-bandwidth link to a lower-latitude location where transmission to a geostationary satellite would be possible.

AREAS WHERE NSF IS EXPLORING CONTRIBUTING TO AN EXTERNALLY LED PARTNERSHIP

Energy-Frontier Electron-Positron Collider (MPS)

The international elementary particle physics community has made an electron-positron collider at the TeV scale its highest priority for a future accelerator project. The electron-positron collider would complement the Large Hadron Collider (LHC) being constructed at CERN, permitting researchers to measure properties of new elementary particles and other phenomena that will not be observed at the LHC. These complementary approaches could open a new chapter in elementary particle physics by discovering new particles and phenomena (e.g. supersymmetric species, dark matter and extra dimensions). Whereas the DOE is the national steward of major accelerator facilities in the United States, NSF is enabling the university community to participate in designing such a facility and may partner in supporting construction and research, as with the LHC.

Satellite Radar Capabilities for Study of Earth Surface Deformation (GEO)

This project would consist of a satellite radar and data receiving, archiving and distribution systems, allowing synoptic study of Earth surface deformation to accuracies better than one centimeter. Developed as a partnership, with NASA playing a lead role, the project would provide a revolutionary new tool for multidisciplinary study of natural phenomena in North America and throughout the world.

APPENDIX II. GLOSSARY OF ACRONYMS

AdvLIGO	Advanced Laser Interferometer Gravitational Wave Observatory
ALMA	Atacama Large Millimeter Array
ARF	Academic Research Fleet
ARRV	Alaska Region Research Vessel
AST	Division of Astronomical Sciences
ATLAS	A Large Toroidal LHC Apparatus
ATM	Division of Atmospheric Sciences
ATST	Advanced Technology Solar Telescope
AUI	Associated Universities, Inc
AURA	Association of Universities for Research in Astronomy
BFA	Office of Budget, Finance and Award Management
BIO	Directorate for Biological Sciences
Caltech	California Institute of Technology
CDR	Conceptual Design Review
CERN	European Organization for Nuclear Research
CI	Cyberinfrastructure
CISE	Directorate for Computer and Information Science and Engineering
CMS	Compact Muon Solenoid
CND	Conceptual Network Design
DBI	Division of Biological Infrastructure
DOE	Department of Energy
DOM	Digital Optical Module
EAR	Division of Earth Sciences
EHR	Directorate for Education and Human Resources
ENG	Directorate for Engineering
EPA	Environmental Protection Agency
EPSCoR	Experimental Program to Stimulate Competitive Research
eV	Electron Volts; one billion ("giga") electron volts is abbreviated GeV, and one quadrillion ("peta") is abbreviated PeV.
GenBank	The public DNA sequence database maintained by the National Center for Biotechnology Information, part of the National Library of Medicine
GEO	Directorate for Geosciences
GEOSS	Global Earth Observation System of Systems
GHz	Gigahertz
GMT	Giant Magellan Telescope
GPS	Global Positioning System
HEPAP	High Energy Physics Advisory Panel
HIAPER	High-performance Instrumented Airborne Platform for Environmental Research
IODP	Integrated Ocean Drilling Program
IOOS	Integrated Ocean Observing System
IT	Information Technology
JOI	Joint Oceanographic Institutions Inc.
JOIDES	Joint Oceanographic Institutions for Deep Earth Sampling
LHC	Large Hadron Collider
LIGO	Laser Interferometer Gravitational Wave Observatory
LSC	LIGO Scientific Collaboration
MMA	Millimeter Array
MOU	Memorandum of Understanding
MPS	Directorate for Mathematical and Physical Sciences
MREFC	Major Research Equipment and Facilities Construction
NA	National Academies
NASA	National Aeronautics and Space Administration
NCAR	National Center for Atmospheric Research
NCBI	National Center for Biotechnology Information, part of the National Library of Medicine
NEON	National Ecological Observatory Network
NOAA	National Oceanographic and Atmospheric Administration
NOAO	National Optical Astronomy Observatory
NRAO	National Radio Astronomy Observatory
NRC	National Research Council
NSB	National Science Board
NSF	National Science Foundation
NSO	National Solar Observatory
NSTC	National Science and Technology Council
OCE	Division of Ocean Sciences
ODP	Ocean Drilling Program
OOI	Ocean Observatories Initiative
OPP	Office of Polar Programs
ORION	Ocean Research Interactive Observatory Networks
OSTP	Office of Science and Technology Policy
PAT	Project Advisory Team
PBO	Plate Boundary Observatory
PDR	Preliminary Design Review
PEP	Project Execution Plan
PM	Photomultiplier
R&RA	Research and Related Activities
R/V	Research Vessel
SAFOD	San Andreas Fault Observatory at Depth
SODV	Scientific Ocean Drilling Vessel
SPSM	South Pole Station Modernization project
UCSD	University of California, San Diego
U.S.	United States
USAP	United States Antarctic Program
USDA	United States Department of Agriculture
USGS	United States Geological Survey

APPENDIX III. REFERENCES

Science and Engineering Infrastructure Report for the 21st Century: The Role of the National Science Foundation, (NSB-02-190, 2003), http://www.nsf.gov/nsb/documents/2002/nsb02190/nsb02190.pdf.

Priority Setting for Large Facility Projects, a National Science Board White Paper, (NSB-04-96, 2004), http://www.nsf.gov/nsb/meetings/2004/may_srprt.doc at Page 14.

Setting Priorities for Large Research Facility Projects Supported by the National Science Foundation, (National Academies Press, 2004), http://books.nap.edu/catalog/10895.html.

Complex Environmental Systems: Synthesis for Earth, Life, and Society in the 21st Century, (NSF Advisory Committee for Environmental Research & Education report, 2003), http://www.nsf.gov/geo/ere/ereweb/acere_synthesis_rpt.cfm.

Environmental Cyberinfrastructure Needs for Distributed Sensor Networks: A Report from a National Science Foundation Sponsored Workshop, (Scripps Institute of Oceanography, 2003), http://www.lternet.edu/sensor_report/.

NSF Geosciences Beyond 2000: Understanding and Predicting Earth's Environment and Habitability, Report of the NSF Advisory Committee for the Geosciences, (NSF 00-28, 2000), http://www.nsf.gov/pubs/2000/nsf0028/nsf0028.doc.

NEON: Addressing the Nation's Environmental Challenges, a report of the National Research Council, (National Academies Press, 2003), http://books.nap.edu/catalog/10807.html.

Grand Challenges in Environmental Sciences, a report of the National Research Council, Committee on Grand Challenges in Environmental Sciences, (National Academies Press, 2001), http://books.nap.edu/catalog/9975.html.

Facilities to Empower Geosciences Discovery 2004-2008, NSF Advisory Committee for Geosciences, (NSF 03-053, 2003), http://www.nsf.gov/geo/facilities/.

SCaLeS: Science Case for Large-Scale Simulation, report of a Department of Energy workshop, (2003), http://www.pnl.gov/scales/.

Beyond the Molecular Frontier: Challenges for Chemistry and Chemical Engineering, a report by the Committee on Challenges for the Chemical Sciences in the 21st Century, (National Academies Press, 2003), http://books.nap.edu/catalog/10633.html.

Envisioning the Agenda for Water Resources Research in the Twenty-First Century, Water Science Technology Board, National Research Council, (National Academies Press, 2001), http://books.nap.edu/catalog/10140.html.

National Nanotechnology Initiative: Research and Development Supporting the Next Industrial Revolution, Supplement to President's FY 2004 Budget Oct. 2003, (2003), http://www.nano.gov/html/res/fy04-pdf/fy04-main.html.

Elementary-Particle Physics: Revealing the Secrets of Energy and Matter, Committee on Elementary-Particle Physics, National Research Council, (National Academies Press, 1998), http://books.nap.edu/catalog/6045.html.

Physics in a New Era: An Overview, Physics Survey Overview Committee, Board on Physics and Astronomy, National Research Council, (National Academies Press, 2001), http://books.nap.edu/catalog/10118.html.

Workshop on The Roadmap for the Revitalization of High-End Computing, (Computing Research Association, 2003), http://www.cra.org/reports/supercomputing.pdf.

Connecting Quarks with the Cosmos: Eleven Science Questions for the New Century, Committee on the Physics of the Universe, National Research Council, (National Academies Press, 2003), http://books.nap.edu/catalog/10079.html.

Materials Science and Technology: Challenges for the Chemical Sciences in the 21st Century, Organizing Committee for the Workshop on Materials and Manufacturing, Committee on Challenges for the Chemical Sciences in the 21st Century, National Research Council, (National Academies Press, 2003), http://books.nap.edu/catalog/10694.html.

Revolutionizing Science and Engineering through Cyberinfrastructure, Report of the National Science Foundation Blue-Ribbon Advisory Panel on Cyberinfrastructure, (NSF, 2003), http://www.nsf.gov/od/oci/reports/toc.jsp.

Understanding the Sun and Solar System Plasmas: Future Directions in Solar and Space Physics, Solar and Space Physics Survey Committee, Committee on Solar and Space Physics, National Research Council, (National Academies Press, 2004), http://books.nap.edu/catalog/11188.html.

The Sun to the Earth—and Beyond: A Decadal Research Strategy in Solar and Space Physics, Solar and Space Physics Survey Committee, National Research Council, (National Academies Press, 2002), http://books.nap.edu/catalog/10477.html.

Strengthening the Linkages Between the Sciences and the Mathematical Sciences, Commission on Physical Sciences, Mathematics, and Applications, (National Academies Press, 2000), http://www.nap.edu/books/0309069475/html/.

How People Learn: Brain, Mind, Experience, and School: Expanded Edition, Committee on Developments in the Science of Learning with additional material from the Committee on Learning Research and Educational Practice, National Research Council, (National Academies Press, 2000), http://books.nap.edu/catalog/9853.html.

Neutrinos and Beyond: A New Window on the Universe, Neutrino Facilities Assessment Committee, National Research Council, (National Academies Press, 2003), http://www.nap.edu/catalog/10583.html.

A 21st Century Frontier for Discovery: The Physics of the Universe: A Strategic Plan for Federal Research at the Intersection of Physics and Astronomy, (Office of Science and Technology Policy, 2004), http://www.ostp.gov/html/physicsoftheuniverse2.pdf.

APPENDIX IV. IMAGE CREDITS

Front Matter

Cover	Photomicrograph by Renfan Shao, Liquid Crystal Materials Research Center, University of Colorado, Boulder
2-3	Matthias Weber, Indiana University

Chapter 1:Research Objectives and Opportunities at the Frontiers of Science and Engineering

8	Gerald Baber, Virginia Tech
10 (top)	Robert B. Moore and Kenneth A. Mauritz, University of Southern Mississippi
10 (bottom)	A. Majumdar, University of California, Berkeley
11 (top)	Paul Thompson and Arthur Toga, University of California, Los Angeles
11 (bottom)	Gerald Baber, Virginia Tech
12, 14 (top)	MODIS images from NASA's Terra satellite supplied by Dr. Ted Scambos; National Snow and Ice Data Center, University of Colorado, Boulder
14 (bottom)	Jeffrey B. Weiss, University of Colorado, Boulder
16	Nicolle Rager Fuller, National Science Foundation
17	Eric J. Heller, Harvard University
18	Chad Mirkin, Northwestern University
19	Eric J. Heller, Harvard University
21	© CERN
23 (top)	Gemini Observatory
23 (bottom)	NASA/ESA
25 (top)	David A. Aguilar, Harvard-Smithsonian Center for Astrophysics
25 (bottom)	John Bally, University of Colorado; Bo Reipurth, University of Hawaii; NOAO/AURA/NSF
27 (top)	Adam Miezianko, Karen Fung, Zavnura Pingkan, Kristopher Rambish
27 (bottom)	Matthias Weber, Indiana University

Chapter 2: Major Research Equipment and Facilities Construction Projects

34	Jonathan Berry, National Science Foundation
35	NRAO/AUI and ESO
37	EarthScope
38	Diagram courtesy of University of Wisconsin-Madison; u Used by permission
39 (left)	IODP/TAMU
39 (right)	The Glosten Associates, Inc.
41	Nicolle Rager Fuller, National Science Foundation
42	John Orcutt, Scripps Institute of Oceanography
43	Laser Interferometer Gravitational-Wave Observatory (LIGO)
44	National Solar Observatory/AURA/NSF

Design by:	Adam Ross and Adrian Apodaca, National Science Foundation