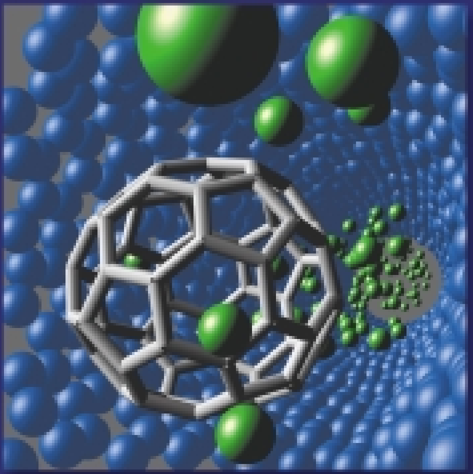
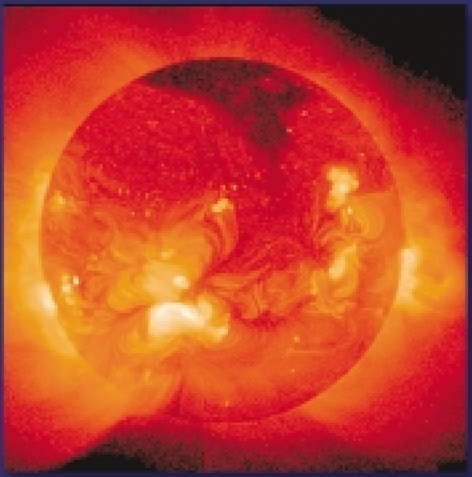
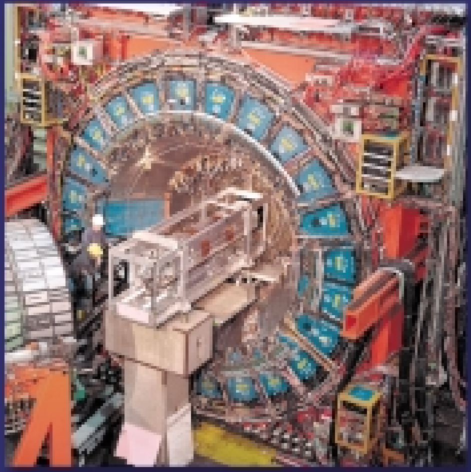
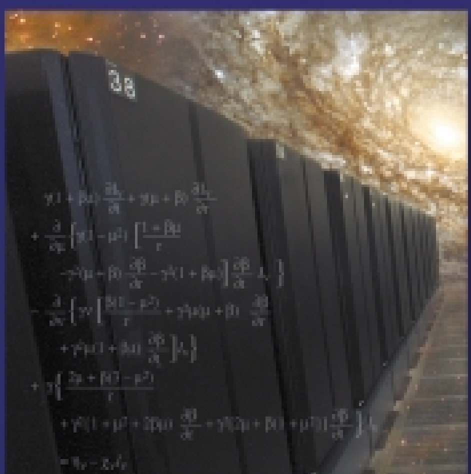
Office of Science
Strategic Plan

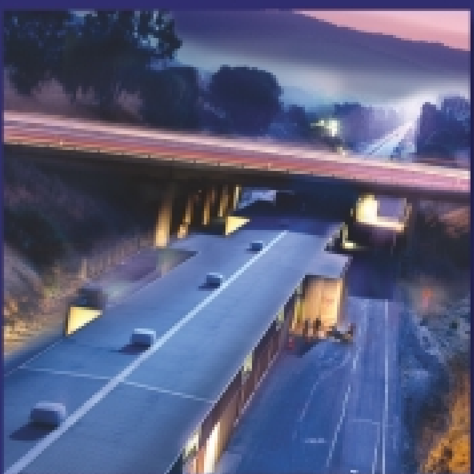
February 2004











Office of Science
U.S. DEPARTMENT OF ENERGY

"Scientific and technological research are a high calling for any individual. And promoting research is an important role of our Federal government. . . . We'll continue to support science and technology because innovation makes America stronger. Innovation helps Americans to live longer, healthier, and happier lives. Innovation helps our economy grow, and helps people find work. Innovation strengthens our national defense and our homeland security. . . ."

— President George W. Bush
June 12, 2002, at the White House presentation
of the National Medals of Science and the
National Medals of Technology

Right to left: President Bush, Secretary of Energy Spencer Abraham, Director of the Office of Science Raymond Orbach, and Secretary of Homeland Security Tom Ridge touring Argonne National Laboratory in July 2002.

Contents

> *"The Department of Energy could well have been called the Department of Science and Energy . . . given our contribution to American science."*
>
> —Secretary of Energy Spencer Abraham,
> June 2002, at Brookhaven National Laboratory

Raymond L. Orbach

Director's Message

These are extraordinary times for science.

We are learning to manipulate matter at the molecular scale. The sequencing of the human genome, a landmark achievement, is providing a foundation from which to explore the most basic mechanisms of life. Computation has become a true third pillar of scientific discovery, complementing theory and experiment and providing insights into systems of otherwise impenetrable complexity. And we are probing the very structure of matter and the beginning of time.

The Office of Science is at the center of these and many other research frontiers, working in concert with other Federal agencies and U.S. universities to deliver the breakthroughs that will transform our future. This Strategic Plan, crafted in close consultation with the U.S. research community, is designed to deliver the scientific advances and support for our mission that will position our Nation for scientific and economic strength and leadership in the years to come.

When I joined the Office of Science after a career as a university scientist and administrator, I came with an appreciation for the four key roles that the Office plays in the U.S. research effort: *We provide solutions to our Nation's energy challenges*, contributing essential scientific foundations to the national, energy, and economic security missions of the U.S. Department of Energy (DOE). *We are the Nation's leading supporter of the physical sciences*, investing in research at over 280 universities, 15 national laboratories, and many international research institutions. *We deliver the premier tools of science to our Nation's science enterprise*, building and operating major research facilities for open access by the science community. *We keep the U.S. at the forefront of intellectual leadership*, supporting the core capabilities, theories, experiments, and simulations at the extreme limits of science.

This is an organization that takes scientific risks with high payoffs. We make long-term investments in people and research programs, while responding with agility to rapid changes at the frontiers of science. We work in partnership with other Federal agencies and the international scientific community. We build and maintain remarkable tools of discovery, such as the Spallation Neutron Source now under construction, and we take great pride in constructing and operating them on time and budget. We balance our signature support for big science and interdisciplinary teams with a broad portfolio of projects conducted by leading university and laboratory investigators.

Underpinning these efforts is an uncompromising commitment to scientific excellence and integrity, a commitment embodied by the cadre of dedicated and highly professional managers who guide our programs. All of our research is competitively selected and peer reviewed.

The Office of Science and its predecessors have proven over the past 50 years that we deliver results. Our legacy includes 79 Nobel laureates associated with DOE and its predecessor agencies since 1934. We have spawned entire new industries, including nuclear medicine technologies that save thousands of lives each year, and the nuclear power industry that now contributes 20% of the power to our Nation's electricity grid. We have been the first to take on new research challenges for the Nation, such as launching the Human Genome Project in 1986, and we were the first Federal agency to investigate the causes of global climate change. We are now working on the challenges that face our Nation in the 21st Century.

At the outset of this strategic planning process, I emphasized the need to identify a set of our highest science priorities, and through our deliberations, we have identified seven items that top our list for the foreseeable future (see sidebar).

Within this list, *Facilities for the Future of Science* crosscuts and supports all of the other priorities while at the same time underpinning research spanning almost all disciplines of science. I am increasingly mindful that the health and vitality of U.S. science and technology depends upon the availability of the most advanced research facilities—the powerful tools of discovery. The DOE Office of Science leads the world in the conception, design, construction, and operation of these large-scale devices. These machines have enabled U.S. researchers to make some of the most important scientific discoveries of the past 70 years, with spin-off technological advances leading to entirely new industries. More than 18,000 researchers and their students from universities, other government agencies (including the National Science Foundation and the National Institutes of Health), private industry, and those from abroad use our facilities each year. These users are both growing in number and diversity.

Because of their critical role in science, in the Fall of 2002, I initiated a process to identify and prioritize future major facilities. The results of this complementary planning effort, complete with detailed descriptions of the facilities, their roles, and the priority-setting process, are contained in the companion document, *Facilities for the Future of Science: A Twenty-Year Outlook*. The list of 28 large-scale facilities (see page 15) represents our view of the projects that will help maintain U.S. scientific leadership for decades to come. These facilities are an integral part of this Strategic Plan.

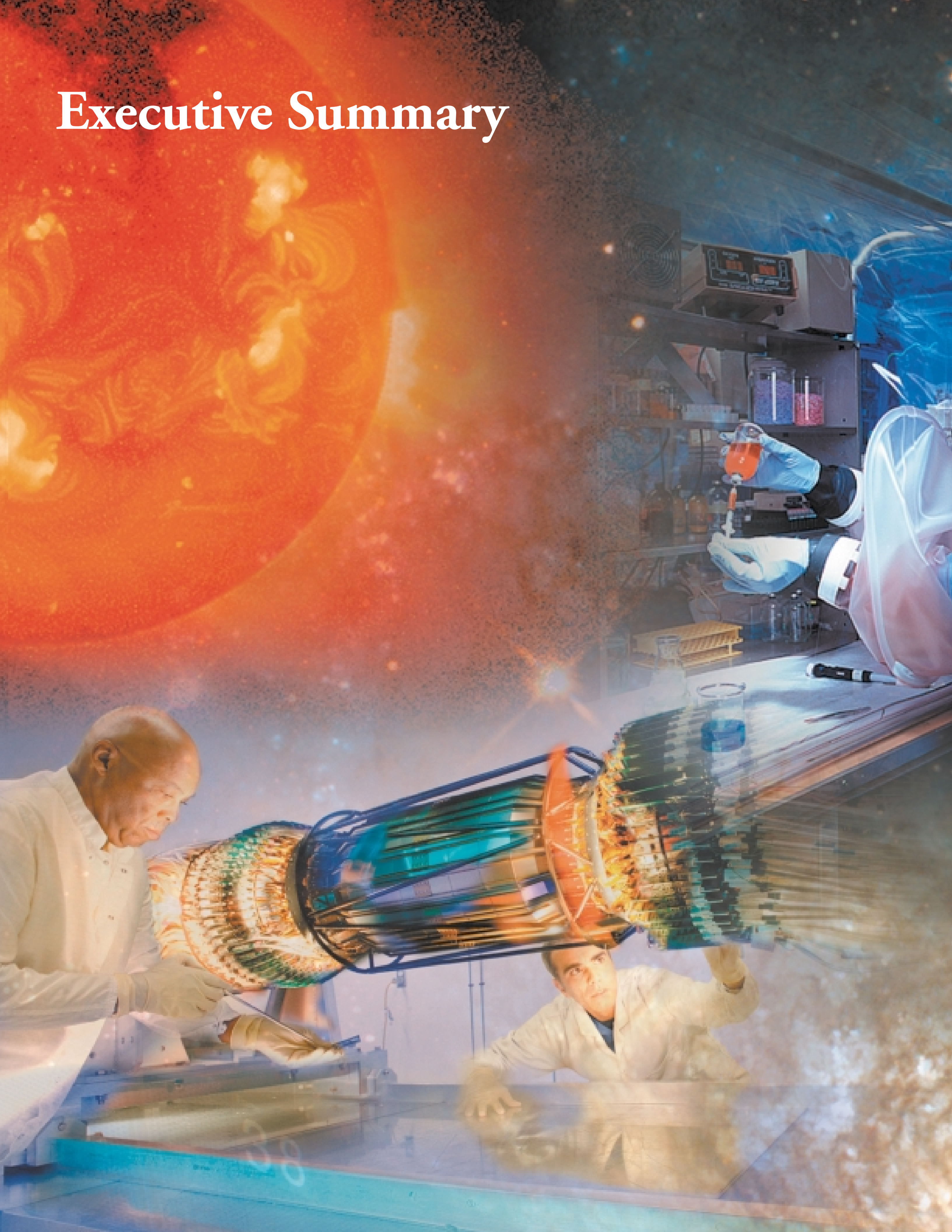
The following pages outline an ambitious agenda for science, one that will lead us to a more secure energy future, a cleaner environment, a healthier citizenry, and great advances in our imagination and knowledge. I trust that the goals of this Plan will fire your imagination as they have ours, and that you will join with us in this exciting quest for scientific discovery and leadership.

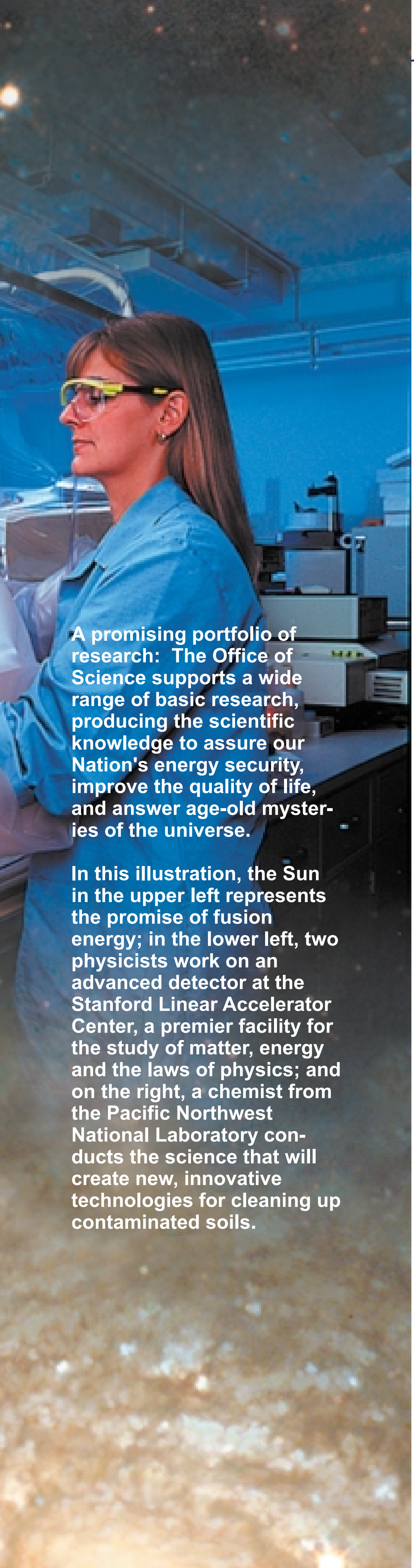
Raymond L. Orbach
Director, Office of Science
U.S. Department of Energy
Office of Science Strategic Plan 2004

Highest Priorities for the Office of Science

- *ITER for Fusion Energy:* Provide the enduring solution to our Nation's energy challenge, conducting the burning plasma experiment that will bring fusion energy within reach as a commercial source of clean, abundant energy.
- *Scientific Discovery through Advanced Scientific Computing:* Expand the broad frontiers of scientific discovery through the power of advanced computation.
- *Nanoscale Science for New Materials and Processes:* Master the ability to construct revolutionary new materials and processes…atom-by-atom and build upon Nature's self-assembling techniques.
- *Taming the Microbial World—the Next Revolution in Genomics:* Harness microbial genomes and the molecular machines of life for energy, the environment, and human health.
- *Dark Energy and the Search for the Genesis:* Illuminate the basic forces of creation and the origins of matter, energy, space, and time.
- *Nuclear Matter at the Extremes:* Explore new forms of nuclear matter at high-energy densities and at the extreme limits of stability.
- *Facilities for the Future of Science:* Deliver the high-priority facilities over the next 20 years that support DOE's and the Nation's research.

Executive Summary





A promising portfolio of research: The Office of Science supports a wide range of basic research, producing the scientific knowledge to assure our Nation's energy security, improve the quality of life, and answer age-old mysteries of the universe.

In this illustration, the Sun in the upper left represents the promise of fusion energy; in the lower left, two physicists work on an advanced detector at the Stanford Linear Accelerator Center, a premier facility for the study of matter, energy and the laws of physics; and on the right, a chemist from the Pacific Northwest National Laboratory conducts the science that will create new, innovative technologies for cleaning up contaminated soils.

Introduction…

This Strategic Plan outlines a 20-year journey filled with enormous potential for the American people. Contained within this Plan is the Office of Science's commitment to invest in some of the most exciting and daring research that humankind has ever conceived, from explorations into the origins of our universe and the constituents of life, to the scientific knowledge that will deliver new, clean, and abundant sources of energy to meet world needs for 10 billion people by the year 2050.

Over the next two decades, we will implement the goals and strategies contained in this Plan, working closely with the U.S. scientific community, Congress, the White House, and other key stakeholders. This implementation will be grounded in sound management principles and with an eye toward the highest possible return on taxpayer investments. We recognize, however, that rapid changes in science and technology, shifts in national priorities, and resources made available through the Federal budget process all create planning uncertainties and, ultimately, a highly dynamic planning environment. Accordingly, this Strategic Plan should be viewed as a living document. Frequent adjustments will be needed.

This Plan builds upon the goals and strategies found in the Department of Energy's (DOE) Strategic Plan, and it is organized around seven goals, six of which correspond to the Office of Science's primary budget categories and major science programs (see chart on page 9). The seventh goal addresses corporate management and resource issues that crosscut all of our programs, including a consolidated future outlook for our major research facilities. It also reflects our commitment to the President's Management Agenda and overall excellence in the management of science.

This Plan also builds on long-term measures included in the Office of Management and Budget's Program Assessment Rating Tool (PART). Extending beyond the PART measures, however, are strategic milestones contained within 20-year timelines at the end of each chapter.

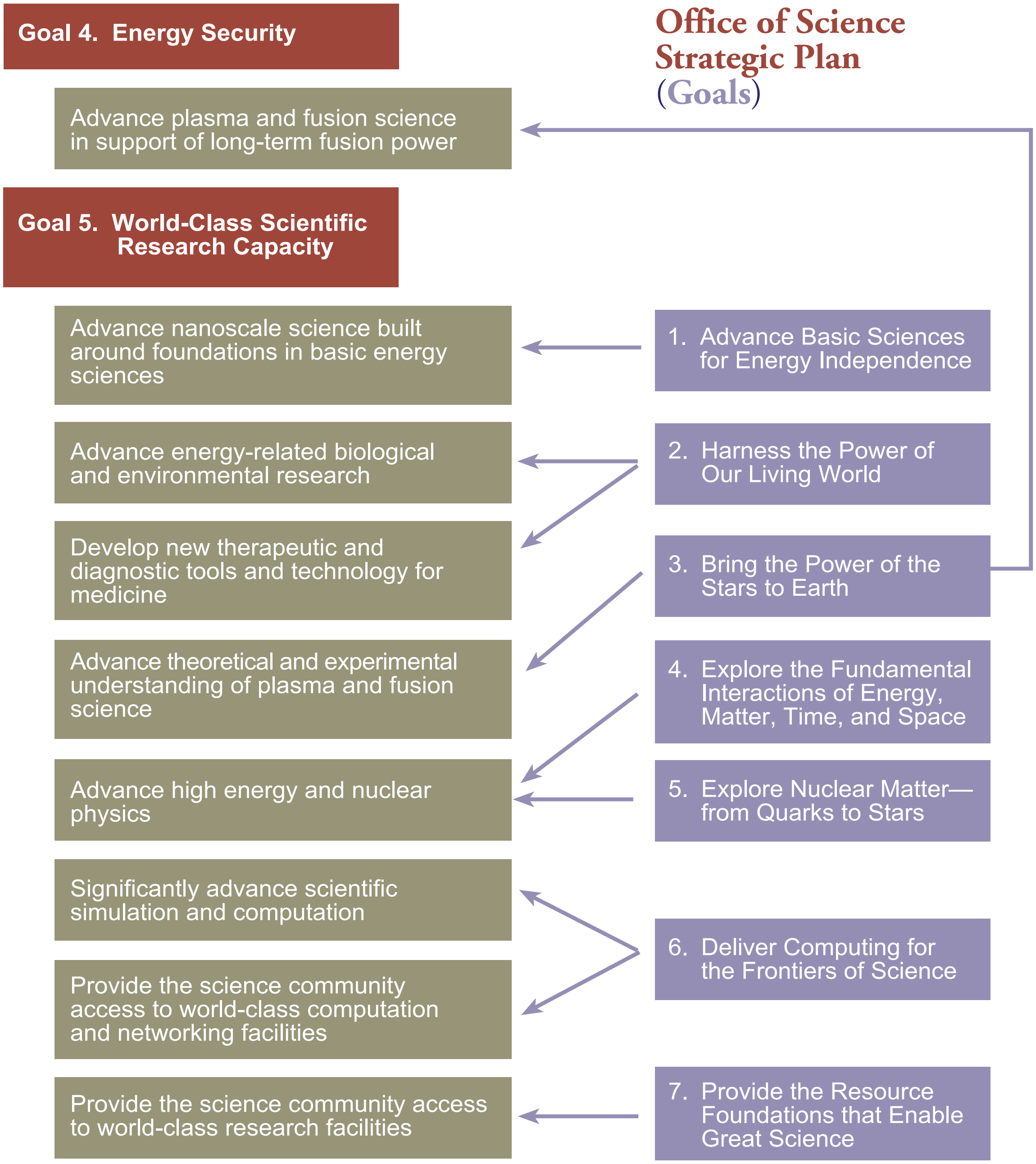
The result is a Plan that provides seamless links to the main Office of Science and DOE planning, budget, and performance assessment processes and documents. Continuing in this tradition, our next step toward implementing this 20-year vision will be to develop multi-year operational plans that will bridge the gap between this Strategic Plan and our annual budget.

In developing this Plan, we pursued a highly participatory process, building on the expert advice of our Advisory Committees, vetting key decisions with the leaders of our national laboratories and principals in the university community, and exploring ideas with a large number of other interested parties (see Appendix A). We considered the range of today's most compelling national challenges and priorities—with energy and security at the top of the list—and explored the possible challenges and opportunities of tomorrow. We reviewed key testimony, policy documents, forecasts, and foresight studies. We also integrated the results of a major planning effort that identified the highest priority next-generation scientific user facilities. That report, *Facilities for the Future of Science: A Twenty-Year Outlook*, and this Plan serve as companion documents.

The Executive Summary of this Plan presents a snapshot of the main elements and provides the context, vision, and essential goals and priorities contained within the document. The individual chapters provide the detailed discussion, including strategies and the performance timelines mentioned above, that will serve as a blueprint for the Office of Science for the next two decades.

Seamless Connections: Alignment of the DOE and Office of Science Strategic Plans

DOE Strategic Plan
(Office of Science-Relevant
Goals and Strategies)



Goal 4. Energy Security

Advance plasma and fusion science in support of long-term fusion power

Goal 5. World-Class Scientific Research Capacity

Advance nanoscale science built around foundations in basic energy sciences

Advance energy-related biological and environmental research

Develop new therapeutic and diagnostic tools and technology for medicine

Advance theoretical and experimental understanding of plasma and fusion science

Advance high energy and nuclear physics

Significantly advance scientific simulation and computation

Provide the science community access to world-class computation and networking facilities

Provide the science community access to world-class research facilities

Office of Science Strategic Plan
(Goals)

1. Advance Basic Sciences for Energy Independence
2. Harness the Power of Our Living World
3. Bring the Power of the Stars to Earth
4. Explore the Fundamental Interactions of Energy, Matter, Time, and Space
5. Explore Nuclear Matter—from Quarks to Stars
6. Deliver Computing for the Frontiers of Science
7. Provide the Resource Foundations that Enable Great Science

Our Mission…

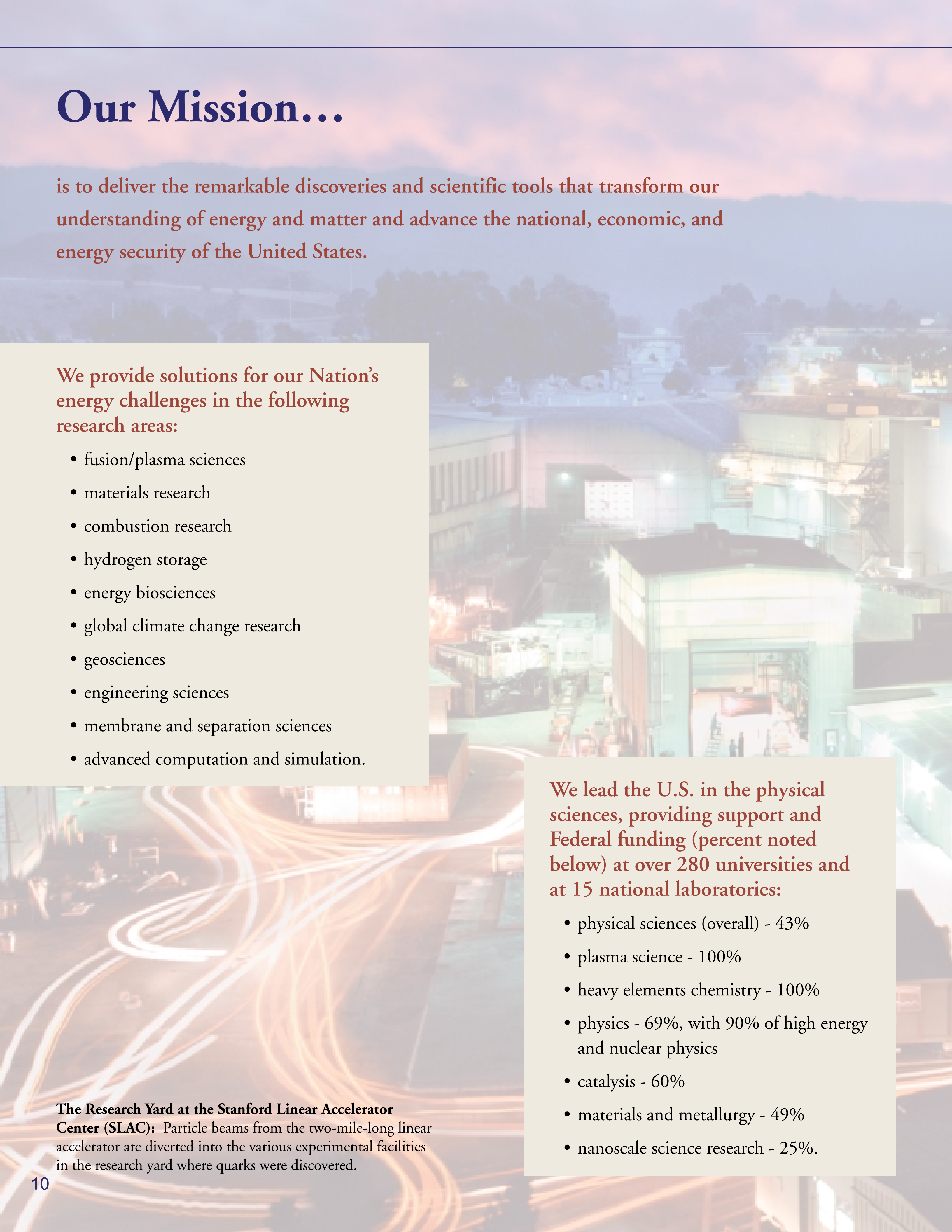
is to deliver the remarkable discoveries and scientific tools that transform our understanding of energy and matter and advance the national, economic, and energy security of the United States.

We provide solutions for our Nation’s energy challenges in the following research areas:

- fusion/plasma sciences
- materials research
- combustion research
- hydrogen storage
- energy biosciences
- global climate change research
- geosciences
- engineering sciences
- membrane and separation sciences
- advanced computation and simulation.

We lead the U.S. in the physical sciences, providing support and Federal funding (percent noted below) at over 280 universities and at 15 national laboratories:

- physical sciences (overall) - 43%
- plasma science - 100%
- heavy elements chemistry - 100%
- physics - 69%, with 90% of high energy and nuclear physics
- catalysis - 60%
- materials and metallurgy - 49%
- nanoscale science research - 25%.



The Research Yard at the Stanford Linear Accelerator Center (SLAC): Particle beams from the two-mile-long linear accelerator are diverted into the various experimental facilities in the research yard where quarks were discovered.

We deliver the premier tools of science to our Nation's research enterprise:

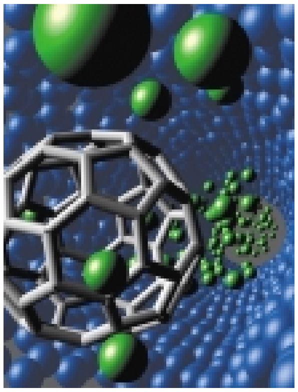
- particle accelerators and detectors
- advanced light sources
- neutron beam sources
- advanced computational and networking facilities
- plasma science facilities
- genome sequencing facilities
- nanoscale science research centers
- specialized centers and facilities for microcharacterization, combustion research, x-ray optics, molecular-level environmental sciences, atmospheric measurement, and more.

We keep the U.S. at the forefront of intellectual leadership by:

- helping to prepare the scientific and technological workforce for the 21st Century
- creating centers of research that attract the world's best scientists
- daring to take scientific risks that have enormous payoff
- sponsoring more than 2,000 graduate and postdoctoral students in research positions at our national laboratories
- constructing major scientific facilities, such as the Spallation Neutron Source, the premier research site for neutron science in the world when completed in 2006
- developing five Nanoscience Research Centers, future home to the world's most advanced nanoscale research efforts
- initiating the Human Genome Project in 1986 and the first Federal research program focused on global climate change in 1978
- discovering 10 of the 12 fundamental particles that constitute matter
- delivering a broad range of intellectual advances in applied mathematics that underpin programs in the physical, biological, and environmental sciences
- sponsoring 35 Nobel laureates since DOE's inception in 1977, and a total of 79 Nobel laureates associated with DOE and its predecessor agencies since 1934
- supporting since 1962 the basic research for 633 projects that resulted in R&D 100 Awards for promising technologies, products, or processes—among the highest number of R&D awards for any government agency or private enterprise.

Our Goals…

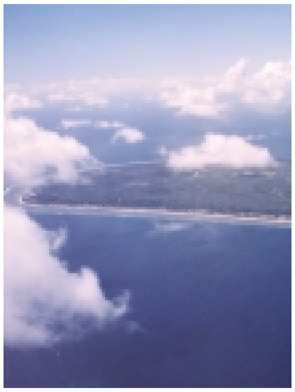
The goals and strategies contained in this Strategic Plan reflect national priorities set by the President and the Congress, our commitment to the missions of the Department of Energy, and the views of the U.S. scientific community. Our focus over the next two decades will be to ensure that the U.S. maintains scientific primacy in the key research disciplines that we support, that our science programs are relevant and useful for identified national priorities, and that we are agile enough to respond to emerging scientific challenges.



1 Advance the Basic Sciences for Energy Independence

Provide the scientific knowledge and tools to achieve energy independence, securing U.S. leadership and essential breakthroughs in basic energy sciences.

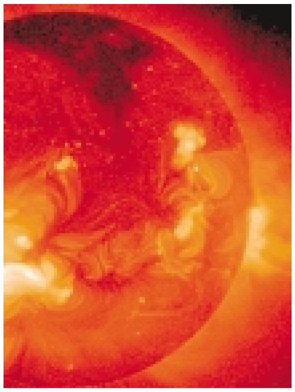
Much of our progress to reduce the energy intensity of our economy has come from advances in chemistry and materials science. We will build on this progress as we begin to design and assemble structures at the molecular level, learn to precisely predict and control chemical reactivity, and understand the behavior of complex systems. We will deliver new science that improves the reliability of our electric grid, makes our transportation system cleaner and more efficient, and enables new generation technologies, from fuel cells to hydrogen power.



2 Harness the Power of Our Living World

Provide the biological and environmental discoveries necessary to clean and protect our environment, offer new energy alternatives, and fundamentally alter the future of medical care and human health.

After two decades of research leadership in genomics, we can now search for molecular-level insights into cellular function, beginning with the characterization of multiprotein complexes. With that knowledge, we will employ the extraordinary efficiency of microbes to meet human needs and develop new approaches to medical care. In addition, through a systems-level understanding of our Earth's climate system, carbon cycle, and biogeochemistry, we will enable regional scale prediction of climate change and the design of mitigation and adaptation measures.



3 Bring the Power of the Stars to Earth

Answer the key scientific questions and overcome enormous technical challenges to harness the power that fuels a star, realizing by the middle of this century a landmark scientific achievement by bringing fusion power to the U.S. electrical grid.

We believe fusion will become a practical energy technology within three to four decades, through either magnetic confinement of plasmas or one of several inertial approaches. Over the next decade, we will resolve critical scientific uncertainties and select the most promising technical approach, including participating in an international burning plasma experiment called ITER.

4

Explore the Fundamental Interactions of Energy, Matter, Time, and Space

Understand the unification of fundamental particles and forces and the mysterious forms of unseen energy and matter that dominate the universe, search for possible new dimensions of space, and investigate the nature of time itself.

With next-generation accelerators, we will test and extend our views of the most basic constituents of matter, and perhaps see the validation of a grand unifying theory of the fundamental forces that govern our world—the goal of particle physics for decades. On the cosmological scale, we hope to reveal the nature and behavior of the enigmatic dark matter and dark energy that we believe account for the bulk of the mass of our universe, and that are responsible for the very startling recent discovery that the expansion of our universe is accelerating.

5

Explore Nuclear Matter—from Quarks to Stars

Understand the evolution and structure of nuclear matter, from the smallest building blocks, quarks and gluons; to the elements in the universe created by stars; to unique isotopes created in the laboratory that exist at the limits of stability, possessing radically different properties from known matter.

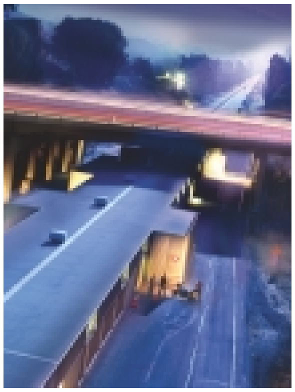
Great strides in our understanding of nuclei and nuclear reactions have led to such profound influences on society as the discovery of fission and fusion and the development of the now vast field of nuclear medicine. With technological advances in accelerators, instrumentation, and computing, we will explore new forms of nuclear structure and matter, and at last unlock the mystery of how protons and neutrons, the basic building blocks of matter, are put together. This knowledge is vital to research in energy and national security, and to understanding the stellar processes that give rise to the known elements in the universe.

6

Deliver Computing for the Frontiers of Science

Deliver forefront computational and networking capabilities to scientists nationwide that enable them to extend the frontiers of science, answering critical questions that range from the function of living cells to the power of fusion energy.

Each of the previous goals, and progress in many other areas of science, depends critically on advances in computational modeling and simulation. Crucial problems that we can only hope to address computationally require us to deliver orders of magnitude greater effective computing power than we can deploy today.



7

Provide the Resource Foundations that Enable Great Science

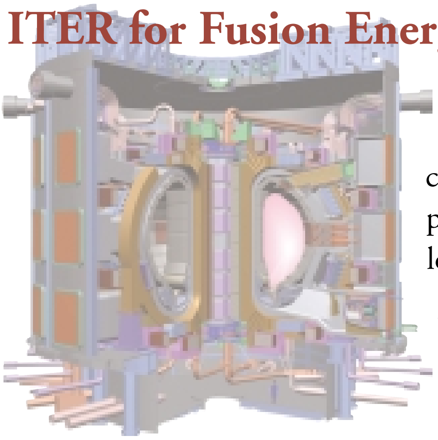
Create and sustain the discovery-class tools, 21st Century scientific and technical workforce, research partnerships, and management systems that support the foundations for a highly productive, world-class national science enterprise.

Our Nation's research enterprise depends upon a solid foundation that has been built through careful investments in people, institutions and major scientific facilities. Of particular note are the "discovery-class" scientific tools that we construct and operate. Our goal is to continue to provide leadership, stewardship, and balance of this vital combined infrastructure.

Our Priorities…

The Office of Science's research priorities flow from our long-term strategic goals and reflect our Nation's commitment to energy independence, a cleaner environment, improved health care, greater economic prosperity, and intellectual leadership. These priorities are a critically important subset of the full range of Office of Science research responsibilities that are more broadly defined by our major goals (pages 12 and 13). Pursuing these research priorities over the next 5 to 10 years and beyond will be challenging, but they hold enormous promise for the future of our Nation and the overall well-being of our citizens.

ITER for Fusion Energy

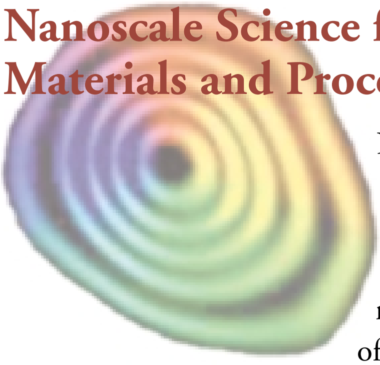


The President has made achieving commercial fusion power the highest long-term energy priority for our Nation. Our challenge is to develop a science-based solution that harnesses fusion energy to power our industries and homes. We will do this by joining an international burning plasma experiment, ITER, and exploring other promising technologies.

Scientific Discovery through Advanced Scientific Computing

Extraordinary advances in computer architecture and software design are making scientific computing a true third pillar of discovery, joining theory and experiment as a standard tool that researchers rely upon to make scientific progress. Scientific computing will enable us to model and simulate experiments that cannot be conducted in a laboratory. This means that biologists can learn the secrets of protein folding, which is essential to understanding basic life processes; and physicists can model the behavior of supernovae, which may explain how the cosmos is ordered. The Office of Science will bring 50 years of leadership in using advanced computers to a multi-agency Federal partnership with computer vendors and the academic community.

Nanoscale Science for New Materials and Processes



Nanoscale science research—the study of matter at the atomic scale—will take us into a realm where the properties of materials are dramatically different from what we have today. Structures composed of just a few atoms and molecules may be engineered to assemble themselves into useful devices such as computers that can store trillions of bits of information on a device no larger than the head of a pin or implantable in vivo diagnostic monitors the size of a cell. Large and complicated structures can be designed, one atom at a time, for desired characteristics such as super-lightweight and ultra-strong materials. The Office of Science will help lead this revolution—with nanoscale research in materials sciences, physics, chemistry, biology, and engineering—and tools that can probe and manipulate matter at the atomic scale.

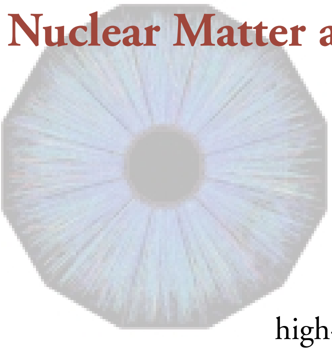
Taming the Microbial World—the Next Revolution in Genomics

Microbes are among Nature's most underappreciated resources. They thrive in extreme environments. They consider toxic waste a gourmet meal, and some are mini-factories that can produce energy supplies. Our challenge is to learn how to get microbes to work for us, to turn microbes into mighty engines of scientific progress. The Office of Science will use the knowledge and tools that we have developed over the past two decades of research into genomics to understand how microbes may be able to clean up chemical and radioactive pollutants and to produce abundant and clean energy.

Dark Energy and the Search for the Genesis

How the universe originated—its genesis—is one of the great mysteries of science. Experiments at the Office of Science's accelerators seek evidence for unification: the blending of today's diverse patterns of particles and interactions into a much simpler picture at high particle energies, like those that prevailed in the very early universe. In one experiment, a partnership with NASA will put a dedicated telescope in Earth orbit to measure the emission of light throughout supernovae explosions across the universe, providing a historical record of its acceleration in the aftermath of the Big Bang. These results are essential to understand the mysterious dark energy that dominates today's universe and drives an accelerating expansion of space.

Nuclear Matter at the Extremes



Understanding how nuclear matter is formed is critical to understanding the processes within stars and how elements are created—including possible new elements—at high-energy densities and the extreme limits of stability. Experiments with colliding gold nuclei are designed to study brief, submicroscopic samples of hot plasma of free quarks and gluons that filled the universe at the tender age of one microsecond. New accelerator studies are planned to explore the extremes of nuclear matter and the processes that form nearly all of our chemical elements in stars and supernovae.

Research Facilities for the Future of Science

The discoveries of the future will require powerful next-generation scientific tools. A list of the 28 highest priority facilities that will be needed over the next 20 years is provided below, grouped into the near-term, midterm, and far-term. These facilities support the Nation's research in areas that are traditionally the responsibility of the DOE. They are described in more detail in the companion document, *Facilities for the Future of Science: A Twenty-Year Outlook.*

	Priority	Program	Facility
Near-Term	1	FES	ITER
	2	ASCR	UltraScale Scientific Computing Capability
	Tie for 3	HEP	Joint Dark Energy Mission
		BES	Linac Coherent Light Source
		BER	Protein Production and Tags
		NP	Rare Isotope Accelerator
	Tie for 7	BER	Characterization and Imaging
		NP	CEBAF Upgrade
		ASCR	Esnet Upgrade
		ASCR	NERSC Upgrade
		BES	Transmission Electron Achromatic Microscope
	12	HEP	BTeV
Mid-Term	13	HEP	Linear Collider
	Tie for 14	BER	Analysis and Modeling of Cellular Systems
		BES	SNS 2-4 MW Upgrade
		BES	SNS Second Target Station
		BER	Whole Proteome Analysis
	Tie for 18	NP/HEP	Double Beta Decay Underground Detector
		FES	Next-Step Spherical Torus
		NP	RHIC II
Far-Term	Tie for 21	BES	National Synchrotron Light Source Upgrade
		HEP	Super Neutrino Beam
	Tie for 23	BES	Advanced Light Source Upgrade
		BES	Advanced Photon Source Upgrade
		NP	eRHIC
		FES	Fusion Energy Contingency
		BES	HFIR Second Cold Source and Guide Hall
		FES	Integrated Beam Experiment

🟥 Near-term
🟦 Mid-term
🟩 Far-term

Programs:
ASCR = Advanced Scientific Computing Research
BES = Basic Energy Sciences
BER = Biological and Environmental Research
FES = Fusion Energy Sciences
HEP = High Energy Physics
NP = Nuclear Physics

Our Vision…

We envision a future where our contributions to the physical, biological, and environmental sciences have transformed the world as we know it. Our discoveries have changed forever how we provide for life's most basic needs—and how we view our own existence within a complex, ever-changing universe.

By 2023, our science will have helped us achieve a large measure of energy independence. The energy intensity of our economy decreases, and energy sources are now more plentiful and clean. There is a new, more competitive menu of renewable energy sources, a safer generation of nuclear power, a hydrogen-based energy storage utilization infrastructure, and an efficient energy distribution network that is greatly enhanced by breakthroughs in nano-designed materials, computation, and other relevant fields of science. Having completed key experiments, the promise of fusion power—clean, almost limitless energy—is closer than ever.

We see a world where our science provides enduring solutions to the environmental challenges posed by growing world populations and energy use. New, cost-effective approaches, some based on the use of engineered microbes, enable us to tackle some of our most intractable cleanup problems. On a global scale, we have a clearer picture of the complex process of climate change, and we have solutions in hand made possible through the biological and environmental sciences, and in particular, through genomics.

Through 2023, our science will sustain critical growth and strength in the U.S. economy. During this period, entirely new industries will be created, and virtually all industries will benefit through the enormously broad reach of breakthroughs in energy and the physical sciences. Our mastery of catalysis, nano-assembly, self-replicating, and complex systems will not only increase our industrial efficiency, but it will create entirely new opportunities for harnessing the power of our material world.

Science fiction will give way to science fact as medical miracles unfold and a new set of promises arises to fill the void. DOE will continue to capitalize on its strengths at the nexus of the physical and life sciences, delivering the nanoscience, biology, precision engineering, and advanced computation that will "close the deal" in these developments and secure our valued contributing role in medical science. Restoring sight to the blind with micro-assembled retinal implants will start the journey, with the next stop, hope for those with spinal cord injuries.

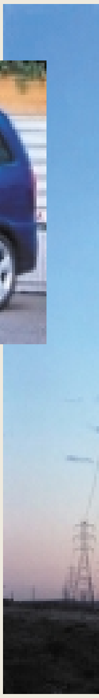
As the future unfolds, not only do our citizens enjoy an improved quality of life, but they are more secure. Our Nation is more secure. DOE science will have provided the science behind innovations in monitors, sensors, computational analysis, structures, materials, and countless areas that help to provide early threat detection and protect those that we serve.

In the not-too-distant future, our universe will seem more familiar to us, and the mysterious properties of matter and energy less complex. Our pursuit of answers to some of the most persistent questions of science will have revealed important secrets and assured U.S. intellectual leadership in key areas of science and mathematics.

At the end of the day, we envision a future where our discoveries have resulted in improved benefits to mankind, whether it was to light the night, heat a home, transport food, cure an illness, or to see and understand the beginning of time itself.

Hydrogen Production and Storage

Fusion Power Generation



Energy

Nanoscale science, materials catalysis, and genomics are just some of the fertile areas of basic research that will open the doors to more efficient and competitive renewable energy, the promise of fusion power, transition to a hydrogen economy, a vastly improved electrical distribution system, and gains in demand-side efficiency.

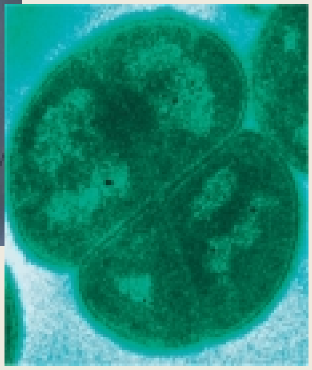
Economy

The ability to create materials atom-by-atom, to precisely control chemical reactions, to make microelectromechanical (MEM) devices the size of a human blood cell—all foretell the scientific breakthroughs that will fuel the U.S. economy in the decades to come.


Efficient Electrical Power Distribution

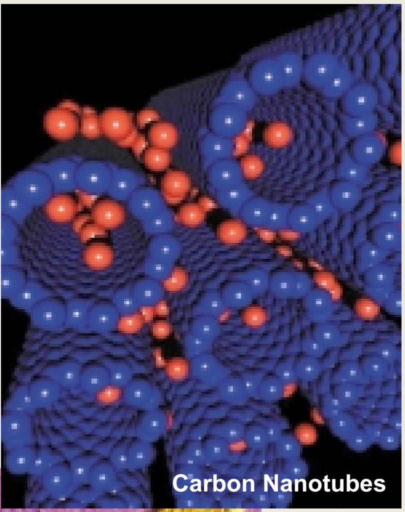
Global Environmental Monitoring

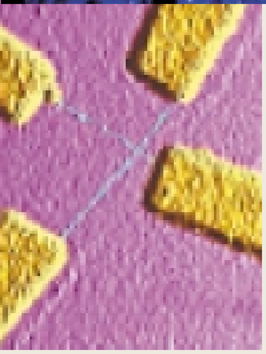

Medical Imaging


Microbe "Workers"

Environment and Health

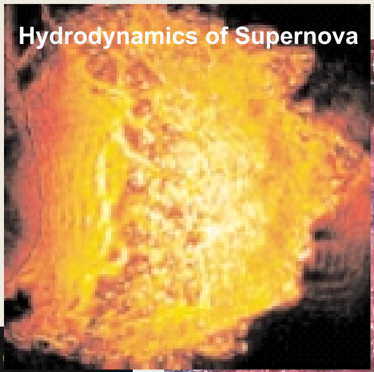
Understanding and protecting our global environment, harnessing the ability of microbes to do work, and advancing such medical technologies as Positron Emission Tomography (PET) and Magnetic Resonance Imaging (MRI) will occur through effective integration of the physical, computational, life, and engineering sciences.


Carbon Nanotubes


Nanoscale Electronics

Intellectual Leadership

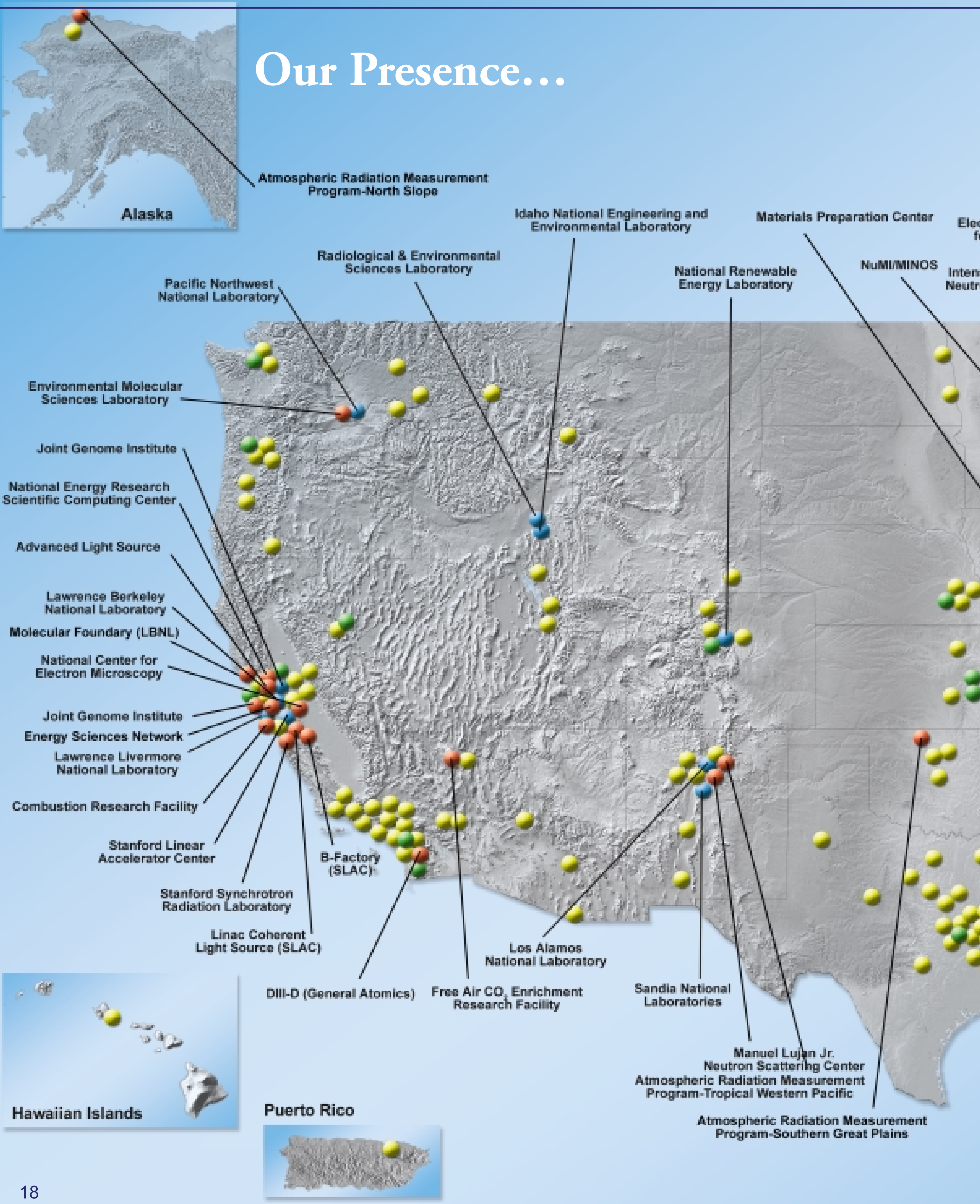
Exploration of such challenging scientific areas as high-energy physics and astrophysics, the essence of nuclear matter, and the hydrodynamics of a supernovae, will extend the frontiers of knowledge and scientific capability.


Hydrodynamics of Supernova


Top Quark Event

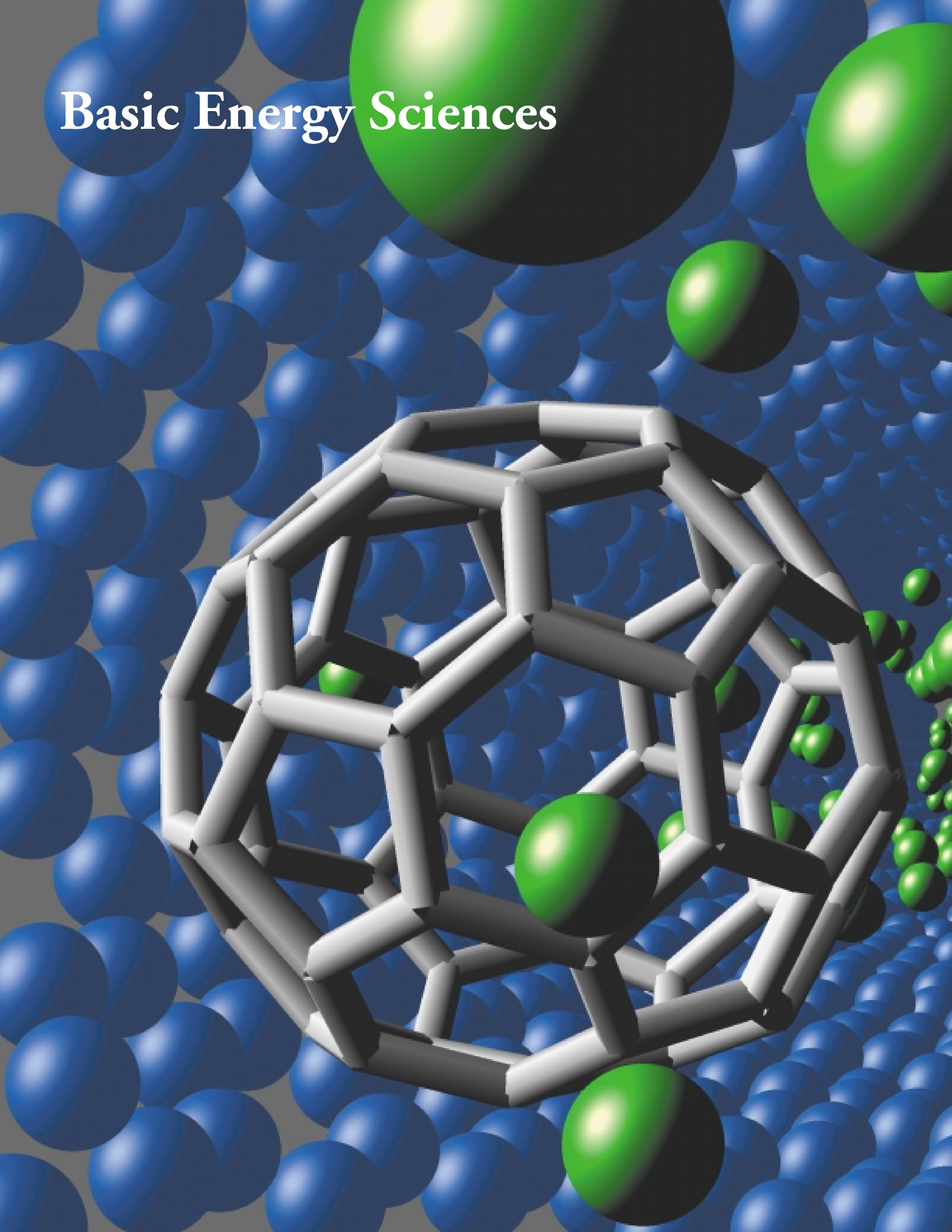

High Energy Physics and Astrophysics

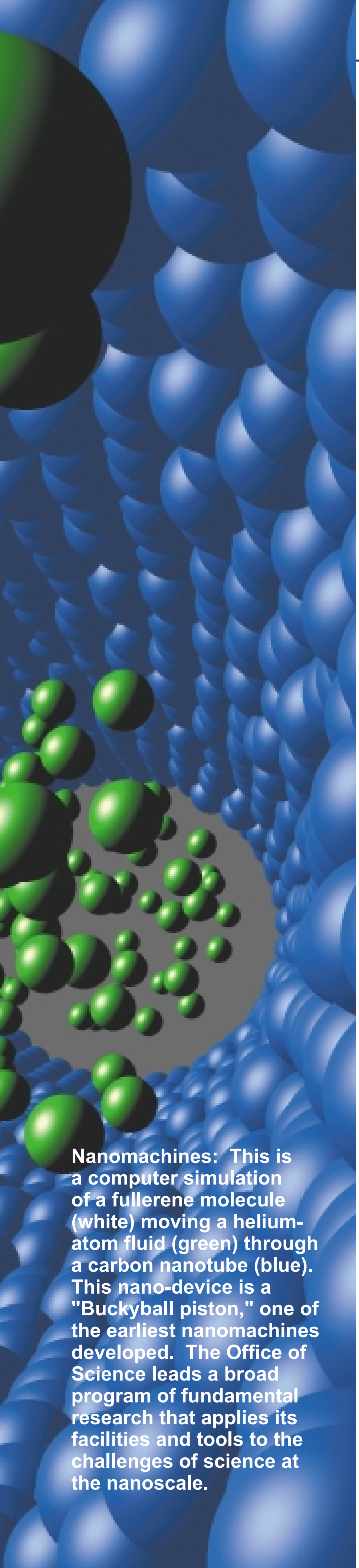
Our Presence…



*See Appendix B for the complete list of University-Based Research and University Research User Facilities

Basic Energy Sciences





Nanomachines: This is a computer simulation of a fullerene molecule (white) moving a helium-atom fluid (green) through a carbon nanotube (blue). This nano-device is a "Buckyball piston," one of the earliest nanomachines developed. The Office of Science leads a broad program of fundamental research that applies its facilities and tools to the challenges of science at the nanoscale.

LBNL

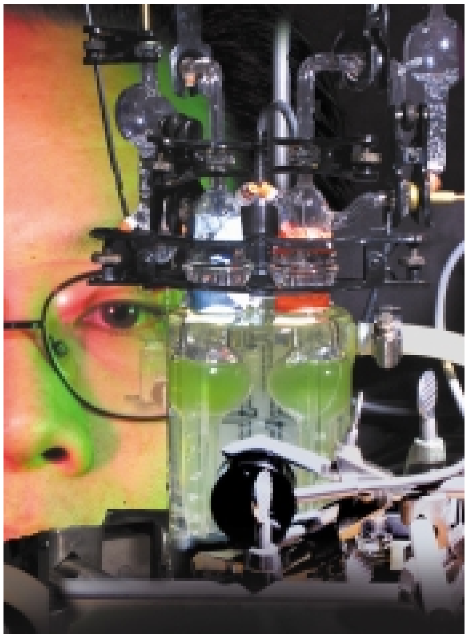
1

Advance the Basic Sciences for Energy Independence

Provide the scientific knowledge and tools to achieve energy independence, securing U.S. leadership and essential breakthroughs in basic energy sciences.

The growth of our economy over the past half-century has derived in substantial part from steady improvements in our energy technologies. In each subsequent decade, we have produced more goods and services with a given amount of energy, and we have produced that energy more efficiently and with less environmental impact. Much of this progress has come from advances in the materials and chemical sciences such as new magnetic materials; high strength, lightweight alloys and composites; novel electronic materials; and new catalysts, with a host of energy technology applications. We are now in the early stages of two remarkable explorations—observing and manipulating matter at the molecular scale and understanding the behavior of large assemblies of interacting components. Scientific discoveries in these two frontiers alone will accelerate our progress toward more efficient, affordable, and cleaner energy technologies. They pose some of the most fascinating and far-reaching scientific challenges of our time:

- What new, useful properties do materials display as we move from the classical or macroscopic world to objects composed of a few to a few thousands of atoms or molecules?
- What range of optical, mechanical, catalytic, electrical, tribological, and other properties can be achieved by designing devices and materials at the molecular scale?
- How can we efficiently assemble molecular-scale structures? How do living organisms construct complex assemblies, and can we apply these approaches to engineer useful devices and materials?
- How can we control chemical reactivity—the making and breaking of chemical bonds—to produce energy and desired materials while eliminating unwanted byproducts?



ORNL

Hydrogen from microalgae: Hydrogen may be one of the best resources to fuel the future economy of America and the world. It can be produced not only with resources such as petroleum, coal, and natural gas, but also from plants and organic waste. DOE's Office of Science, working in partnership with the Office of Energy Efficiency, has unlocked the secret to increasing the hydrogen yield of a certain type of green microalgae that shows promise of producing hydrogen cheaply, easily, and cleanly. This research is a collaboration among the National Renewable Energy Laboratory, Oak Ridge National Laboratory, and the University of California at Berkeley.

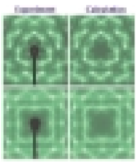
- How can we design, model and exploit complex systems—systems composed of large numbers of interacting components and/or components operating at different spatial or temporal scales—such as novel magnetic or superconducting materials?

Our ability to answer these and related questions depends on our ability to observe, characterize, manipulate, and computationally model matter at the atomic or molecular scale. This is a fundamentally interdisciplinary effort, linking science and engineering, and providing the foundation for a broad spectrum of scientific and technical advances. Essential tools for this research include current generation synchrotron x-ray and neutron scattering sources, and the more advanced sources to come, higher resolution electron microscopes and other atomic probes, and terascale computers. The Office of Science will deliver the leading-edge tools, sustain the interdisciplinary research, and create the knowledge necessary to realize the extraordinary potential of the basic energy sciences to meet our energy and other critical needs.

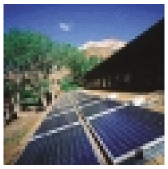
As an integral part of this Strategic Plan, and in *Facilities for the Future of Science: A Twenty-Year Outlook*, we have identified the need for eight future facilities to realize our Basic Energy Sciences vision and to meet the science challenges described in the following pages. Two of the facilities are near-term priorities: the **Linac Coherent Light Source (LCLS)** and the **Transmission Electron Achromatic Microscope (TEAM)**. The LCLS will provide laser-like radiation 10 billion times greater in power and brightness than any existing x-ray light source, enabling the study of matter and chemical reactions at speeds and levels of detail well beyond what is currently possible. TEAM will be the first of a new generation of electron microscopes that, by correcting for distortions in focus inherent to all current electron microscopes, will give much clearer images and allow the use of much larger experimental chambers. All

Our History of Discovery…Select Examples

1960-1994
Revealed the enzymatic mechanism of the molecule adenosine triphosphate (ATP), the energy currency of living cells.
(1997 Nobel Prize)

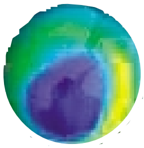


1980s
Developed synchrotron radiation light sources, which made many science discoveries possible such as ultra-high density computer hard drives.



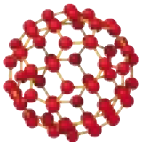
1980-2000
Achieved materials breakthroughs that reduced the cost of solar electricity by 100-fold.

1960 *1970* *1980*



1974
Discovered the effect of CFCs on the ozone layer, providing the scientific knowledge to protect our living planet.
(1995 Nobel Prize)

1981
Developed new opto-electronic materials and devices for wireless communications, semiconductor lasers, supermarket scanners, remote sensing, and medical diagnostics.



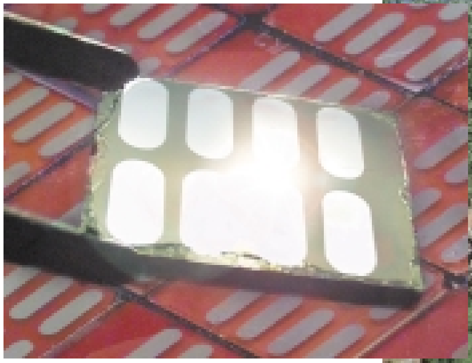
1985
Discovered a new class of carbon structure—the Buckyball.
(1996 Nobel Prize)

eight facilities are included in our Basic Energy Sciences Strategic Timeline at the end of this chapter and in the facilities chart in Chapter 7 (page 91), and they are discussed in detail in the *Twenty-Year Outlook*.

Our Strategies

1.1 Advance the core disciplines of the basic energy sciences, producing transformational breakthroughs in materials sciences, chemistry, geosciences, energy biosciences, and engineering.

The Office of Science will advance leading-edge research programs in the natural sciences, emphasizing fundamental research in materials sciences, chemistry, geosciences, and aspects of biosciences encompassed by the DOE missions, and it will provide world-class, peer-reviewed research results that are responsive to our Nation's energy security needs as well as the needs of the broad scientific community. As part of a thorough program of fundamental research, the Office of Science will implement a comprehensive plan based on the findings and recommendations of the Basic Energy Sciences Advisory Committee workshop, *Basic Research Needs to Assure a Secure Energy Future*. For example, new materials will be developed that impact solid-state lighting, smart windows, vehicular transportation, thermoelectric conversion, hydrogen storage, electrical storage, and improved fuel cells, leading to significant increases in efficiency. In addition, new catalysts will be designed that exert exquisite control over chemical reactions so as to specify the reaction products and the rates at which they form.

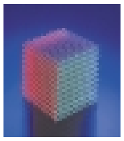


LBNL

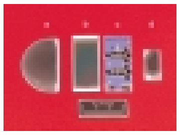
NREL

Nanoscience for energy applications: The photovoltaic array on the south roof of the Visitor Center at Zion National Park provides a significant portion of the electricity needs for the building as well as an uninterrupted power supply for use during power outages. DOE's Office of Science, working in partnership with the Office of Energy Efficiency, has provided the research that has improved solar cell efficiency and reduced solar energy costs 100-fold. New nanoscience research is bringing chemists, materials scientists, physicists, and theorists together to create devices such as this hybrid solar cell (offset left), which combines nanotechnology with plastic electronics. The result is a photovoltaic device that is cheaper and easier to manufacture than current semiconductor counterparts.

1986
Discovered organic-based magnets that are lighter, more flexible, and less energy-intensive to make than conventional magnets.

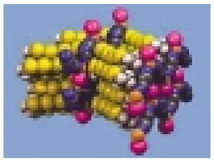


1990
Developed photonic bandgap crystals for revolutionary control of light propagation for sensors, antennas, lasers, solar cells, and telecommunications equipment.

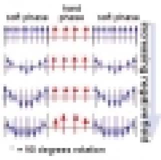


1996
Developed lithium batteries with high-energy storage capacity and virtually no adverse environmental impact.

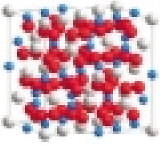
1990 *2000*



1990
Developed the first purely organic superconductors.



1993
Advanced the science of magnetic materials and paved the way for the manufacture of magnet structures with greater mechanical strength and stability.



1998
Discovered material to immobilize plutonium—gadolinium zirconate.

"The biggest single challenge for the next few decades: Energy for 10 billion people! At minimum we need 10 terawatts of power from some clean new energy source by 2050. For worldwide peace and prosperity, we need it to be cheap."

—Richard Smalley, shared the 1996 Nobel Prize in Chemistry for the discovery of fullerenes (Buckyballs)

The ability to simulate accurately the behavior of a system under many different conditions can enhance the effectiveness of experimental investigation and can even replace experiments in cases where they are too difficult or too expensive. There are a large number of areas of research in the natural sciences where simulation could have an enormous impact. Our ability to simulate has lagged behind what we can see experimentally, mostly due to major bottlenecks in the application of theory and computation in modeling the behavior of single atoms and molecules within a larger, more complex system.

Advanced crystallization processes: Scientists pursuing better and cheaper crystals for laser fusion have developed a "rapid-growth" method for producing the world's largest single crystal optical elements—crystals that weigh 600 to 700 pounds. By understanding and controlling the crystallization process at the molecular level, complex microstructures can be synthesized that will affect disciplines and technologies ranging from pharmaceuticals (such as crystallized proteins, among them human insulin) to new optical materials. This rapid-growth method was developed by DOE's Office of Science in partnership with the National Nuclear Security Administration to supply the crystal plates for the giant laser in the National Ignition Facility (NIF), which is currently under construction at Lawrence Livermore National Laboratory. This large-scale rapid-growth crystal growing technique is expected to save millions of dollars for both construction and later operation of the NIF, which will also help to maintain the safety and reliability of the Nation's nuclear weapons stockpile.

LLNL

To help realize this strategy, the synchrotron radiation light sources, electron-beam microcharacterization centers, and neutron scattering facilities will help reveal the atomic details of metals and alloys; glasses and ceramics; semiconductors and superconductors; polymers and biomaterials; proteins and enzymes; catalysts, sieves, and filters; and materials under extremes of temperature, pressure, strain, and stress. Using these powerful probes of science, we will be able to design new materials, atom-by-atom, and observe their creation as they unfold. Once the province of specialists, mostly physicists, these facilities are now used by thousands of researchers annually from all disciplines.

Our strategy includes the following emphases:

- Using the foundation of programs in materials sciences, chemistry, geosciences, energy biosciences, and engineering, create new options for the production, storage, distribution, and conservation of energy with basic research in areas such as hydrogen, nano-designed materials, nuclear fuel cycles and actinide chemistry, heterogeneous catalysis, novel membrane assemblies, and innovative energy conversion pathways.
- Remove simulation bottlenecks in order to accelerate the pace of scientific discovery, for example, bridge electronic-through-macroscopic length and time scales; simulate opto-magneto-electronic properties of materials;

understand chemical reactivity in solutions, solids, and turbulent flows; and explore a systems approach to molecular recognition, self-assembly, and chemical reactivity.

- Complete construction of the Spallation Neutron Source, which will be the world's most intense pulsed neutron source, and which will enable the study of materials that were previously not accessible to study. It is scheduled for commissioning in 2006.
- Design and construct the revolutionary x-ray light source called the LCLS to provide laser-like radiation in the x-ray region of the spectrum that is 10 billion times greater in peak power and peak brightness than any existing source. The high brilliance of the ultra-short pulses from the LCLS might make it possible to obtain the structure of a single molecule using only one pulse of light, a vast improvement over current methods.
- Explore new concepts in electron microscopy that will allow previously unimaginable studies of materials structure, chemistry, and the effect of external forces on materials during deposition, reaction, and deformation at the subnanometer level.

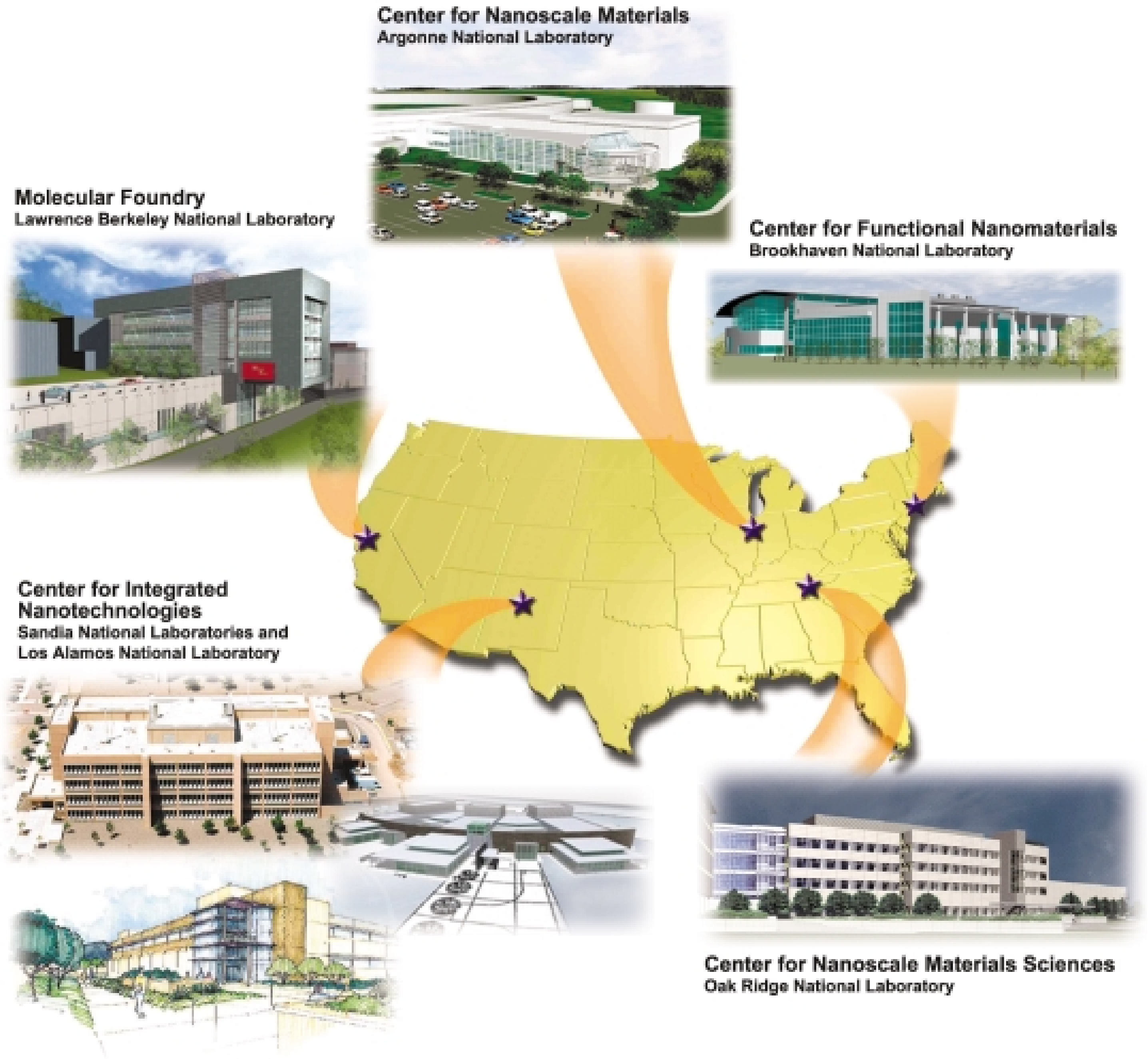
ORNL

Spallation Neutron Source (SNS): This accelerator-based neutron source facility will provide the most intense pulsed neutron beams in the world for scientific research and industrial development. Neutron research helps scientists and engineers improve materials used in high-temperature superconductors; powerful lightweight magnets; aluminum bridge decks; and stronger, lighter plastic products. The SNS is currently being built at Oak Ridge National Laboratory in collaboration with Argonne National Laboratory, Brookhaven National Laboratory, Lawrence Berkeley National Laboratory, Los Alamos National Laboratory, and Thomas Jefferson National Accelerator Facility, and will be completed in 2006.

1.2 Lead the nanoscale science revolution, delivering the foundations and discoveries for a future built around controlled chemical processes and materials designed one atom at a time or through self-assembly.

The main elements of the Office of Science nanoscale research program are the establishment of five Nanoscale Science Research Centers (NSRCs) and the support for nanoscale research in targeted areas addressing forefront science and DOE mission needs. The NSRCs are a new way of doing business for the dispersed cottage industry of researchers currently working on the enormous set of problems that together define "nanoscale science." The ability to fabricate complex structures using chemical, biological, and other synthesis techniques; characterize them; assemble them; integrate them into devices; and do all this in one place will change the way materials research is done. Our strategy includes the following emphases:

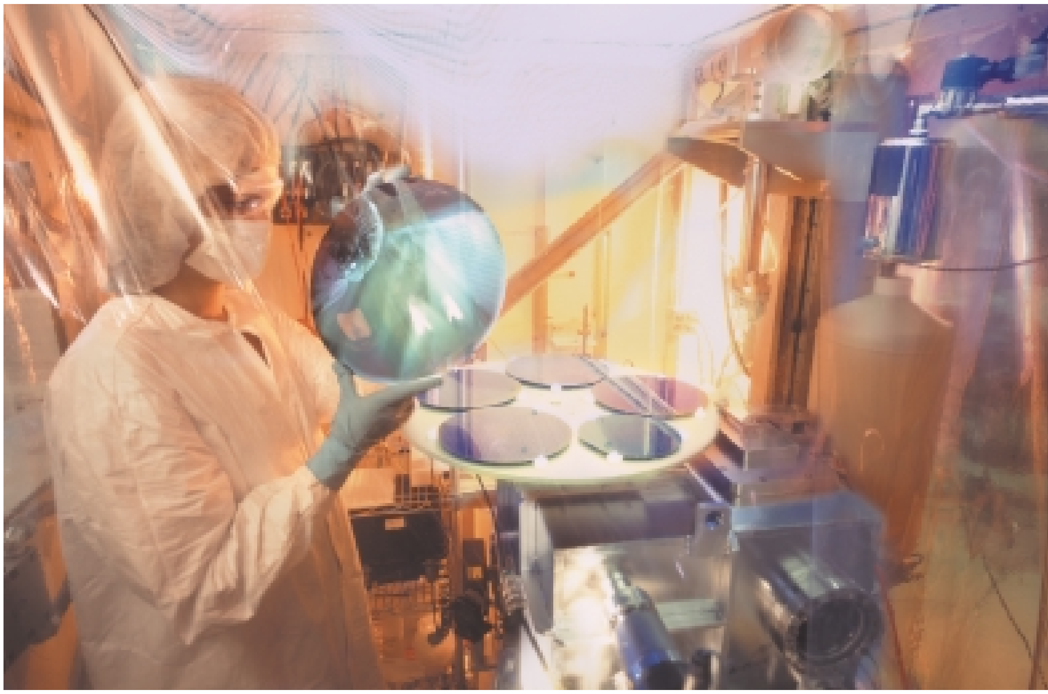
- Attain a fundamental understanding of phenomena unique to the nanoscale.



Nanoscale Science Research Centers: The Office of Science will build five new Nanoscale Science Research Centers to provide the Nation's research community with world-class resources for the synthesis, processing, fabrication, and analysis of materials at the nanoscale. User programs being initiated at the Centers will give the research community immediate access to their emerging capabilities.

- Achieve the ability to design and synthesize materials at the nanoscale to produce materials with desired properties and functions, using as necessary the tricks and tools of Nature's assemblies, both living and nonliving.
- Integrate nanoscale objects into microscale assemblies and macroscale devices.
- Develop experimental characterization tools and theory/modeling/simulation tools to advance nanoscale science.

1.3 Master the control of energy-relevant complex systems that exhibit collective, cooperative, and/or adaptive behaviors, i.e., systems that cannot be described as the sum of their parts.


SLAC

Stanford Synchrotron Radiation Laboratory: Physicists build particle accelerators to explore the fundamental nature of matter. However, bending the particle beams produces synchrotron radiation. First viewed as a problem, this radiation was soon recognized as an ultrapowerful beam—a pinpoint of light 30 times brighter than the sun. Scientists use it to study a wide range of materials at the Stanford Linear Accelerator Center (SLAC) (as depicted above) and at other Office of Science light sources around the U.S. Now, an important tool of science, synchrotron radiation produces leading-edge discoveries spanning many fields and disciplines within the materials and life sciences.

Entering this century, we find science and technology at yet another threshold: the study of simplicity will give way to the study of "complexity" as the unifying theme. The triumphs of science in the past century, which improved our lives immeasurably, can be described as elegant solutions to problems reduced to their ultimate simplicity. The new millennium is taking us into the world of complexity. Here, simple structures interact to create new phenomena, assembling themselves into devices that begin to answer questions that were, until the 21st Century, the stuff of science fiction. Understanding collective, cooperative, and adaptive phenomena and emergent behavior takes many forms. Our strategy includes the following emphases:

- Understand interactions among individual components that lead to coherent behavior that often can be described only at higher levels than those of the individual units. This can produce remarkably complex and yet organized behavior.
- Explore electrons interacting with each other and with the host lattice in solids that can give rise to magnetism and superconductivity.
- Investigate chemical constituents interacting in solution that can give rise to complex pattern formation and growth.
- Research and learn to synthesize and adapt the processes that underlie living systems, whereby they self-assemble their own components, self-repair as necessary, and reproduce; explore how they sense and respond to even subtle changes in their environments.

Our Timeline and Indicators of Success

Our commitment to the future, and to the realization of **Goal 1: Advance the Basic Sciences for Energy Independence**, is not only reflected in our strategies, but also in our Key Indicators of Success, below, and our Strategic Timeline for Basic Energy Sciences (BES), at the end of this chapter.

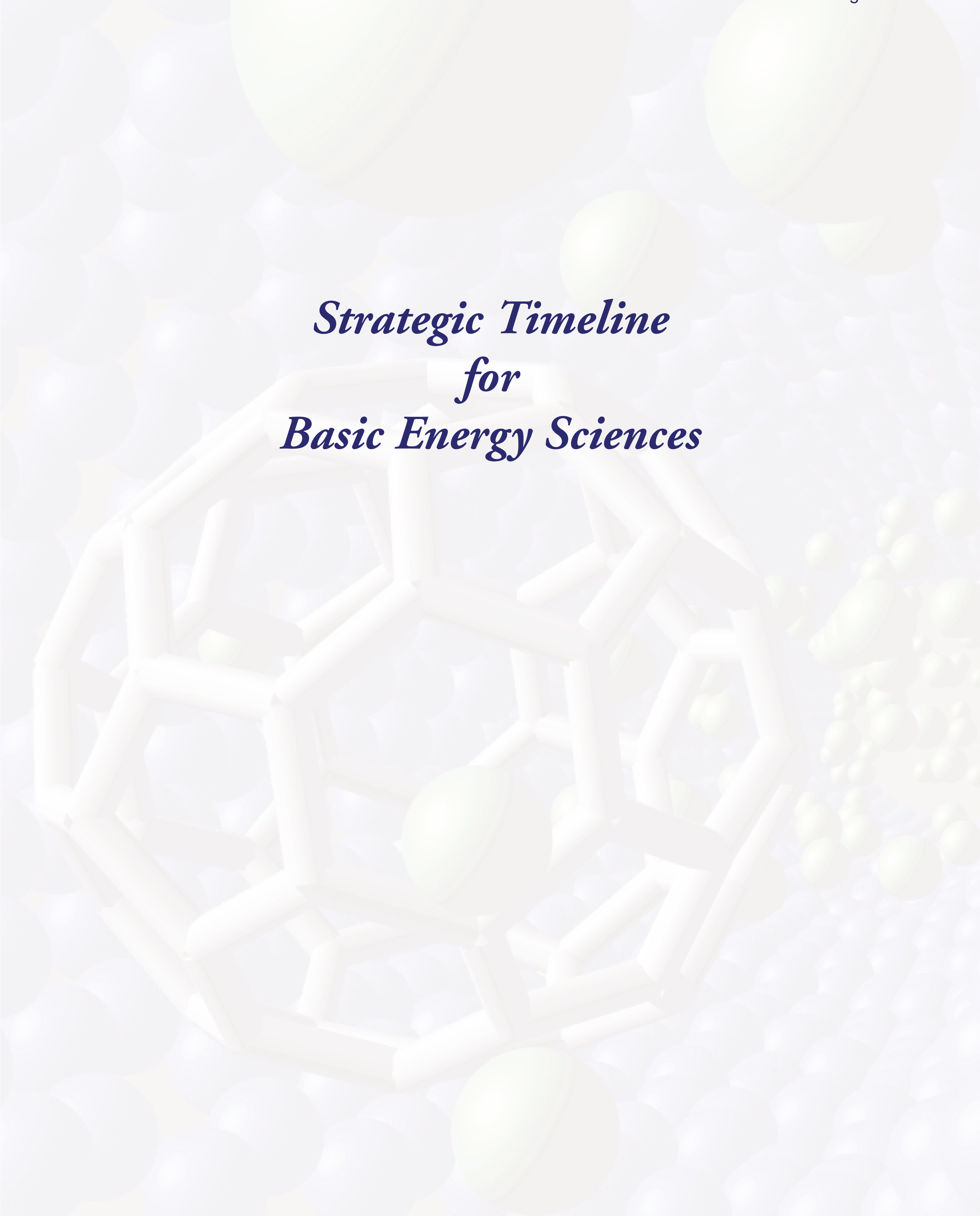
Our BES Strategic Timeline charts a collection of important, illustrative milestones, representing planned progress within each strategy. These milestones, while subject to the rapid pace of change and uncertainties that belie all science programs, reflect our latest perspectives on the future—what we hope to accomplish and when we hope to accomplish it—over the next 20 years and beyond. Following the science milestones, toward the bottom of the timeline, we have identified the required major new facilities. These facilities, described in greater detail in the DOE Office of Science companion report, *Facilities for the Future of Science: A Twenty-Year Outlook*, reflect time-sequencing that is based on the general priority of the facility, as well as critical-path relationships to research and corresponding science milestones.

Additionally, the Office of Science has identified Key Indicators of Success, designed to gauge our overall progress toward achieving Goal 1. These select indicators, identified below, are representative long-term measures against which progress can be evaluated over time. The specific features and parameters of these indicators, as well as definitions of success, can be found on the web at **www.science.doe.gov/measures.**

Key Indicators of Success:

- Progress in designing, modeling, fabricating, characterizing, analyzing, assembling, and using a variety of new materials and structures, including metals, alloys, ceramics, polymers, biomaterials, and more—particularly at the nanoscale—for energy-related applications.
- Progress in understanding, modeling, and controlling chemical reactivity and energy transfer processes in the gas phase, in solutions, at interfaces, and on surfaces for energy-related applications, employing lessons from inorganic, organic, self-assembling, and biological systems.
- Progress in developing new concepts and improving existing methods for solar energy conversion and other major energy research needs identified in the Basic Energy Sciences Advisory Committee workshop report, *Basic Research Needs to Assure a Secure Energy Future.*
- Progress in conceiving, designing, fabricating, and using new instruments to characterize and ultimately control materials.

Strategic Timeline
for
Basic Energy Sciences



Strategic Timeline—E

2003 2005 2007 2009 2011 2013

The Science

Core Disciplines of the Basic Energy Sciences

- Initiate research programs on hydrogen production and storage methods (2005)
- Initiate research programs on materials degradation in hostile environments (2005)
- Initiate expansion of materials, chemistry, and biochem programs (2005)
- Complete joint strategic plan and roadmap with the Office of Nuclear Energy (2005)

- Establish a program to develop computational tools for simulation, virtual testing, and design of materials (2006)

- Test biofilms for ability to generate electricity from organic waste (2007)
- Identify key physical processes that help maintain stability of materials during neutron irradiation (2007)

- Complete first draft GEN IV material properties database in support of nuclear power (2010)

- Increase hydrogen production through chemical, biochemical, and biomimetic systems (2011)
- Realize improvements in hydrogen and fuel cells through modest earlier investments in basic research (2011)

Nanoscale Science

- Enable the production of new composite materials and joining technologies with fabrication at the nanoscale (2011)

Energy-Relevant Complex Systems

- Develop new tools and advanced computers to enable scientists to simulate and model materials of much greater complexity for new energy technologies (2007)

- Design various complex interactions of atomic and molecular species to exhibit new physical phenomena for use in new energy applications (2011)

Future Facilities**

Linac Coherent Light Source (LCLS): The LCLS will provide laser-like radiation 10 billion times greater in power and brightness than any existing x-ray light source.

Transmission Electron Achromatic Microscope (TEAM): TEAM will be the first of a new generation of electron microscopes.

Spallation Neutron Source (SNS) 2-4 MW Upgrade: The SNS upgrade will more than double its power.

SNS Second Target Station: The second target station at the SNS will provide a long wavelength neutron source.

***These strategic milestones are illustrative and depend on funds made available through the Federal budget process.**

****For more detail on these facilities and the overall prioritization process, see the companion document, *Facilities for the Future of Science: A Twenty-Year Outlook.***

Basic Energy Sciences*

2015 2017 2019 2021 2023 2025

- Enable hydrogen and other low-carbon fuels to become significant components of the U.S. energy portfolio due to the accomplishment of one or more BES grand challenges (2025)

- Develop new materials that enable the widespread use of solid state lighting, improved fuel cells, breakthroughs for materials in radiation environments, new battery concepts, advanced membranes, hybrid solar cells, smart materials, and more (2015)
- Enable the practical start of the hydrogen economy with new knowledge on hydrogen production, storage, and use (2015)

- Enable the efficient, inexpensive conversion of sunlight to products such as fuels (2025)

- Use the complexity of matter as an asset rather than an obstacle by "tuning" the properties of matter with small changes in composition or with the application of pressure or a magnetic field (2025)

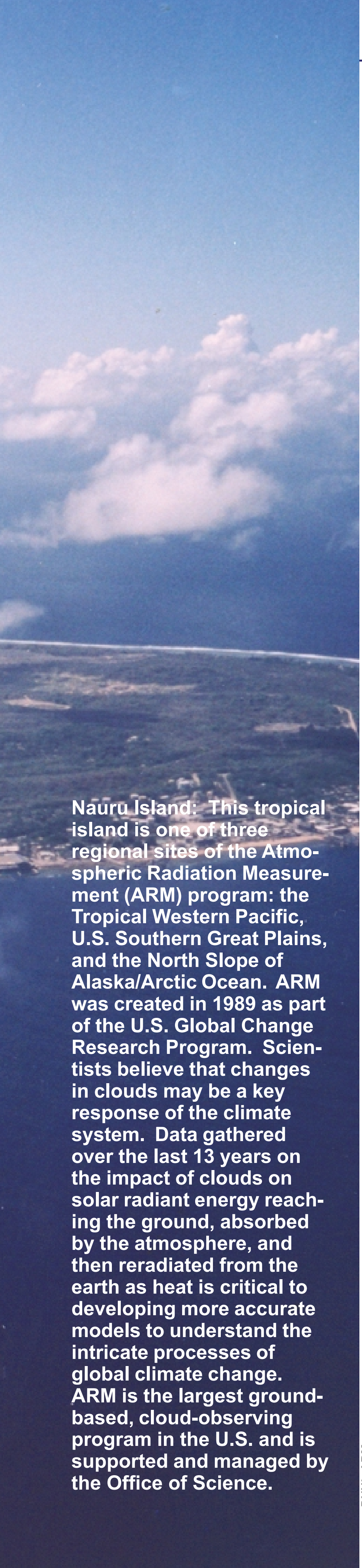
National Synchrotron Light Source Upgrade (NSLS II): The NSLS upgrade will create and install the next-generation design for a synchrotron light source storage ring.

Advanced Light Source (ALS) Upgrade: The ALS upgrade will allow the facility to expand to accommodate new instruments to explore the traditionally difficult spectral region at the border between optics and electronics (called the "terahertz-gap").

Advanced Photon Source (APS) Upgrade: The APS upgrade will create a "super storage ring" of electrons that will greatly enhance the brilliance of the facility.

High-Flux Isotope Reactor (HFIR) Second Cold Source and Guide Hall: Construction of the cold source and guide hall at HFIR will complete the facility, more than doubling its capabilities.

Biological and Environmental Research



Nauru Island: This tropical island is one of three regional sites of the Atmospheric Radiation Measurement (ARM) program: the Tropical Western Pacific, U.S. Southern Great Plains, and the North Slope of Alaska/Arctic Ocean. ARM was created in 1989 as part of the U.S. Global Change Research Program. Scientists believe that changes in clouds may be a key response of the climate system. Data gathered over the last 13 years on the impact of clouds on solar radiant energy reaching the ground, absorbed by the atmosphere, and then reradiated from the earth as heat is critical to developing more accurate models to understand the intricate processes of global climate change. ARM is the largest ground-based, cloud-observing program in the U.S. and is supported and managed by the Office of Science.

PNNL-ARM

2 Harness the Power of Our Living World

Provide the biological and environmental discoveries necessary to clean and protect our environment, offer new energy alternatives, and fundamentally alter the future of medical care and human health.

Over billions of years of evolution, Nature has created life's machinery—from molecules, microbes, and complex organisms to the biosphere—all displaying remarkable capacities for efficiently capturing energy and controlling precise chemical reactions. The natural, adaptive processes of these systems offer important clues to designing solutions to some of our greatest challenges. In the next decade, science will reveal the mechanisms and genetic secrets by which microorganisms develop, survive, and function in different environments. We will be able to manipulate matter at the micro, nano, and molecular scales; and we will be able to model and predict biological and environmental interactions on a regional and global basis. Such capabilities will provide us unprecedented opportunities to forge new pathways to energy production, environmental management, and medical diagnosis and treatment.

To realize this vision, many challenging scientific questions will have to be answered:

- What are the fundamental genetic processes, structures, and mechanisms that living systems use to control their responses to their environment, and how can we predict and repeat those processes to put Nature to work for us?
- How do we design new and revolutionary technologies and processes, using and combining principles of biological and physical systems that offer new solutions for challenges from medicine to environmental cleanup?
- How do clouds influence climate change, and how does human activity affect the behavior of clouds? How sensitive is climate to different levels of greenhouse gases and aerosols in the environment?

Answers to these and other questions will come only through effective convergence of the physical, life, and computational sciences. We have the track record and infrastructure to conduct the large-scale, complex, and interdisciplinary research to meet the challenge. Already, the Office of Science has delivered genome sequencing, protein crystallography, advanced tools for understanding the environment at the molecular level, integrated climate modeling, and advanced imaging tools. With anticipated new facilities, such as those for Genomics: GTL, as well as high-performance computational platforms and cutting-edge measurement tools, we are prepared to harness the power of our living world for a secure, environmentally sound, and energy-rich future.

As an integral part of this Strategic Plan, and in *Facilities for the Future of Science: A Twenty-Year Outlook*, we have identified the need for four future facilities to realize our Biological and Environmental Research vision and to meet the science challenges described in the following pages. Two of the facilities are near-term priorities: the **Protein Production and Tags** facility and the **Characterization and Imaging of Molecular Machines** facility. The Protein Production and Tags facility will use highly automated processes to mass produce and characterize tens of thousands of proteins per year, create "tags" to identify these proteins, and make these products available to researchers nationwide. The facility for Characterization and Imaging of Molecular Machines will build on capabilities provided by the Protein Production and Tags facility to provide researchers with the ability to isolate, characterize, and create images of the thousands of molecular machines that perform the essential functions inside a cell. All four facilities are included in our Biological and Environmental Research Strategic Timeline at the end of the chapter and in the facilities chart in Chapter 7 (page 93), and they are discussed in detail in the *Twenty-Year Outlook*.

Our Strategies

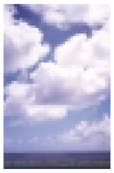
2.1 Tap the power of genomics and microbial systems for solutions to our Nation's energy and environmental challenges.

After launching the Human Genome Project in the 1980s, the Office of Science was part of an international collaboration that recently finished sequencing the entire human genome. Yet, we have only begun to understand how complex biological systems work—going from single genes to genetic networks to complex biological functions and characteristics, whether in humans or single-celled microbes. We continue to push the frontiers of biology, including the complex systems interactions, by studying microbes that can be used to help us solve DOE mission needs.

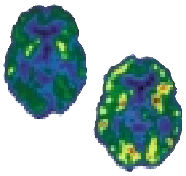
Microbes have been found in every conceivable environment on Earth, from boiling deep-ocean thermal vents to Arctic ice flows to toxic environments. The remarkable ability of microbes to flourish in extreme conditions demonstrates that they long ago developed systems for novel energy conversion and environmental cleanup.

Our challenge is to put those microbes—and their systems of molecular machines that allow them

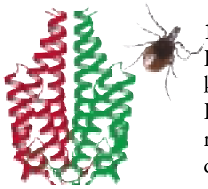
Our History of Discovery…Select Examples



1970
Discovered the complex processes and interactions behind acid rain.



1990
Imaged the biochemistry of human addiction using Positron Emission Tomography. (PET technology was enabled by DOE science breakthroughs.)

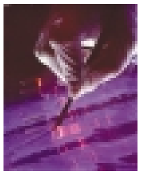


1995
Determined the structure of key surface proteins in Lyme Disease bacteria, offering new opportunities for detection and treatment.

1970 1980 1990

1986
Pioneered the quest to sequence the Human Genome.

1995
Sequenced the tiny pathogen, *Mycoplasma genitalium*, the smallest genome that sustains life.



1996
Provided fundamental research in capillary-based DNA sequencing that led to development of DNA sequencing machines that revolutionized genome sequencing . . . and modern biotechnology.

to survive—to work for us. Nature has designed remarkable arrays of multiprotein molecular machines with exquisitely precise and efficient functions and controls. With the help of the DOE Joint Genome Institute, and the future Genomics: GTL facilities, we will uncover the mysteries of biological systems that will enable our Nation's scientists to harness the power of genomics and microbial systems. Our strategy includes the following emphases:

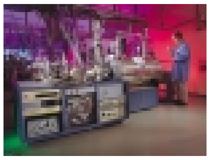
- Decode and compare the genetic instructions of diverse microorganisms by unraveling their DNA sequences to reveal their capabilities for energy production, carbon sequestration, and environmental cleanup.
- Discover the molecular machines encoded in each microbe's genetic instructions, determining what molecular machines are present, what proteins they are made of, where they are found in cells, and how they do their work.
- Produce computational models of molecular machines in action to understand the fundamental principles controlling the function of molecular machines and thus biological systems, providing us with knowledge to use or even redesign these machines.
- Examine genetic regulatory networks to understand the genetic circuitry in a cell that controls the molecular machines.
- Explore the biochemical capabilities of complex microbial communities to fully utilize the potential found in natural microbial communities.


LBNL

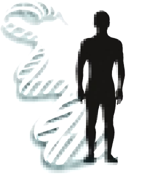
Frontiers in genomic science: Why would the Department of Energy's Office of Science be interested in this beautiful but peculiar fish? It turns out that the Fugu, or puffer fish, contains essentially the same genes as the human genome but in about one-eighth the total amount of DNA. Human gene hunters can sort through the Fugu genome much faster and easier than the human genome because it has far less non-coding DNA. DOE's Joint Genome Institute (JGI), the world's major public genome sequencing center, conducted this research as part of the Human Genome Project, an initiative pioneered by DOE, to give scientists a powerful new tool to help them better understand the human genome—from insights into diseases to the impacts of energy and energy byproducts on human physiology and health. Under the Office of Science Genomics: GTL program, JGI is now shifting attention to a new and equally promising frontier. By studying the genomes of a variety of micro-organisms, scientists are exploring the capabilities of the natural world to produce energy, clean up waste, and possibly slow or halt climate change.

1996
Verified the existence of the third branch of life (Archaea)—*Methanococcus jannaschi.*

1998
Developed computational tools for discovering genes.

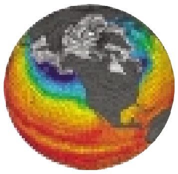


2000
Developed mass spectrometry for rapid determination of bacterial proteome that reduces analysis time from years to days.

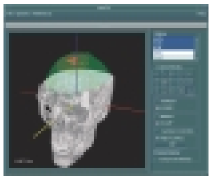


2001
Published a complete draft of the DNA sequence of the human genome as part of an international consortium.

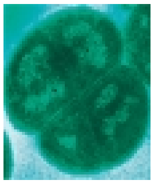
2000



1996
Delivered high-resolution ocean model for climate simulation.

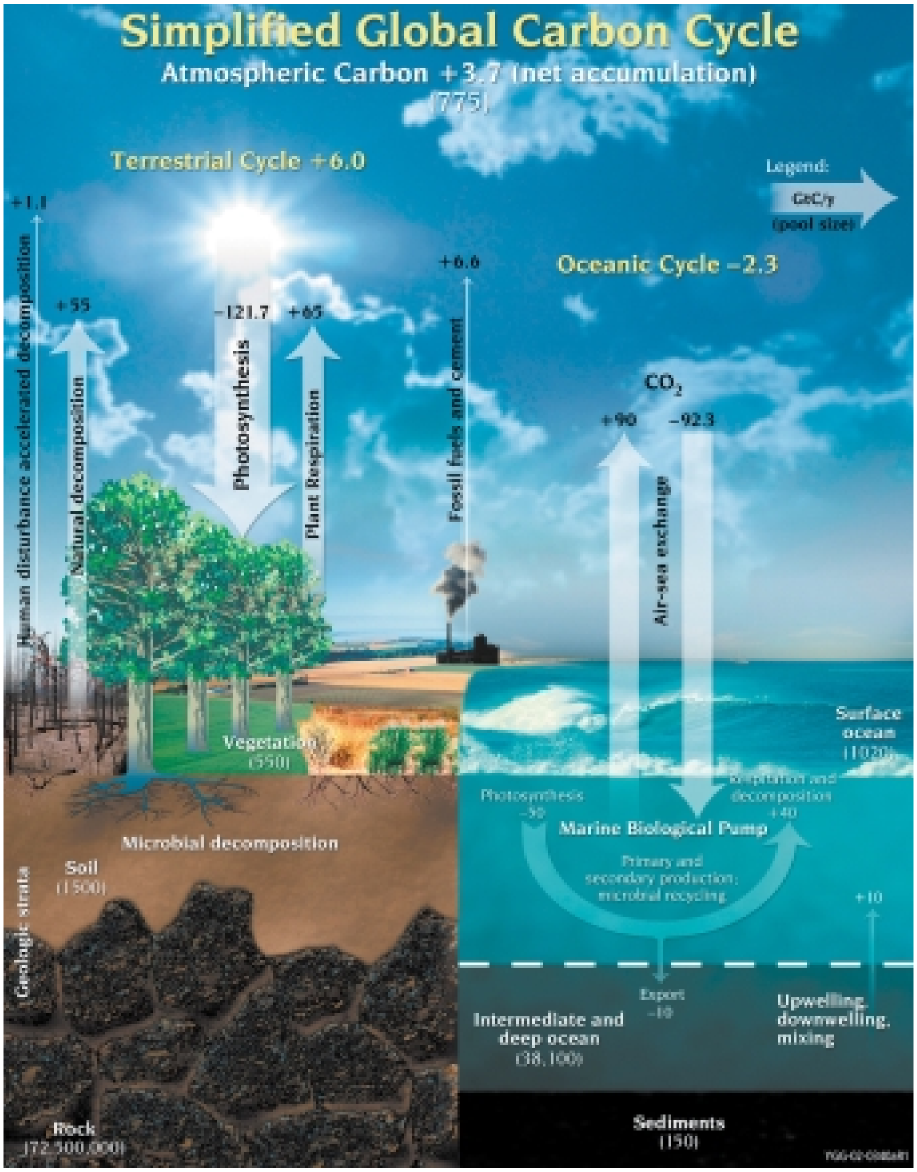


1999
Improved neutron beams for cancer treatment.



2000
Engineered radiation-resistant bacteria for bioremediation.

- Develop predictive models of complete microbial communities to anticipate how they will behave and change in response to various signals from their environment.



ORNL

Carbon cycle: In the past 60 years, the amount of anthropogenic carbon dioxide emitted to the atmosphere, primarily from use of fossil fuels, has risen from preindustrial levels of 280 parts per million to present levels of over 365. The relationship between climate change and increasing levels of carbon dioxide is a matter of intense study. Predictions of global energy use in the next century suggest a continued increase in carbon emissions and rising concentrations of atmospheric carbon dioxide unless major changes are made in the way we produce and use energy. Carbon sequestration is receiving attention as a promising solution, and the Office of Science is performing much of the basic research. In carbon sequestration, the gas is trapped or "fixed" in solid form in the terrestrial biosphere, underground, or in oceans, thus slowing or halting the buildup of greenhouse gasses. Research emphases range from the possible use of engineered geologic repositories, to enhancing Nature's own tool kit and sequencing the genomes of promising micro-organisms, putting them to work on this global problem.

2.2 Unravel the mysteries of Earth's changing climate and protect our living planet.

We are making progress in measuring and modeling changes in climate. This is no simple matter given the complex interactions of air, land, and ocean processes that affect climate. Despite our progress, we still cannot definitively distinguish between natural and human-caused climate changes, we do not fully understand the effects and roles of clouds and aerosols on climate, and we have limited ability to predict regional effects. More importantly, we have only begun to explore ways to mitigate and/or adapt to these effects. Ultimately, we need to be able to understand the factors that determine Earth's climate well enough to predict climate and climate impacts decades, or even centuries, in the future. We are developing the novel research tools, models, and integrated experiments and computational science to find the answers. Our strategy includes the following emphases:

- Determine the effects of clouds and aerosols on climate, in particular their interactions with long-wave radiation, how and where clouds form and dissipate in the atmosphere, and how changes in clouds and aerosol distributions alter the Earth's radiation balance.
- Predict future climate at regional scales, advancing mathematics and computation to simulate the

dynamics, chemistry, and biology of the Earth system on decade to century time scales.

- Distinguish natural and human-caused climate change based on improved climate models that more accurately reflect changes in radiative forcing due to increases in greenhouse gases and aerosols in the atmosphere.
- Understand and enhance Nature's processes for sequestering atmospheric carbon from fossil fuel use, including the capacity of terrestrial and oceanic ecosystems and opportunities to capitalize on the biophysical and biochemical mechanisms that control uptake in plants, soils, and ocean plankton.
- Determine how ecosystems respond to environmental change, developing a theoretical and empirical basis spanning molecular interactions to whole ecosystems.
- Predict and assess the effects of climate change based on models of human actions and costs and benefits of alternatives for mitigation and adaptation.

2.3 Understand the complex physical, chemical, and biological properties of contaminated sites for new solutions to environmental remediation.

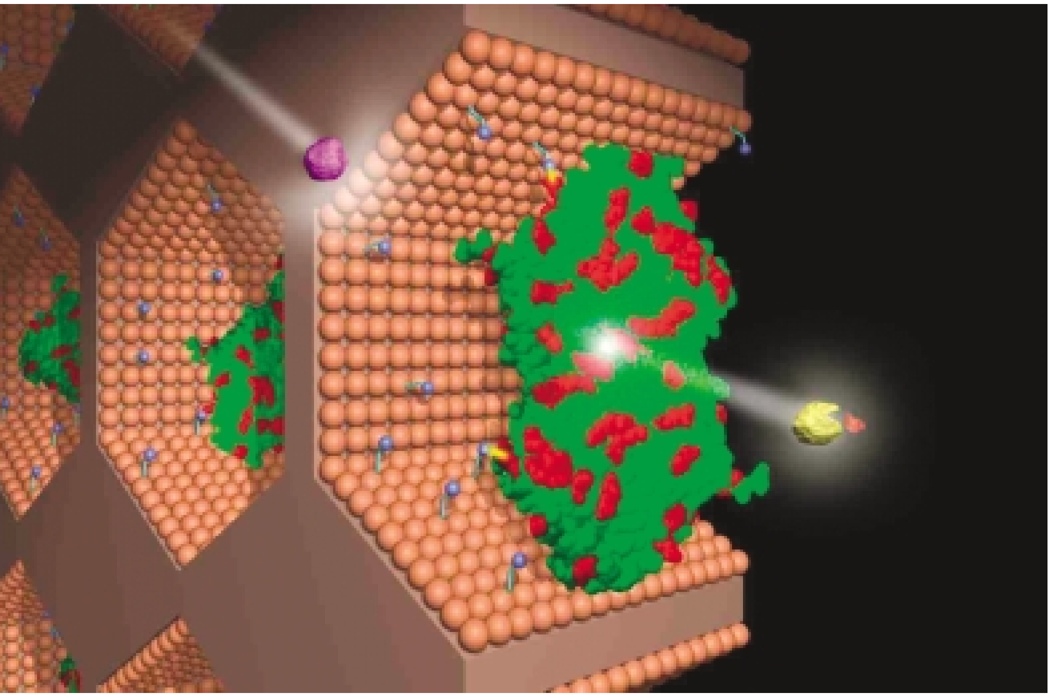
As a legacy of DOE's nuclear security mission over the last half-century and extending through the Cold War, large tracts of land surrounding DOE weapons production and other sites became contaminated. The magnitude of some of these problems is enormous, and many cannot be addressed using current technology. Despite progress on many fronts, efficient, effective, and affordable solutions to environmental contamination continue to elude us, whether the contaminants are radionuclides, toxic metals, or organic compounds. There is much we need to learn. How do contaminants interact with minerals, plant materials, and microbes in soils? How do they move to the groundwater or other locations where they can adversely affect human health?

PNNL

Microbes for environmental cleanup: Many of the aging waste tanks built on the Hanford Site in Richland, Washington, contain radioactive and chemical waste, a legacy from plutonium production. Some of the tanks are leaking into the soil and groundwater around the sites. Research to remediate these waste sites requires a clear understanding of both the environment and the contaminants. Microbes are being studied for their natural or engineered abilities to assist in environmental cleanup. Individual microbes and communities of microbes have already "found" solutions for many of our current challenges in environmental cleanup and energy production. *Shewanella oneidensis* (offset left) can convert soluble metals into insoluble forms, which could keep some contaminants from migrating into groundwater. Other microbes use toxic or radioactive substances as energy sources, rendering them into harmless byproducts.

This poor understanding of how contaminants behave in Nature restricts the development of cost-effective cleanup strategies and, in some cases, our ability even to recognize problems. Our challenge is to understand natural cleanup methods, put them to work, and improve cleanup decisions in the future. Our strategy includes the following emphases:

- Predict the fate and transport of contaminants with improved tools and understanding of interdependent biological, chemical, and physical processes.
- Take laboratory experiments and theory to the field, testing our theoretical predictions and models of the complex natural environment over considerable distances and time scales.
- Provide the next generation of computational and experimental capabilities for detailed understanding of contaminant behavior, including synchrotron light sources and the William R. Wiley Environmental Molecular Sciences Laboratory at the Pacific Northwest National Laboratory.
- Use Nature's own tool kit and rely on new understanding of the biology of microbes and microbial communities, geochemistry, plants and ecosystems, biomimetic agents, and nanomachines to explore innovative options for cleaning up the environment.
- Develop a basic understanding of complex chemical behavior of stored radioactive wastes to enable the discovery of novel separations and other treatment methods that can dramatically reduce the costs and risks of radioactive waste treatment and disposal.


PNNL

Biotechnology teams with nanotechnology for deactivation of toxic substances: Specially developed enzymes (green) embedded in a synthetic material, which was created to immobilize the enzymes and enhance their activity and stability, can transform toxic substances (purple molecule at left) to harmless byproducts (yellow and red molecules at right). Such nanostructures could eventually be used for a broad range of enzyme-based methods to produce energy, remove or deactivate contaminants, and store carbon to mitigate global climate change.

2.4 Master the convergence of the physical and the life sciences to deliver revolutionary technologies for health and medical applications.

The Office of Science has been at the center of medical technology innovations, with a focus on energy's impact on human health and the powerful imaging and radioisotope tools that have been the foundation of nuclear medicine. The future of technology development appears even brighter with the availability of micro- and nano-structured materials and the emerging capability to actually "see" genes and networks of genes in action in living tissues. This makes possible the ability to track the progression of disease as it unfolds at the genetic level. Also, new radiotracers and imaging concepts will explore both normal and abnormal health, from the development of cancer to brain function. On a larger physical scale, medical imaging may be possible for patients in motion, such as infants. Our strategy includes the following emphases:

- Restore sight to the blind using the microelectronics, material science technologies, and specialized expertise of the national laboratories to design and fabricate an implantable artificial retina.
- Enable medical imaging of moving patients with modified PET and MRI technology, capitalizing on advances in mathematics, computation, and detectors from high-energy physics to compensate for motion.
- Develop highly selective, ultra-sensitive biosensors based on the national laboratories' expertise in miniaturized optical systems and single-molecule detection, for medical, environmental, and national security applications.

SNL

Artificial retina: This project, funded by a $9 million, three-year grant from the Office of Science, will build a prototype that creates 1000 points of light through 1000 tiny microelectromechanical systems (MEMS) electrodes. The tiny electrodes may eventually be positioned on the retinas of those blinded by diseases such as age-related macular degeneration and retinitis pigmentosa to help them see again.

- Image genes as they are turned on and off in any organ of the body by forming fluorescent or radioisotopic images, giving us new capabilities for the diagnosis of disease.
- Develop new radiotracers and molecular tags to image the chemistry of life and disease, built around our capabilities in structural genomics, proteomics, radiochemistry, and more generally, the physical sciences.
- Determine the health risks of exposure to low doses of ionizing radiation to adequately and appropriately protect DOE nuclear workers and the general public while making effective use of our national resources.

> *"Medical advances may seem like wizardry. But pull back the curtain, and sitting at the lever is a high-energy physicist, a combinatorial chemist, or an engineer."*
>
> —Harold Varmus, president of Memorial Sloan-Kettering Cancer Center, former Director of the National Institutes of Health, and 1989 Nobel laureate, in an October 2000 *Washington Post* article where he noted that the physical sciences sponsored by the Office of Science are of critical value to the Nation.

Our Timeline and Indicators of Success

Our commitment to the future, and to the realization of **Goal 2: Harness the Power of Our Living World,** is not only reflected in our strategies, but also in our Key Indicators of Success, below, and our Strategic Timeline for Biological and Environmental Research (BER), at the end of this chapter.

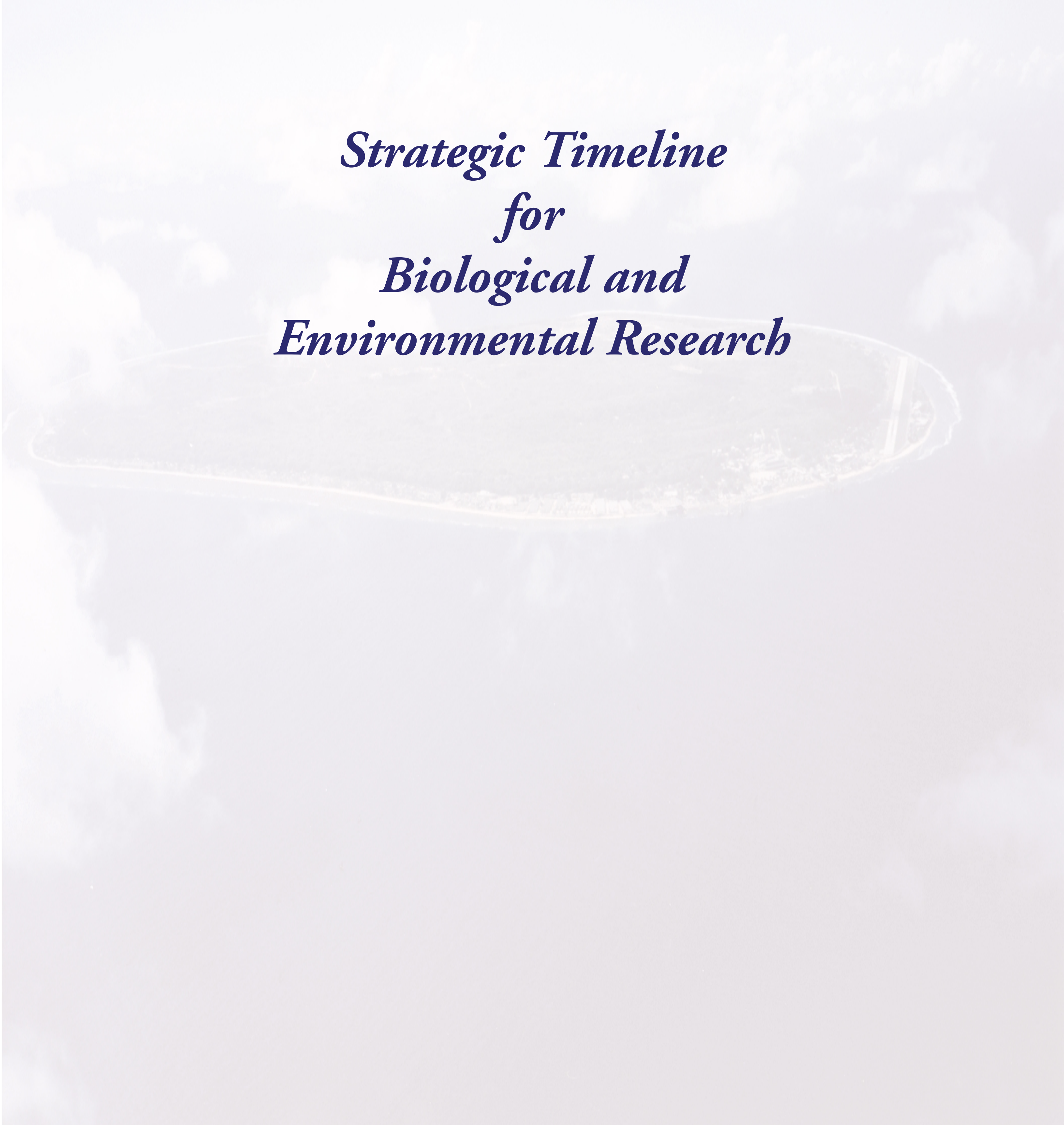
Our BER Strategic Timeline charts a collection of important, illustrative milestones, representing planned progress within each strategy. These milestones, while subject to the rapid pace of change and uncertainties that belie all science programs, reflect our latest perspectives on the future—what we hope to accomplish and when we hope to accomplish it—over the next 20 years and beyond. Following the science milestones, toward the bottom of the timeline, we have identified the required major new facilities. These facilities, described in greater detail in the DOE Office of Science companion report, *Facilities for the Future of Science: A Twenty-Year Outlook,* reflect time-sequencing that is based on the general priority of the facility, as well as critical-path relationships to research and corresponding science milestones.

Additionally, the Office of Science has identified Key Indicators of Success, designed to gauge our overall progress toward achieving Goal 2. These select indicators, identified below, are representative long-term measures against which progress can be evaluated over time. The specific features and parameters of these indicators, as well as definitions of success, can be found on the web at **www.science.doe.gov/measures**.

Key Indicators of Success:

- Progress in characterizing the multi-protein complexes (or the lack thereof) that involve a scientifically significant fraction of a microbe's proteins. Develop computational models to direct the use and design of microbial communities to clean up waste, sequester carbon, or produce hydrogen.
- Progress in delivering improved climate data and models for policymakers to determine safe levels of greenhouse gases. By 2013, reduce differences between observed temperature and model simulations at subcontinental scales using several decades of recent data.
- Progress in developing science-based solutions for cleanup and long-term monitoring of DOE contaminated sites. By 2013, a significant fraction of DOE's long-term stewardship sites will employ advanced biology-based cleanup solutions and science-based monitors.

Strategic Timeline for Biological and Environmental Research



Strategic Timeline—Biological

2003 2005 2007 2009 2011 2013

The Science

Life Sciences

- Initiate Genomics: GTL research program (2003)
- Develop artificial chromosome (2006)
- Complete mathematical model for microbial community that detoxifies uranium (2007)
- Complete photosynthetic microbe able to continuously make hydrogen (2008)
- Develop new knowledge base for cost-effective cleanup of environmental contamination (2012)
- Design new strategies for enhanced capture of atmospheric carbon dioxide (2012)
- Increase biobased sources of fuel and electricity (2012)

Climate Change Research

- New measurements of clouds where observations are missing (2006)
- Include realistic clouds in a climate model (2007)
- Measure ecosystem responses to climate change, measurements never made before (2008)
- Provide a climate model that links the Earth's climate system with the Earth's biological systems (2010)

Environmental Remediation

- Create Environmental Remediation Sciences Division (2003)
- Develop alternative cesium separations process for HLW to be deployed at SRS, ensuring vitrification will remain on schedule (2006)
- Complete work on the technical basis for leaving in place cesium, technetium, uranium, strontium, or other radionuclides from soils beneath tank farm at the Hanford Site (2007)
- Provide new technologies for in situ characterization of contaminants that cannot be identified today (2008)
- Validate bioremediation of metals and rads in the field (2008)
- Provide a suite of field characterization techniques for long-term monitoring of closed sites (2012)

Medical Sciences

- Test new biocompatible materials for chip, electrodes, and hermetic seal for the artificial retina (2002)
- Design and microfabricate 60-electrode artificial retina device (2003)
- Radiotracer chemistry/probes to detect defective gene expression (2003)
- Complete in vitro testing of 60-electrode artificial retina device and implant prototype into dogs (2004)
- Implant and test 60-electrode devices in humans (2005)
- Begin design and fabrication of 1000-electrode artificial retina device (2005)
- Complete microfabrication of 1000-electrode prototype artificial retina (2006)
- Preclinical testing of radiolabeled probes for imaging defective genes (2006)
- Complete in vitro testing and implant 1000-electrode artificial retina devices into dogs (2007)
- Complete in vitro testing and implant 1000-electrode artificial retina devices into dogs (2009)

Future Facilities**

Protein Production and Tags: This facility will use highly automated processes to mass-produce and characterize tens of thousands of proteins per year, create "tags" to identify these proteins, and make these products available to researchers nationwide.

Characterization and Imaging of Molecular Machines: This facility will build on capabilities provided by the Protein Production and Tags facility to provide researchers with the ability to isolate, characterize, and create images of the thousands of molecular machines that perform the essential functions inside a cell.

***These strategic milestones are illustrative and depend on funds made available through the Federal budget process.**

****For more detail on these facilities and the overall prioritization process, see the companion document, *Facilities for the Future of Science: A Twenty-Year Outlook.***

and Environmental Research*

2015 2017 2019 2021 2023 2052

- Save billions of dollars in toxic waste cleanup (2032)
- Stabilize atmospheric carbon dioxide to counter global warming (2042)
- Mature bioenergy industry established (2052)

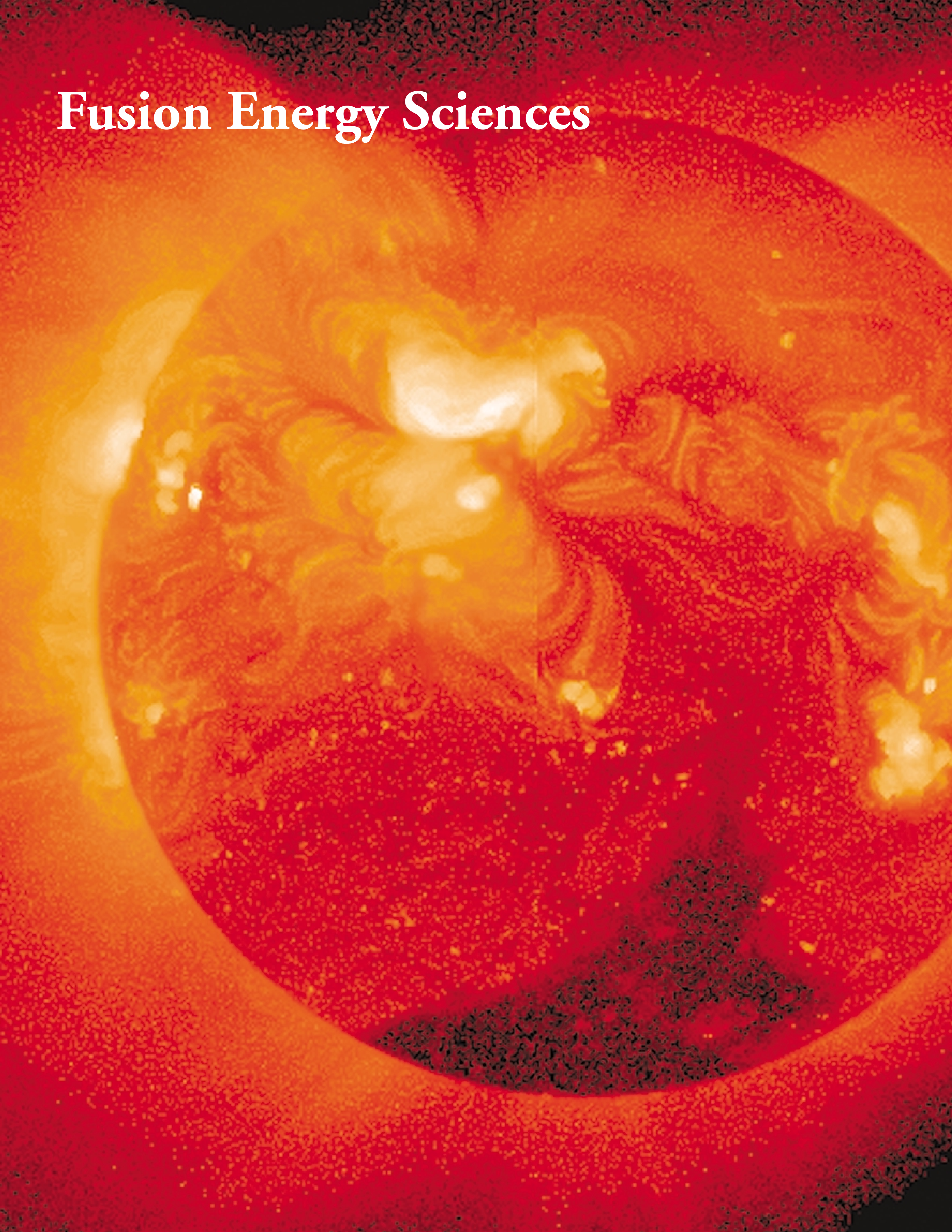
- Unambiguous detection of human-induced climate change (2015)
- Deliver an Earth system model capable of robustly predicting natural and human-induced climate change and its environmental consequences (2020)
- Enable determination of a safe level of greenhouse gases in the atmosphere (2030)

- Deliver accurate predictive models that eliminate unneeded remediation strategies (2018)
- Use genomic and nanoscience capabilities to develop remediation strategies for individual waste sites (2027)
- Completion of high-level waste treatment, saving tens of billions in cost (2029)

Analysis and Modeling of Cellular Systems: This facility will combine advanced computational, analytical, and experimental capabilities to study how multi-cellular systems, including microbial communities, function at the molecular level.

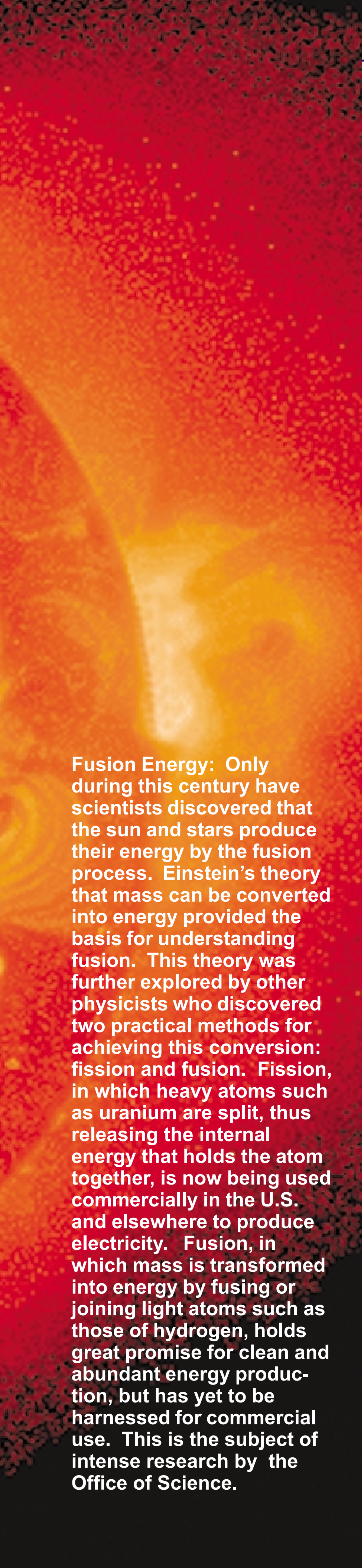
Whole Proteome Analysis: This facility will provide researchers with the ability to investigate how microbes adapt to changes in their environment by turning certain portions of their genome “on” and “off.”

Fusion Energy Sciences



3

Bring the Power of the Stars to Earth



Fusion Energy: Only during this century have scientists discovered that the sun and stars produce their energy by the fusion process. Einstein's theory that mass can be converted into energy provided the basis for understanding fusion. This theory was further explored by other physicists who discovered two practical methods for achieving this conversion: fission and fusion. Fission, in which heavy atoms such as uranium are split, thus releasing the internal energy that holds the atom together, is now being used commercially in the U.S. and elsewhere to produce electricity. Fusion, in which mass is transformed into energy by fusing or joining light atoms such as those of hydrogen, holds great promise for clean and abundant energy production, but has yet to be harnessed for commercial use. This is the subject of intense research by the Office of Science.

PPPL

Answer the key scientific questions and overcome enormous technical challenges to harness the power that fuels a star, realizing by the middle of this century a landmark scientific achievement by bringing fusion power to the U.S. electric grid.

When fusion power becomes a commercial reality, current national concerns over imported oil, rising gasoline prices, smokestack pollution, and other problems associated with our dependence on oil and other fossil fuels will largely disappear. We will have achieved energy independence. Fusion power plants will provide economical and abundant energy without greenhouse gas emissions, while creating manageable waste and little risk to public safety and health.

Making fusion energy a part of our national energy solution is among the most ambitious scientific and engineering challenges of our era. The following are some of the major scientific questions we will answer:

- Can we successfully control a burning plasma that shares the characteristic intensity and power of the sun?
- How can we use nanoscale science to construct radically new materials that will withstand the temperatures and forces needed for commercial fusion power?
- To what extent can we use scientific simulation to model the behavior of the fusion fuel that is found at the center of the sun—or in the confines of a functioning commercial prototype?

Our ultimate success in answering these questions requires that we understand and control remarkably complex and dynamic phenomena occurring across a broad range of temporal and spatial scales. We must also develop materials, components, and systems that can withstand temperatures exceeding those that are typical of a star. The experiments required for a commercially viable fusion power technology constitute a complex scientific and engineering enterprise that must be sustained over several decades. We can

"Everytime you look up at the sky, every one of those points of light is a reminder that fusion power is extractable from hydrogen and other light elements, and it is an everyday reality throughout the Milky Way Galaxy."

—Carl Sagan, Spitzer Lecture,
October 1991

now define the specific challenges that must be overcome, see promising approaches to addressing those challenges, and confidently anticipate the availability of even more powerful computational and experimental measurement capabilities.

As an integral part of this Strategic Plan, and in *Facilities for the Future of Science: A Twenty-Year Outlook*, we have identified the need for four future facilities to realize our Fusion Energy Sciences vision and to meet the science challenges described in the following pages. One of the facilities, **ITER**, is a near-term priority. ITER is an international collaboration to build the first fusion science experiment capable of producing a self-sustaining fusion reaction, called a "burning plasma." It is the next essential and critical step on the path toward demonstrating the scientific and technological feasibility of fusion energy. All four facilities are included in our Fusion Energy Sciences Strategic Timeline at the end of this chapter and in the facilities chart in Chapter 7 (page 93), and they are discussed in detail in the *Twenty-Year Outlook*.

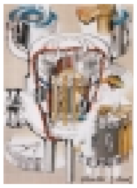
Our Strategies

Given the substantial scientific and technological uncertainties that we know exist, we will employ a portfolio strategy that explores a variety of magnetic and inertial confinement approaches and leads to the most promising commercial fusion concept. Advanced computational modeling will be central to guiding and designing experiments that cannot be readily investigated in the laboratory, such as testing the agreement between theory and experiment and exploring innovative designs for fusion plants.

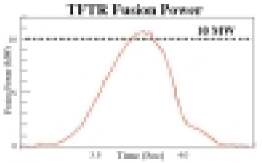
To ensure the highest possible scientific return on limited resources, we will extensively engage with and leverage other DOE programs and the investments of other agencies in such areas as materials science, ion beam physics, and laser physics. Large-scale experimental facilities will be necessary to test approaches for self-heated (burning) fusion plasmas, for inertial fusion experiments, and for testing materials and components under extreme conditions. Where appropriate, the

Our History of Discovery…Select Examples

1978
Achieved ion temperatures in excess of 58,000,000°C—the minimum required for a self-sustaining fusion reaction.



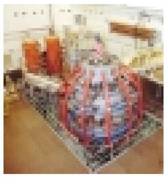
1983
Exceeded the Lawson criterion—the product of the plasma density and energy confinement time required for fusion energy breakeven—on MIT's Alcator-C device.



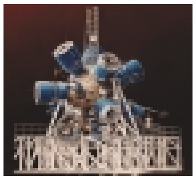
1994
TFTR achieves 10.7 million watts of power.

1970 1980

1982
Started the Tokamak Fusion Test Reactor (TFTR).



1985
Conceived the Spherical Torus—a plasma confinement device that can confine a higher plasma pressure for a given magnetic field strength.



1987
Achieved 100x compression on Nova laser-fusion facility.

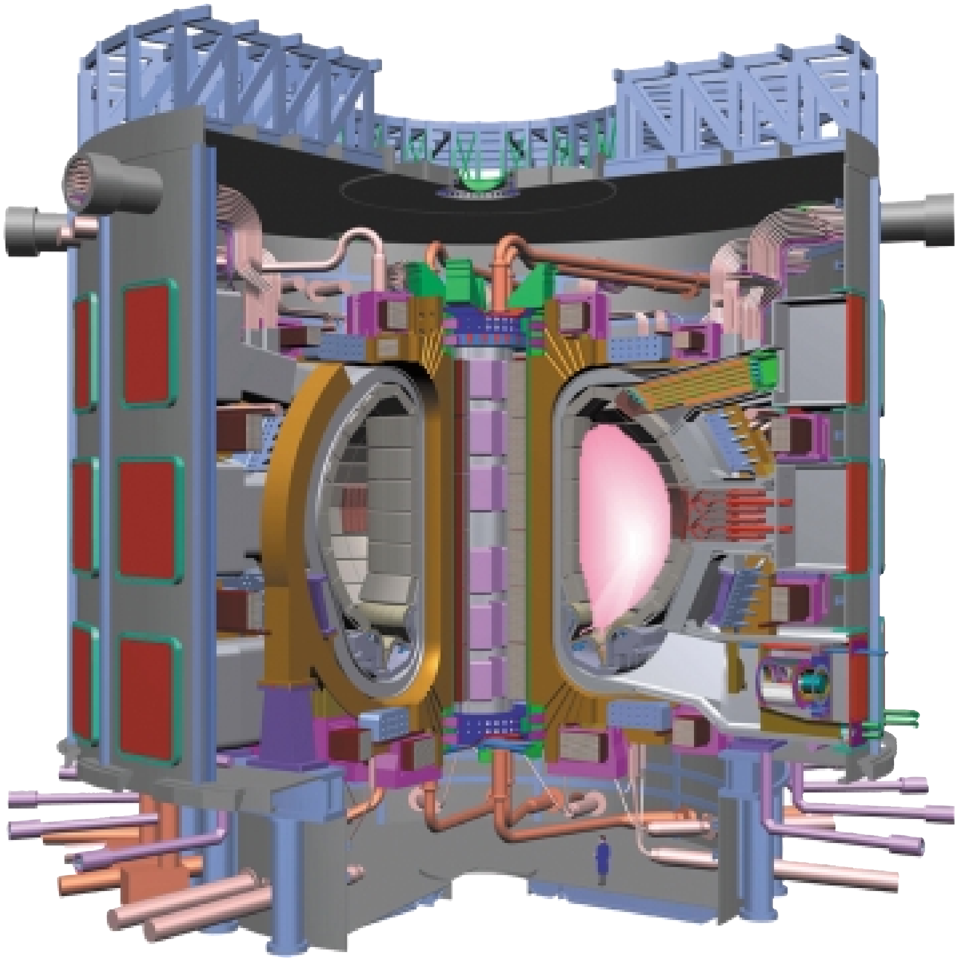
rewards, risks, and costs of major facilities will be shared through international collaborations.

The overall Fusion Energy Sciences effort will be organized around a set of four broad goals.

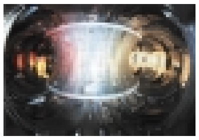
3.1 Demonstrate with burning plasmas the scientific and technological feasibility of fusion energy.

Our goal is to demonstrate a sustained, self-heated fusion plasma, in which the plasma is maintained at fusion temperatures by the heat generated by the fusion reaction itself, a critical step to practical fusion power. Our strategy includes the following emphases:

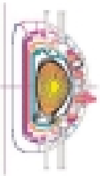
- As decided by the President, we will participate in negotiations that could lead to participation in the international magnetic fusion experiment, ITER project, with the European Union, Japan, Russia, China, South Korea, and perhaps others, as partners.
- For inertial fusion, we depend on DOE's National Nuclear Safety Administration's (NNSA's)



ITER: The U.S. is engaging in negotiations with international partners aimed at constructing the world's first sustained burning plasma experiment, capable of producing 500 million watts of fusion power for periods of five minutes or more. The Office of Science will be a primary participant in the ITER experiment.



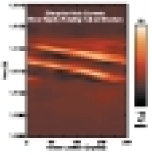
1995
TFTR sets the record for highest temperature achieved in a laboratory plasma, more than thirty times hotter than the center of the sun.



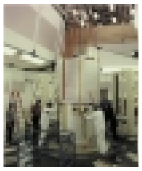
2001
Theory and experiment on DIII-D show that through plasma rotation and active control of plasma stability using specialized coils you can increase the plasma pressure limit above conventional limits.

1990

2000



1995
Measurements of disruption halo currents in Alcator C-Mod tokamak determine their predictive scalings, asymmetric structure, and toroidal rotation, information necessary for establishing engineering loads.



2000
Successfully completed testing of the world's largest pulsed superconducting magnet—Central Solenoid Model Coil—which is the prototype for the solenoid coil to be used in ITER.

2002
The Madison Symmetric Torus at U.Wisconsin reduced magnetic fluctuations in the plasma resulting in a 10-fold improvement in energy confinement.

National Ignition Facility, which is expected to achieve its full energy within five years, demonstrate target ignition in about a decade, and, combined with other experiments, lead to a future inertial fusion Engineering Test Facility.

> *"The results of ITER will produce clean, safe, renewable, and commercially available fusion energy by the middle of this century."*
>
> —President George W. Bush,
> January 2003

3.2 Develop a fundamental understanding of plasma behavior sufficient to provide a reliable predictive capability for fusion energy systems.

Basic research is required in turbulence and transport, nonlinear behavior and overall stability of confined plasmas, interactions of waves and particles in plasmas, the physics occurring at the wall-plasma interface, and the physics of intense ion beam plasmas. Our strategy includes the following emphases:

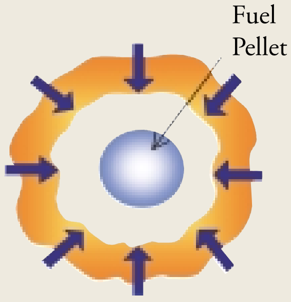
- Conduct basic research through individual-investigator and research-team experimental, computational, and theoretical investigations.
- Launch a major effort to advance state-of-the-art computational modeling and simulation of plasma behavior in partnership with the Office of Science's Advanced Scientific Computing Research program.
- Support basic plasma science, partly with the National Science Foundation, connecting both experiments and theory with related disciplines such as astrophysics.

3.3 Determine the most promising approaches and configurations to confining hot plasmas for practical fusion energy systems.

Both magnetic and inertial confinement approaches to fusion have potential for practical fusion-energy-producing systems. Within each of these two broad approaches, there are many possible configurations and designs for practical fusion systems, almost certainly including some yet to be conceived. Our strategy includes the following emphases:

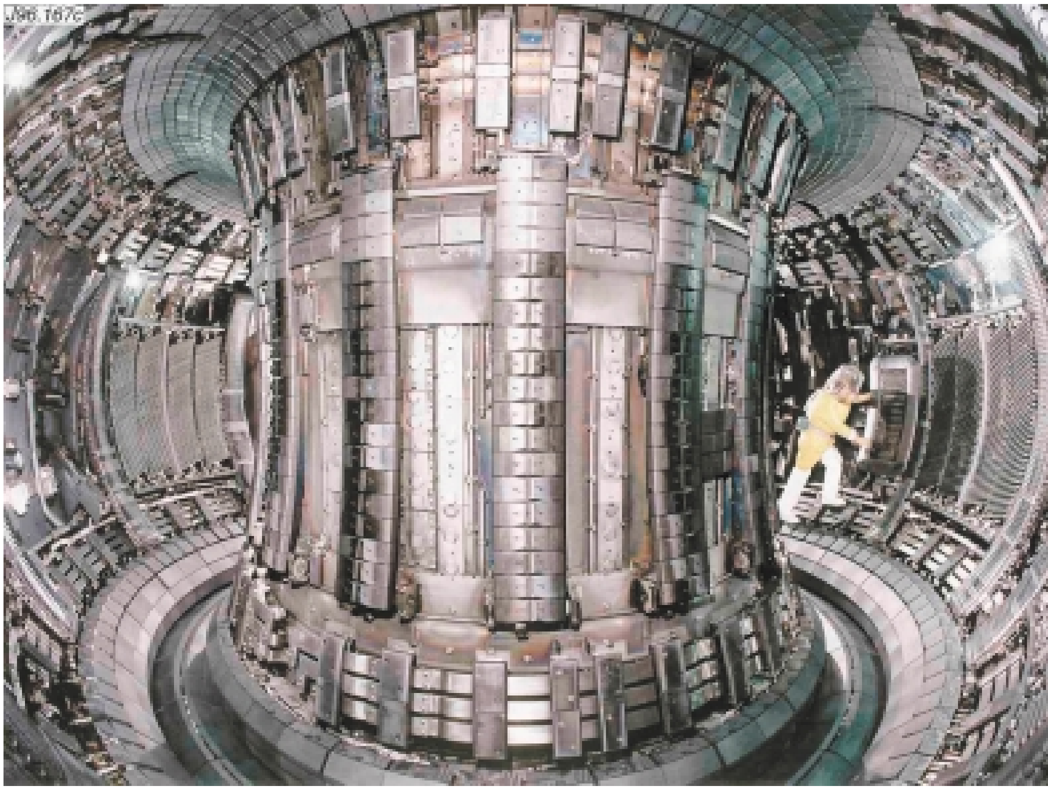
Magnetic and Inertial Confinement: The two principal approaches for confining fusion fuel on Earth are magnetic and inertial. Magnetic fusion relies on magnetic forces to confine the charged particles of the hot plasma fuel for sustained periods of fusion energy production. Inertial fusion relies on intense lasers or particle beams to rapidly compress a pellet of fuel to the point where fusion occurs, yielding a burst of energy that would be repeated to produce sustained energy production.

Magnetic



Inertial

- In line with the recommendations of the Fusion Energy Sciences Advisory Council, we will continue vigorous investigation of both magnetic and inertial confinement approaches.
- Innovative magnetic confinement configurations will be explored through experiments, such as the National Spherical Torus Experiment at Princeton Plasma Physics Laboratory and a planned compact stellarator experiment, as well as smaller experiments at multiple sites, and through advanced simulation and modeling.
- Heavy ion beams, dense plasma beams, lasers, or other innovative approaches (e.g., fast ignition) to produce high-energy density plasmas will be explored for potential applications to inertial fusion energy.
- Research in high-energy density physics will be supported in coordination with other Federal agencies.
- The NNSA's National Ignition Facility, along with other experiments and simulations in the U.S., will provide definitive data on inertial fusion target physics.



EFDA-JET

Joint European Torus (JET): Predecessor to ITER, the JET Joint Undertaking was established in June 1978 to construct and operate the largest (of its time) single project within the European nuclear fusion program. JET began operating in 1983 and was the first fusion facility in the world to achieve a significant production of controlled fusion power (nearly 2 MW) with a deuterium-tritium experiment in 1991. After 1991, JET was enhanced by the installation of a divertor to handle higher levels of exhaust power. Deuterium experiments in the ITER geometry have made essential contributions to the ITER divertor design, and to the definition of the size, heating requirements, and operating conditions of ITER. The Office of Science continues to collaborate in JET research to help build diagnostics, participate in experiments, and conduct joint research.

3.4 Develop the new materials, components, and technologies necessary to make fusion energy a reality.

The environment created in a fusion reactor poses great challenges to materials and components. Materials must be able to withstand high fluxes of hot neutrons and endure high temperatures and high thermal gradients, with minimal degradation. Our strategy includes the following emphases:

- Design materials at the molecular scale to create novel materials that posses the necessary high-performance properties, leveraging investments through our Fusion Energy Sciences program with the materials research of our Basic Energy Sciences program.
- Create additional facilities, as may be needed, as a follow-on to the ITER project, for testing materials and components for high duty-factor operation in a fusion power plant environment.
- Explore "liquid first-wall" materials to ameliorate first-wall requirements for both inertial fusion energy (IFE) and advanced magnetic fusion energy (MFE) concepts.

Our Timeline and Indicators of Success

Our commitment to the future, and to the realization of **Goal 3: Bring the Power of the Stars to Earth,** is not only reflected in our strategies, but also in our Key Indicators of Success, below, and our Strategic Timeline for Fusion Energy Sciences (FES) at the end of this chapter.

Our FES Strategic Timeline charts a collection of important, illustrative milestones, representing planned progress within each strategy. These milestones, while subject to the rapid pace of change and uncertainties that belie all science programs, reflect our latest perspectives on the future—what we hope to accomplish and when we hope to accomplish it—over the next 20 years and beyond. Following the science milestones, toward the bottom of the timeline, we have identified the required major new facilities. These facilities, described in greater detail in the DOE Office of Science companion report, *Facilities for the Future of Science: A Twenty-Year Outlook*, reflect time-sequencing that is based on the general priority of the facility, as well as critical-path relationships to research and corresponding science milestones.

Additionally, the Office of Science has identified Key Indicators of Success, designed to gauge our overall progress toward achieving Goal 3. These select indicators, identified below, are representative long-term measures against which progress can be evaluated over time. The specific features and parameters of these indicators, as well as definitions of success, can be found on the web at **www.science.doe.gov/measures**.

Key Indicators of Success:

- Progress in developing a predictive capability for key aspects of burning plasmas, using advances in theory and simulation benchmarked against a comprehensive experimental database of stability, transport, wave-particle interaction, and edge effects.
- Progress in demonstrating enhanced fundamental understanding of magnetic confinement and in improving the basis for future burning plasma experiments through research on magnetic confinement configuration optimization.
- Progress in developing the fundamental understanding and predictability of high-energy density plasma physics, including potential energy-producing applications.

Strategic Timeline
for
Fusion Energy Sciences

Strategic Timeline—F

2003 2005 2007 2009 2011 2013

The Science

Burning Plasma Demonstration

- Initiate experiments on the National Ignition Facility (NIF) to study ignition and burn propagation in IFE-relevant fuel pellets (2012)

Fundamentals of Plasma Behavior

- Achieve a fundamental understanding of tokamak transport and stability in pre-ITER plasma experiments (2009)

Plasma Confinement

- Evaluate the ability of the compact stellarator configuration to confine a high-temperature plasma (2012)

- Achieve long-duration, high-pressure, well-confined plasmas in a spherical torus sufficient to design and build fusion-power-producing Next-Step Spherical Torus (2008)
- Demonstrate use of active plasma controls and self-generated plasma current to achieve high-pressure/well-confined steady-state operation for ITER (2008)

- Evaluate the feasibility/attractiveness of potential drivers, including heavy ion beams, dense plasma beams, and lasers for fusion approaches involving high-energy density (2009)

Materials, Components, and Technologies

- Start production of superconducting wire needed for ITER magnets (2006)

- Deliver to ITER for testing the blanket test modules needed to demonstrate the feasibility of extracting high-temperature heat from burning plasmas and for a self-sufficient fuel cycle (2013)

Future Facilities**

ITER: ITER is an international collaboration to build the first fusion science experiment capable of producing a self-sustaining fusion reaction, called a "burning plasma."

Next-Step Spherical Torus (NSST) Experiment: The NSST will be designed to test the spherical torus, an innovative concept for magnetically confining a fusion reaction.

***These strategic milestones are illustrative and depend on funds made available through the Federal budget process.**

****For more detail on these facilities and the overall prioritization process, see the companion document, *Facilities for the Future of Science: A Twenty-Year Outlook.***

usion Energy Sciences*

2015 2017 2019 2021 2023 2025

- Complete ITER experiments to determine plasma confinement in parameter range required for an energy-producing plasma (2017)
- Complete experiments on NIF to advance the science of ignition and burn propagation needed to design optimized fuel pellets for an Inertial Fusion Energy plant (2020)
- Complete experiments on ITER to determine the impact of the fusion process on the stability of energy-producing plasmas (2020)
- Achieve high fusion power for long durations on ITER to define engineering requirements for fusion power plants (2025)

- Major aspects relevant to burning plasma behavior observed in experiments prior to full operation of ITER are predicted with high accuracy and are understood (2015)
- Determine the physics limits that constrain the use of inertial fusion energy drivers in future key integrated experiments needed to resolve the scientific issues for inertial fusion energy and high-energy density physics (2015)
- Deliver a complete integrated simulation of a power-producing plasma, validated with ITER results, that enables the design of fusion power plants (2020)

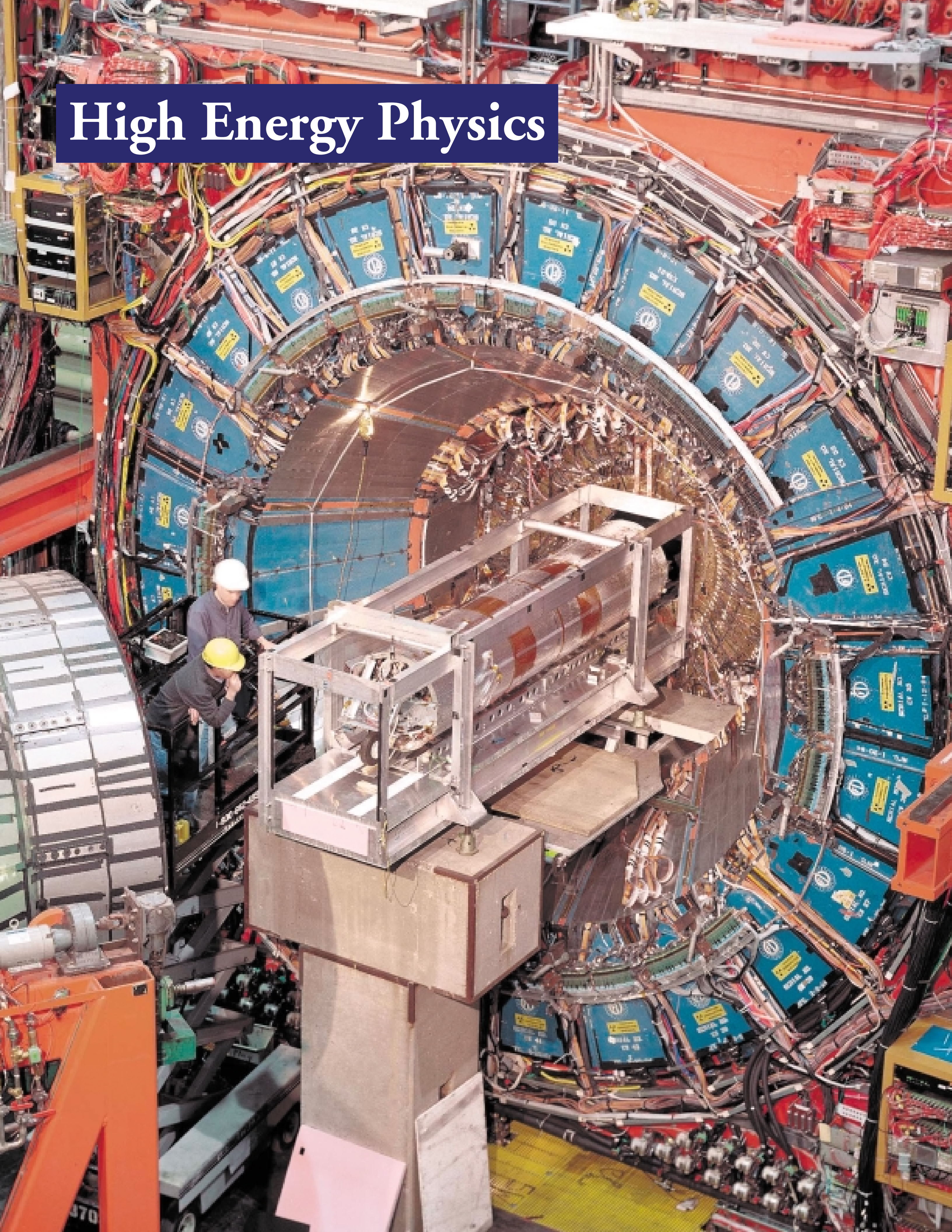
- Determine the potential of one or more of the promising plasma configurations (for example a spherical torus) for use as a component test facility or a fusion power source (2020)
- Resolve key scientific issues and determine the confinement characteristics of a range of attractive confinement configurations (2015)

- Complete first phase of testing in ITER of blanket technologies needed in power-producing fusion plants capable of extracting high-temperature heat from burning plasmas and having a self-sufficient fuel cycle (2024)
- Complete first round of testing in a component test facility to validate the performance of chamber technologies needed for a power-producing fusion plant (2025)

Fusion Energy Contingency: If ITER construction and operation goes forward as planned, additional facilities to develop and test power plant components and materials will be needed to complete the process of making fusion energy a viable commercial energy resource by mid-century.

Integrated Beam Experiment (IBX): The IBX will be an intermediate-scale experiment to understand how to generate and transmit the focused, high-energy ion beam needed to power an IFE reaction.

High Energy Physics



4

Explore the Fundamental Interactions of Energy, Matter, Time, and Space

Understand the unification of fundamental particles and forces and the mysterious forms of unseen energy and matter that dominate the universe, search for possible new dimensions of space, and investigate the nature of time itself.

Led by great physicists like Galileo, Einstein, and Heisenberg, we have learned much about the universe. In the early 20th Century, we learned that it is expanding and that space-time is curved. We discovered the quantum nature of matter, a profound advance with many practical benefits. We learned that all matter is built of just 12 types of particles interacting by four basic forces.

Nevertheless, we are continually humbled by what we do not understand. For example, we learned recently that the expansion of the universe is accelerating, not slowing down as we had thought. This astonishing fact is attributed to “dark energy” that accounts for nearly three-quarters of the energy of the universe.

Nearly a quarter of the energy is made up of another mysterious substance dubbed “dark matter.” Only around 4% is ordinary matter.

These are a few of the basic questions yet to be answered:

- How were the patterns of particles and forces we see today unified in the early universe?
- What is the nature of dark energy? Of dark matter? Why do they make up most of the universe?
- Are there more than four dimensions of space-time? If so, how can we detect them?

Answering these questions will reveal much about the creation and fate of our universe. Computing resources that dwarf current capabilities will be unleashed on challenging calculations of subatomic structure, while new accelerators will be needed to investigate unification at high energies. Understanding unification and the cosmos is a challenge, but one that is well

The Collider Detector at Fermilab (CDF): This experimental collaboration is committed to studying high-energy particle collisions at the world's highest-energy particle accelerator. The goal is to discover the identity and properties of the particles that make up the universe and to understand the forces and interactions between those particles.

SLAC

suited to the large-scale research teams and international partnerships that we bring together.

As an integral part of this Strategic Plan, and in *Facilities for the Future of Science: A Twenty-Year Outlook*, we have identified the need for four future facilities to realize our High Energy Physics vision and to meet the science challenges described in the following pages. Two of the facilities are near-term priorities: the **Joint Dark Energy Mission (JDEM)** and the **BTeV**. JDEM is a space-based probe, developed in partnership with NASA, designed to help understand the recently discovered mysterious "dark energy," which makes up nearly three quarters of the universe and evidently causes its accelerating expansion. BTeV ("B-particle physics at the TeVatron") is an experiment designed to use the Tevatron proton-antiproton collider at the Fermi National Accelerator Laboratory (currently the world's most powerful accelerator) to make very precise measurements of several aspects of fundamental particle behavior that may help explain why so little antimatter exists in the universe. All four facilities are included in our High Energy Physics Strategic Timeline at the end of the chapter and in the facilities chart in Chapter 7 (page 93), and they are discussed in detail in the *Twenty-Year Outlook.*

Our Strategies

In developing strategies to pursue these exciting opportunities, the Office of Science has been guided by long-range planning reports: *The Way to Discovery* (2002), High Energy Physics Advisory Panel (HEPAP); and *Connecting Quarks with the Cosmos* (2003), National Research Council.

4.1 Explore unification phenomena.

Unification is simplicity at the heart of matter and energy. The complex patterns of particles and forces we see today emerged from a much more symmetric universe at the extremely high energies of its first moments. Indications of this simpler world must occur at energies just beyond the reach of current accelerators. A principal strategy is to find out how our complex patterns merge into a unified picture at higher energies.

The Standard Model of particles and forces asserts that all matter is made of elementary particles called fermions. These are of two types: quarks and leptons, each of which comes in six "flavors." Four fundamental interactions are known: strong, weak, electromagnetic, and gravitational, which vary substantially in strength and range. The first three interactions are carried by another class of particles called gauge bosons. No quantum theory of gravity has been established and gravity is not included in the Standard Model.

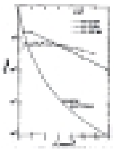
At energies above one trillion electron volts (1 TeV), the electromagnetic and weak interactions are unified into the electroweak interaction, and two of its bosons are massless. At about 1 TeV, this electroweak symmetry is broken and the bosons acquire mass. The Standard Model attributes this to a new field called the Higgs, but the Higgs boson has not yet been observed.

Three of the leptons are neutrinos, which feel only the weak interaction, were thought to be massless, and barely interact with matter. Recent

Our History of Discovery…Select Examples

1950s
Discovered strange particles, nuclear antimatter, and nuclear resonances.

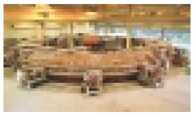
1962
Discovered the muon neutrino.
(1988 Nobel Prize)



1969
Found first direct evidence for quarks.
(1990 Nobel Prize)

1950 1960

1950s
Invented strong focusing, which led to higher energy accelerators (synchrotrons).



1956
Predicted parity violation in weak interaction.
(1957 Nobel Prize)

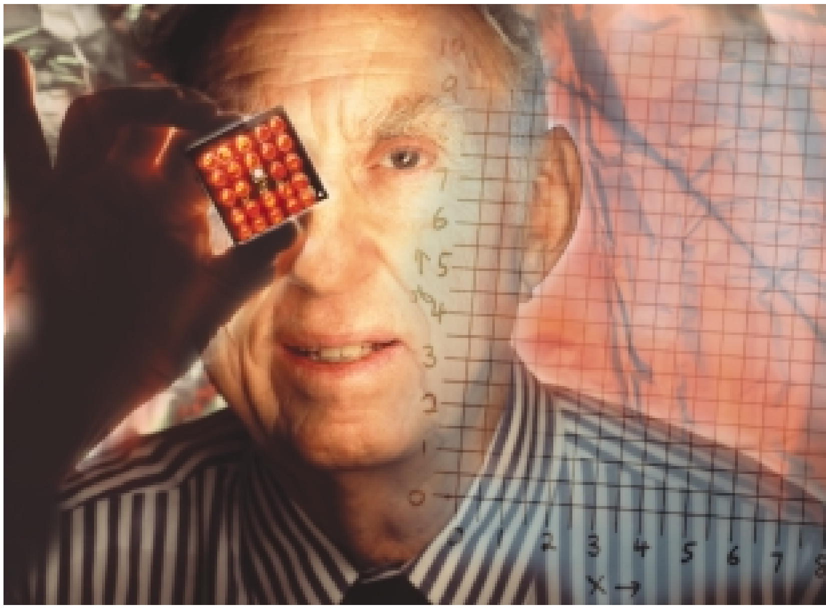
1964
Observed direct charge-parity violation, showing that matter and antimatter do not always behave symmetrically.
(1980 Nobel Prize)

experiments have shown that a neutrino produced in one flavor oscillates among all three flavors as it travels. This can only happen if neutrinos do have mass, which has important consequences for the Standard Model and for the universe.

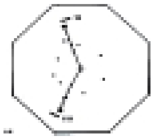
The Standard Model explains many observations at the energies our particle accelerators can reach today, but is known to have problems at higher energies. The theory requires 18 arbitrary and independent parameters whose values are unexplained. It is clear that the Standard Model must be substantially extended.

Physicists are striving to develop a quantum field theory for gravity, using "string theories," which explain particles as vibration modes of a tiny string-like bit of energy. String theories involve supersymmetry, a deep connection between fermions and bosons at high energies. Supersymmetry predicts that every known fermion has a boson partner and vice versa. Some of these partners must have masses low enough to be created at the TeV energy scale. Thus, our highest energy accelerators should be able to test supersymmetry by searching for the lightest supersymmetric particles.

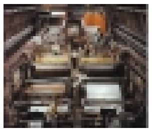
All string theories require several extra spatial dimensions beyond the three we now observe. These may be detected at accelerators by giving



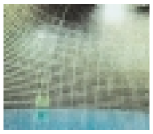
Constituents of matter: In the instant of collision, accelerated particles approaching the speed of light reveal their constituent parts. Martin Perl (above), at Stanford Linear Accelerator Center, discovered a new type of fundamental particle—the Tau lepton. This type of particle had not been observed prior to Perl's work and the discovery had crucial implications, providing new evidence of the third family of fundamental particles. His work inspired confidence in the Standard Model, the theory developed by physicists to explain matter and the forces of Nature, and for his efforts he was awarded the 1995 Nobel Prize in physics. Like many before him, and the many who will follow, his discoveries help shape our understanding about our physical universe, press the limits of theory and experimentation, and provide the intellectual content for a new generation of science education.



1977
Discovered the tau lepton.
(1995 Nobel Prize)



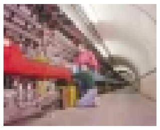
1977
Discovered the bottom quark.



1998
Discovered neutrino oscillations, with neutrinos produced in Earth's atmosphere.
(2002 Nobel Prize)

1970 *1980* *1990* *2000*

1974
Discovered the charm quark.
(1976 Nobel Prize)



1986
Began operating the Tevatron, first accelerator with superconducting magnets.

1995
Discovered the top quark.

2000
Discovered the tau neutrino.

FNAL

Colliders and the science of matter: The Tevatron, operated by Fermi National Accelerator Laboratory since 1986, is a proton-antiproton collider that currently offers the world's highest energy particle collisions. With the tau neutrino observation in 2000, Fermilab has discovered three of the four particles of the third generation of the Standard Model: the bottom quark, the top quark, and the tau neutrino. Fermilab physicists and collaborators will now zero in on the mass of the undiscovered Higgs boson, one of the last crucial components of the theoretical framework of particle physics.

"When we try to pick out anything by itself, we find it is tied to everything else in the universe."

—John Muir (1838-1914), U.S. naturalist and explorer

particles enough energy that they feel the effects of extra dimensions. A direct discovery of extra dimensions would be an epochal event.

Our strategy includes the following emphases:

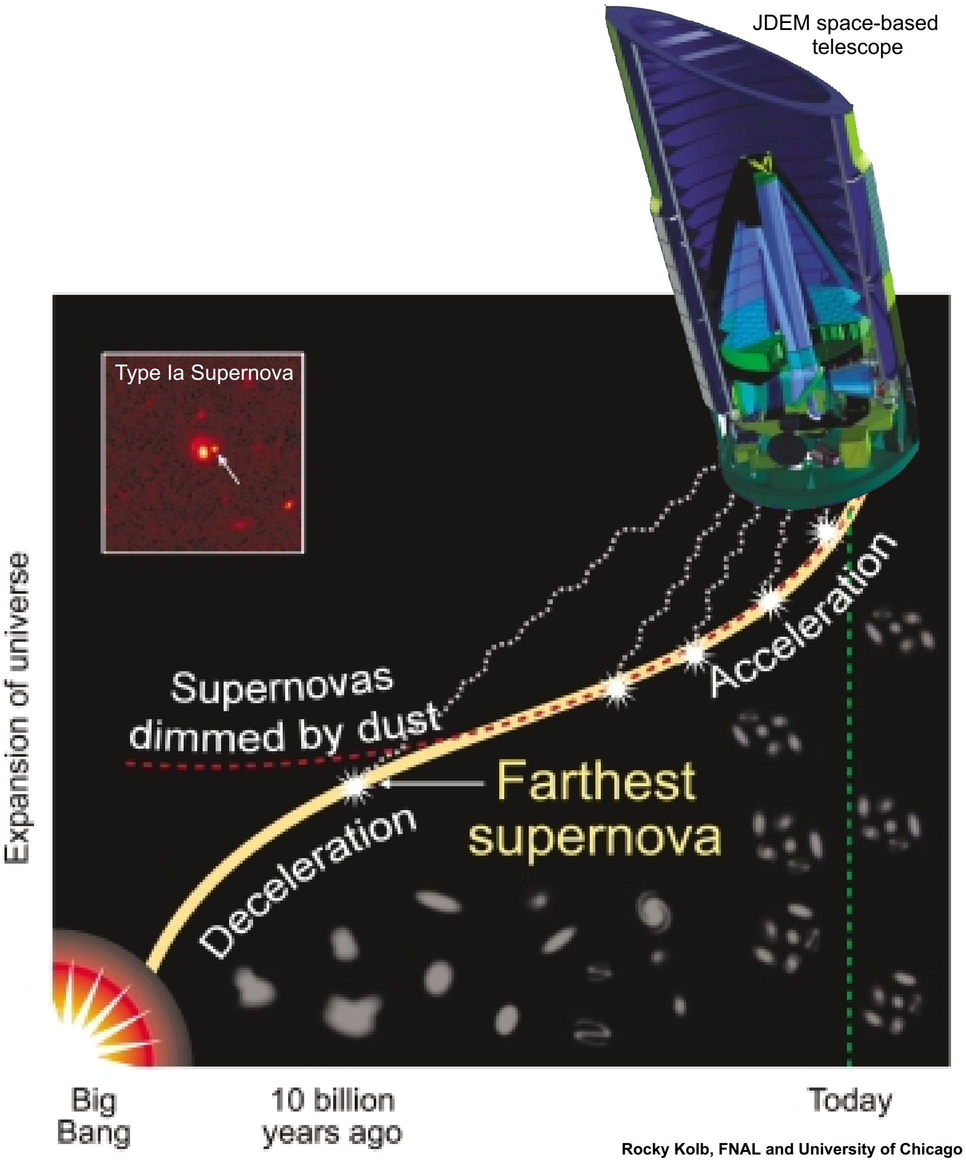
- Use the Tevatron proton-antiproton collider at the Fermi National Accelerator Laboratory to make detailed studies of the top quark discovered there in 1995.
- Search for evidence of unification at the Tevatron, such as the Higgs boson, supersymmetric particles, and extra dimensions.
- Use the B-Factory at the Stanford Linear Accelerator Center to improve our knowledge of the weak interactions of quarks.
- Study neutrino oscillation and double beta decay to learn more about lepton flavor mixing and neutrino masses.
- Develop a string theory that explains the observed particles and includes a quantum theory of gravity.
- Continue our collaboration with the CERN laboratory in Switzerland to complete construction of the Large Hadron Collider there and then use it to study unification. When it begins operations in 2007, this proton-proton collider will extend the energy frontier well beyond the reach of the Tevatron.
- Participate in the development of an international linear electron-positron collider for research at the TeV energy scale. Such a facility has been recommended by HEPAP and by expert panels in Asia and Europe as an essential tool for exploring unification.
- Pursue advanced accelerator development aimed at finding better ways to accelerate particles, with the promise of increasing their energies beyond one TeV.

4.2 Understand the cosmos.

The universe began in an extremely hot, dense condition and has undergone a tremendous expansion, greatly reducing its energy density. The early universe can be described by a unified picture of particles and forces. As it expanded and cooled, however, this simpler universe "froze out" into the complexity we see today.

In 1998, we learned that the expansion of the universe is now accelerating rather than decelerating. This means that some unknown source is producing an antigravity force stronger than gravity. This mysterious dark energy now composes 73% of the total matter and energy content of the universe. The second largest fraction, 23%, is called dark matter and it has not been identified either. Ordinary matter, including all the stars and galaxies, amounts to around 4%.

Since the science of the very large and the very small are intertwined, we will develop joint research programs with NASA and other partners to combine high energy physics research with related programs in astrophysics and cosmology.



Rocky Kolb, FNAL and University of Chicago

Amazing discovery in 1998 in studies of distant Type Ia supernovae: The Big Bang expansion of the universe is accelerating rather than decelerating. This expansion has been speeding up for the past few billion years, after a long period of slowing down. The source of the "antigravity" force pushing space outward is called "dark energy" and is still a profound mystery. Plans are underway to launch a space telescope, the JDEM, which could investigate the mystery by making more precise measurements of supernovae from many different times in the history of the universe.

Identify dark energy.

Explaining the dark energy that is pulling the universe apart is crucial for understanding its evolution. Our strategy includes the following emphases:

- Work in partnership with NASA to observe distant supernovae using a dedicated telescope in earth orbit. The JDEM will precisely measure the emission of light from supernovae located at a wide range of distances, providing a history of accelerating and decelerating periods in the life of the universe.
- Develop a theoretical understanding of dark energy. Our best attempts to calculate the vacuum energy density give results that are much too large.

Identify dark matter.

The nature of dark matter has not yet been determined, but we suspect that it consists of weakly interacting massive particles. A prime candidate is the lowest mass supersymmetric particle, left as a remnant of a very early stage of the universe. Our strategy includes the following emphases:

- Search for weakly interacting massive particles in cosmic rays.
- Search for supersymmetric particles produced in accelerator experiments.

Accelerator Technology for the Nation

Accelerators underpin virtually every activity of the DOE's Office of Science and, increasingly, of the entire scientific enterprise. From biology to medicine, from materials to metallurgy, from elementary particles to the cosmos, accelerators provide our window to the microcosm, forming the basis for scientific understanding and applications spanning countless fields.

Over the last century, particle accelerators have changed the way we look at Nature and the universe we live in and have become an integral part of the Nation's technical infrastructure. For example:

- 10,000 cancer patients are treated every day in the United States with electron beams from linear accelerators.
- Accelerators produce short-lived radioisotopes that are used in over 10 million diagnostic medical procedures and 100 million laboratory tests every year in the United States.
- Nuclear diagnostic medicine and radiation therapy together save countless lives and generate about $20 billion in business annually.
- The use of ion beams from accelerators to embed doped layers in semiconductors is essential to the multi-billion-dollar semiconductor industry.
- Ion implantation is also used to harden surfaces such as those of artificial hip or knee joints, high-speed bearings, or cutting tools.
- X-ray lithography with intense x-ray beams from synchrotron light sources is used to etch microchips and other semiconductor devices. Accelerators are also used for accurate, nondestructive dating of archeological samples and art objects.

DOE's Office of Science, like its predecessor agencies, has played the lead Federal role in developing these powerful tools and in establishing national accelerator facilities for scientific research. Among Federal funding agencies, the DOE Office of Science is unique in its stewardship of the development and operation of these large user facilities. Accelerator science is an interdisciplinary field spanning a range of technologies from applied superconductivity and microwave generation to high-performance computing. This is an area in which DOE is a recognized leader—bringing together diverse skills to tackle problems that can only be solved by a multidisciplinary approach.

As we look to the future, we project a need for an initiative in accelerator research and development to advance the frontiers of science, to expand collaborations, and to pursue educational opportunities.

The initiative will balance the full spectrum of needs for the Nation, including research and applications.

- Study the large-scale structure of the universe and infer the distribution of dark matter.

Explain the matter/antimatter puzzle.

There appears to be no antimatter in the universe now, although equal amounts of matter and antimatter should have been created in the early universe. This is one of the great mysteries of physics. Our strategy includes the following emphases:

- Use the SLAC B-Factory to provide sensitive measurements of a minute asymmetry in the weak interactions of quarks that may help explain the absence of antimatter.
- Conduct an experiment on the International Space Station to search for antimatter in cosmic rays.

Study the cosmic role of neutrinos.

Neutrinos permeate the universe and hardly interact with matter, yet play a key role in the explosion of stars. The recent discovery of neutrino mass has important consequences for these supernovae. Our strategic emphases in this section overlap with those listed in section 4.1, for exploring unification phenomena:

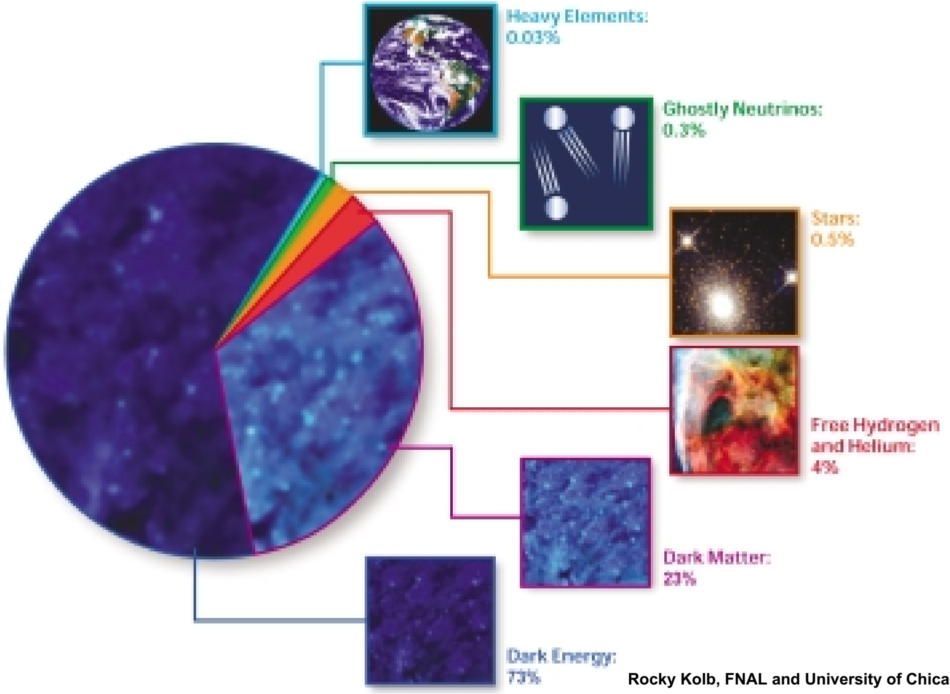
- Study neutrino masses and mixing in much more detail using new accelerator beams and detectors.
- Search for neutrino-less double beta decay to provide an absolute scale of neutrino masses.

Investigate high energy astrophysics.

High energy physics research can help solve important problems in astrophysics—the origin of the highest-energy cosmic rays, core-collapse supernovae and the associated neutrino physics, and galactic and extragalactic gamma-ray sources. Our strategy includes the following emphasis:

- Develop detectors on the ground and in space that will be used to study high-energy cosmic rays and gamma rays.

> *"I have deep faith that the principle of the universe will be beautiful and simple."*
>
> —Albert Einstein



Rocky Kolb, FNAL and University of Chicago

Makeup of the universe: We do not know what makes up 96% of the universe. Current estimates are that 73% of the universe consists of dark energy and another 23% is dark matter, neither of which we really understand. The part we do understand, including all of the bright stars and galaxies in the sky, makes up only 4% of the universe.

Our Timeline and Indicators of Success

Our commitment to the future, and to the realization of **Goal 4: Explore the Fundamental Interactions of Energy, Matter, Time, and Space,** is not only reflected in our strategies, but also in our Key Indicators of Success, below, and our Strategic Timeline for High Energy Physics (HEP), at the end of this chapter.

Our HEP Strategic Timeline charts a collection of important, illustrative milestones, representing planned progress within each strategy. These milestones, while subject to the rapid pace of change and uncertainties that belie all science programs, reflect our latest perspectives on the future—what we hope to accomplish and when we hope to accomplish it—over the next 20 years and beyond. Following the science milestones, toward the bottom of the timeline, we have identified the required major new facilities. These facilities, described in greater detail in the DOE Office of Science companion report, *Facilities for the Future of Science: A Twenty-Year Outlook*, reflect time-sequencing that is based on the general priority of the facility, as well as critical-path relationships to research and corresponding science milestones.

Additionally, the Office of Science has identified Key Indicators of Success, designed to gauge our overall progress toward achieving Goal 4. These select indicators, identified below, are representative long-term measures against which progress can be evaluated over time. The specific features and parameters of these indicators, as well as definitions of success, can be found on the web at **www.science.doe.gov/measures**.

Key Indicators of Success:

- Progress in measuring the properties and interactions of the heaviest known particle (the top quark) in order to understand its particular role in the Standard Model.
- Progress in measuring the matter-antimatter asymmetry in many particle decay modes with high precision.
- Progress in discovering or ruling out the Standard Model Higgs particle, thought to be responsible for generating the mass of elementary particles.
- Progress in determining the pattern of the neutrino masses and the details of their mixing parameters.
- Progress in confirming the existence of new supersymmetric (SUSY) particles, or ruling out the minimal SUSY "Standard Model" of new physics.
- Progress in directly discovering or ruling out the existence of new particles that could explain the cosmological "dark matter."

Strategic Timeline
for
High Energy Physics

Strategic Timeline—

2003 2005 2007 2009 2011 2013

The Science

Explore Unification

- Begin studies of neutrino mass differences and flavor mixing with NuMI/MINOS to clarify neutrino's role in Standard Model of particles and forces (2005)
- Measure properties and interactions of the top quark to understand its role in Standard Model (2007)
- Use results from Tevatron Run 2 at energy frontier to discover or set better limits for Higgs boson, supersymmetric particles, and extra dimensions (2008)
- Begin research at Large Hadron Collider at CERN in Switzerland, guided by Tevatron results and extending frontier to substantially higher-energy (2008)
- Use computer simulations to calculate strong interactions between particles so precisely that theoretical uncertainties no longer limit our understanding of these interactions (2009)
- Determine the pattern of neutrino masses and details of neutrino mixing parameters (2011)
- Use early results from Large Hadron Collider to define initial physics objectives of Linear Collider (2012)
- Measure W boson mass with high precision to understand its relationship with the top quark and Higgs boson (2013)

Understand the Cosmos

- Begin using full array of detectors in Pierre Auger Observatory in Argentina to study origins of extremely high-energy cosmic rays (2005)
- Complete initial survey with Gamma-ray Large Area Space Telescope and use results to study high-energy gamma ray sources and astrophysical acceleration mechanisms (2009)
- Measure matter/antimatter asymmetry in quark sector with high precision (2013)

Future Facilities**

Joint Dark Energy Mission (JDEM): JDEM is a space-based probe, developed in partnership with NASA, designed to help understand the recently discovered mysterious "dark energy" that makes up more than 70% of the universe.

B-Particle Physics at the TeVatron (BTeV): BTeV is an experiment designed to use the Tevatron proton-antiproton collider at the Fermi National Accelerator Laboratory to make very precise measurements of several aspects of fundamental particle behavior.

***These strategic milestones are illustrative and depend on funds made available through the Federal budget process.**

****For more detail on these facilities and the overall prioritization process, see the companion document, *Facilities for the Future of Science: A Twenty-Year Outlook.***

*High Energy Physics**

2015 2017 2019 2021 2023 2026

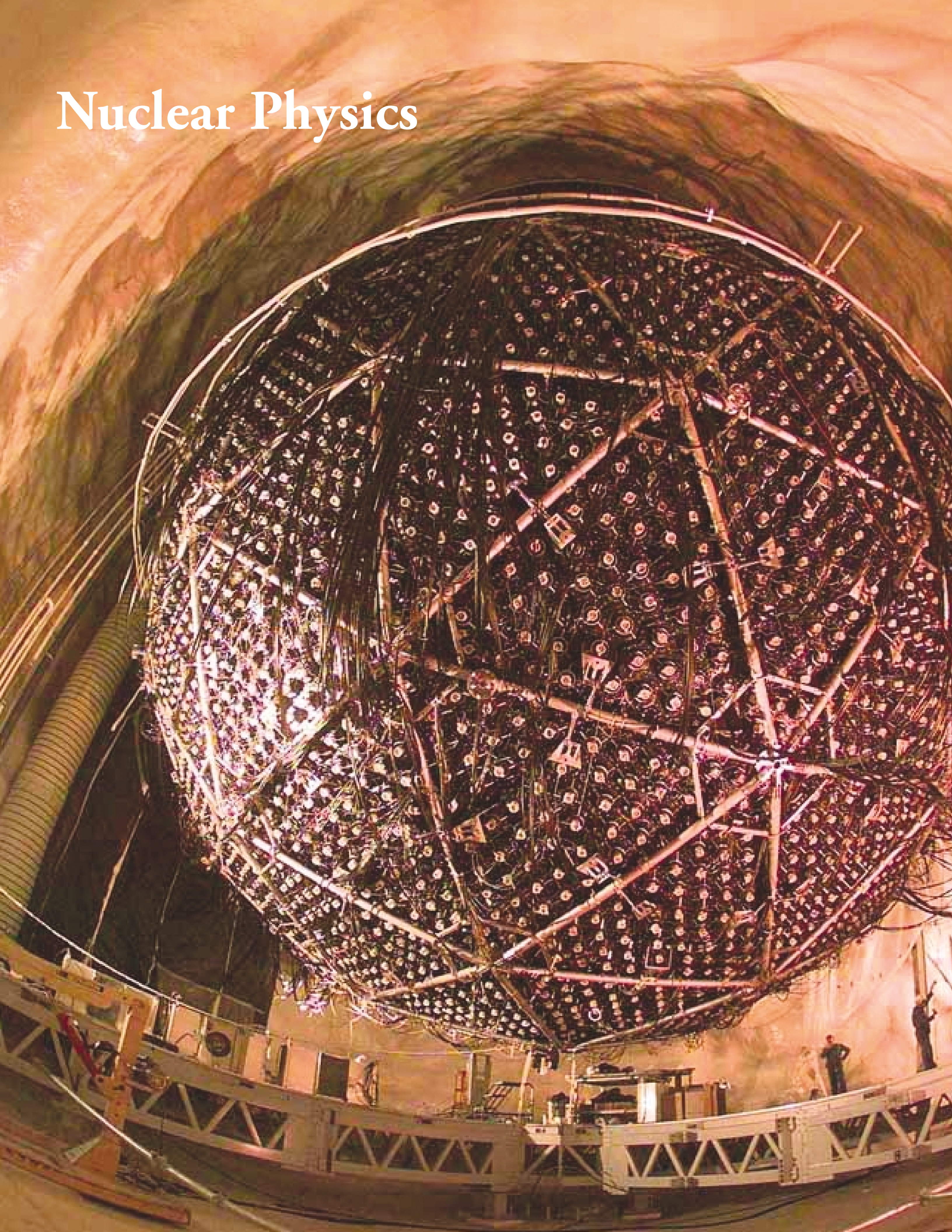
- Discover or rule out Standard Model Higgs boson, thought to be source of elementary particle mass (2014)
- Discover supersymmetric particles or rule out minimal supersymmetric Standard Model of new physics (2020)
- Discover extra dimensions or set limits on their extent (2022)
- Validate a theoretical model of relationships among top quark, W boson, and Higgs boson (2023)
- Measure neutrino masses from studies of double beta decay, helping to set energy scale for unification (2026)

- With DOE/NASA Joint Dark Energy Mission, precisely measure expansion history of universe, to determine the nature of dark energy (2017)
- Determine the role of supersymmetric particles in dark matter (2020)
- Using Super Neutrino Beam, begin measurements of matter/antimatter asymmetry in lepton sector (2021)
- Use knowledge of neutrino mass to clarify role of neutrinos in dark matter and stellar explosions (supernovae) (2026)

Linear Collider: The Linear Collider will allow physicists to make the world's most precise measurements of Nature's most fundamental particles and forces at energies comparable to those of the Large Hadron Collider (LHC).

Super Neutrino Beam: The Super Neutrino Beam will allow more comprehensive studies of the neutrino properties by producing a neutrino beam 10 times more intense than those available with current accelerators.

Nuclear Physics



The Sudbury Neutrino Observatory (SNO): This unusual observatory, built 6,800 feet underground in the Creighton mine near Sudbury, Ontario, Canada, is one of two international underground neutrino detectors in which the Office of Science is a collaborator. The other detector is KamLAND in Japan. These underground observatories were built to study neutrinos from the sun or from nuclear power reactors, and their combined research has recently determined that the mysterious elementary particle called the neutrino has mass and oscillates among three “flavors” as it travels through space. The 2002 Nobel Prize in physics recognized an Office of Science-supported scientist, Ray Davis, Jr., for his discovery of solar neutrinos in the late 1960s. His findings motivated the search for neutrino oscillations.

LBNL

5

Explore Nuclear Matter—from Quarks to Stars

Understand the evolution and structure of nuclear matter, from the smallest building blocks, quarks and gluons; to the elements in the universe created by stars; to unique isotopes created in the laboratory that exist at the limits of stability, possessing radically different properties from known matter.

Nucleons were born in the first minutes after the “Big Bang” and their subsequent synthesis into nuclei goes on in the ever-continuing process of nuclear synthesis in stars and supernovae. Nuclear matter makes up most of the mass of the visible universe. It is the stuff that makes up our planet and its inhabitants. Nuclear matter was once inaccessible for humans to study, but in the first half of the 20th Century, great strides in our understanding of nuclei and nuclear reactions were rapidly made, leading to such profound influences on society as the discovery of fission and fusion and the development of the now vast field of nuclear medicine.

Today, understanding nuclear matter and its interactions has become central to research in nuclear physics and important to research in energy, astrophysics, and national security. However, only with the development of the theory of the strong interaction, a strongly coupled quantum field theory called Quantum Chromodynamics (QCD), in just the last few decades, has a quantitative basis emerged to describe nuclear matter in terms of its underlying fundamental quark and gluon constituents. We have only recently acquired more sensitive tools to make the measurements and calculations needed to fully explore this quark structure of the nucleon, of simple nuclei, of nuclear matter, and even of the stars, opening an exciting new era in nuclear physics. The field of nuclear physics can be described in terms of five broad questions:

- What is the structure of the nucleon? Relating the observed properties of protons, neutrons, and simple nuclei to the underlying fundamental quarks is a central problem of modern physics.
- What is the structure of nucleonic matter? A central goal of nuclear physics is to explain the properties of nuclei and nuclear matter.

"The most incomprehensible thing about our universe, is that it can be comprehended."

—Albert Einstein

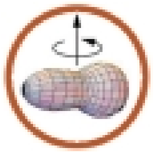
- What are the properties of hot nuclear matter? When nuclear matter is sufficiently heated, QCD predicts that the individual nucleons will lose their identities and the quarks and gluons will become "deconfined" into quark-gluon plasma; nuclear physicists are searching intensely for this new state of matter at high-energy density.
- What is the nuclear microphysics of the universe? How the nuclei of the chemical elements we find on earth were formed in stars and supernovae is a puzzle that relates to our very being.
- What is to be the new Standard Model (the current theory of elementary particles and forces)? Precision experiments deep underground and at low energies provide essential complementary information to searches for new physics in high-energy accelerator experiments.

Answering these questions will reveal important discoveries about how the visible matter of the physical world around us is put together, how the early universe developed from its initial extremely hot and dense state, the dynamics of stars and other cosmic objects, and how the very elements that we are made of came to be. Vast computing resources will be used to perform the challenging calculations of subatomic structure needed to address these questions, while new accelerators will be needed to study rare nuclei and nuclear reactions at high-energy densities. This research will primarily be performed by international research teams that are a hallmark of Office of Science physics, and will provide world leadership in all the major thrusts of nuclear physics.

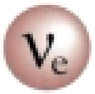
As an integral part of this Strategic Plan, and in *Facilities for the Future of Science: A Twenty-Year Outlook*, we have identified the need for five future facilities to realize our Nuclear Physics vision and to meet the

Our History of Discovery…Select Examples

1948-1955
Discovered that atomic nuclei have a shell structure analogous to the discrete electron orbits in atoms.
(1963 Nobel Prize)



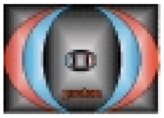
1950s
Discovery of the connection between collective motion and particle motion in atomic nuclei.
(1975 Nobel Prize)



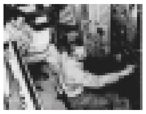
1956
Discovered the electron neutrino.
(1995 Nobel Prize)

1957
Discovery of CP (conservation of parity) violation with beta decay experiments, overturning one of the fundamental laws of Nature.

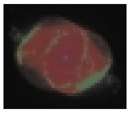
1950 1960



1950s
Discovered that protons and neutrons have a definite size and form, using new electron scattering techniques.
(1961 Nobel Prize)



1953
Discovery of the neutrino emitted from the core of a nuclear reactor.
(1995 Nobel Prize)



1950s-1960s
Demonstrated that nuclear processes in stars could manufacture all the elements, starting with just the hydrogen and helium produced in the Big Bang.
(1983 Nobel Prize)

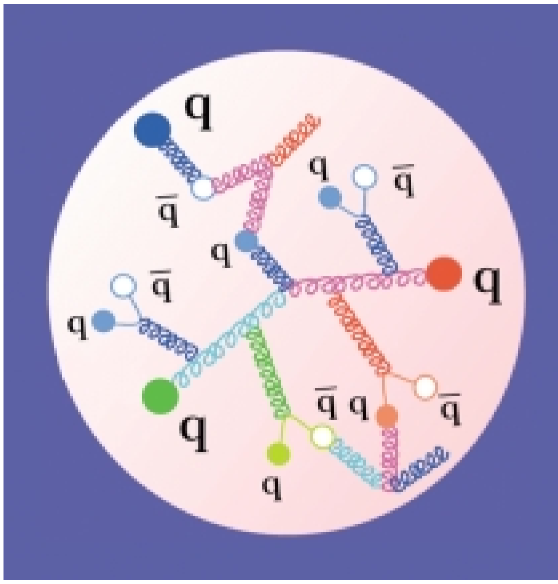
science challenges described in the following pages. Two of the facilities are near-term priorities: the **Rare Isotope Accelerator (RIA)** and the **Continuous Electron Beam Accelerator Facility (CEBAF) Upgrade**. The RIA will be the world's most powerful research facility dedicated to producing and exploring rare isotopes that are not found naturally on Earth. The upgrade to the CEBAF at Thomas Jefferson National Accelerator Facility (TJNAF) is a cost-effective way to double the energy of the existing beam, and thus provide the capability to study the structure of protons and neutrons in the atom with much greater precision than is currently possible. All five facilities are included in our Nuclear Physics Strategic Timeline at the end of the chapter and in the facilities chart in Chapter 7 (page 93), and they are discussed in detail in the *Twenty-Year Outlook*.

Our Strategies

In developing strategies to pursue these exciting opportunities, the Office of Science has been guided by the long-range planning report, *Opportunities in Nuclear Science* (2002), prepared by its advisory panel, the Nuclear Science Advisory Committee (NSAC); and by *Connecting Quarks with the Cosmos* (2003), a report prepared by the National Research Council Committee on Physics of the Universe.

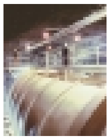
5.1 Understand the structure of the nucleon.

Protons and neutrons, collectively called nucleons, are the building blocks of nuclear matter and thus form the heart of every atom in the universe. But nucleons are themselves composed of quarks bound together by gluons, the carriers of the strong force. This strong force is responsible for the structure of nucleons and their composite structures, atomic nuclei, as well as neutron stars. The nucleus is an ideal system to study the strong interaction, which can be described by a strongly coupled quantum field theory called QCD. To understand nucleon structure, we will pursue several approaches.

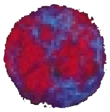


Artist's impression of a nucleon: It contains three quarks (the large red, green, and blue disks). But a boiling sea of virtual quarks and gluons (the colored springs) are also shown: each of these appears for just a moment and then disappears, like bubbles in a tea kettle.

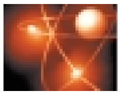
1967
Nobel Prize awarded for discovery of the energy source that powers the stars. Virtually all the energy produced by stars arises from nuclear fusion, in which the nuclei of hydrogen atoms are converted into helium.



1968
Detection of solar neutrinos, ghostlike particles produced in the nuclear reactions that power the sun.
(2002 Nobel Prize)

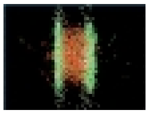


1970s
Further substantiated the neutron-capture measurements theory of nucleosynthesis as the process of formation of the chemical elements in the universe.
(1983 Nobel Prize)



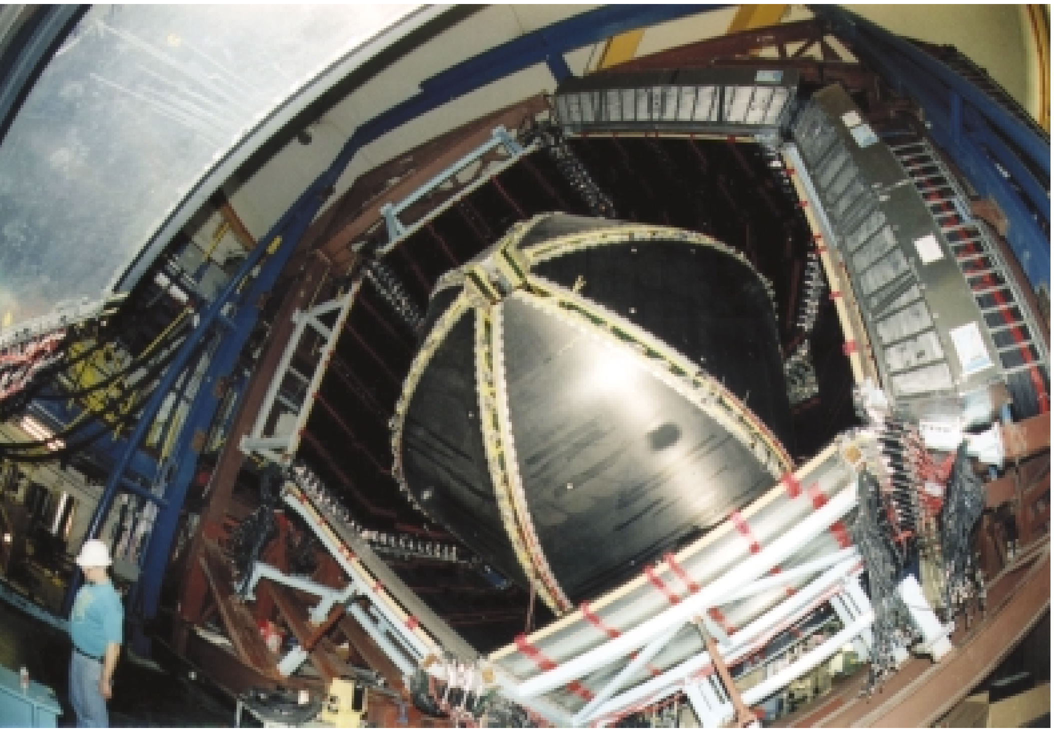
1985
Began operating TJNAF, world's first polarized, high intensity "electron microscope" to study the structure of the nucleon and the atomic nucleus.

1998-2000
Discovered neutrino oscillations, changing our picture of the universe and causing revisions of theory to include neutrino mass. Neutrino mass has important consequences for astrophysics and for the current theory of elementary particles and fields.



2000
Began operating RHIC, the world's only heavy ion collider, to study primordial matter in the universe. In 2002-2003, the first hot, dense nuclear matter was created at RHIC.

1970 1980 1990 2000



Probes for the composition of nuclear matter: The Continuous Electron Beam Accelerator Facility (CEBAF) Large Acceptance Spectrometer (CLAS) is a particle detection system at the Office of Science's Thomas Jefferson National Accelerator Facility. CEBAF enables scientists to explore the frontier of our understanding of the composition of nuclear matter.

Probe the mechanism of quark confinement inside the nucleon.

Although protons and neutrons can be separately observed, their quark and gluon constituents cannot, because they are permanently confined inside the nucleons. While the mechanism of quark confinement is qualitatively explained by QCD, a quantitative understanding remains one of our great intellectual challenges.

Our strategy includes the following emphases:

- Use high-intensity polarized electron beams at the TJNAF to measure properties of the proton, neutron, and simple nuclei for comparison with theoretical calculations to provide an improved quantitative understanding of their quark structure.
- Use high-energy polarized proton-proton collisions at the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory to determine the proton structure—how the quarks and particularly the gluons, the carriers of the strong force, assemble themselves to give the proton's properties.
- Upgrade TJNAF to provide higher-energy electron and photon beams to probe quark confinement and nucleon structure in a regime that will allow a more complete determination of the quark properties.

Search for gluon saturation.

Recent calculations suggest that, in high-energy collisions, nucleons and nuclei can behave in a completely new way, as if filled or "saturated" with many gluons. These gluons have remarkable properties, analogous both to spin glasses and to the Bose-Einstein condensates studied in condensed matter and atomic physics. This gluonic system may have universal properties, independent of the nucleus in which it resides, whose study could greatly increase our understanding of the quark-gluon structure of matter at high energy. Our strategy includes the following emphasis:

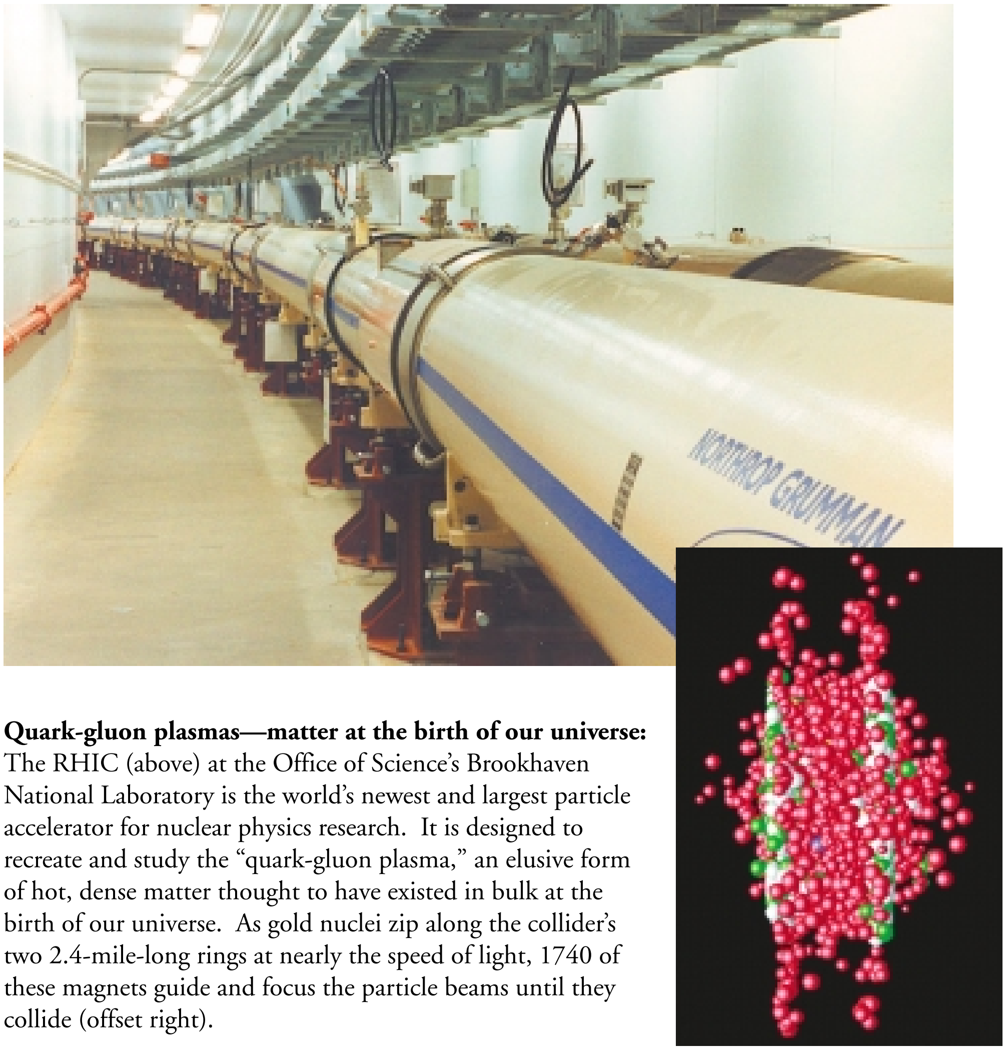
- Explore the development of an electron-nucleus collider that would allow the gluon saturation of nuclear matter to be seen.

5.2 Understand the structure of nucleonic matter.

Nuclei are the core of atoms and account for almost all the observable matter in the world around us. The naturally occurring stable nuclei are but a small fraction of the nuclei that can possibly exist. Most of the unstable nuclei (those that undergo radioactive decay) cannot be created for study by existing experimental facilities. Investigating these nuclei, and in particular those at the extreme limits of stability, offers a rich opportunity for major scientific discovery. Unbalanced neutron and proton numbers decrease the stability of a nucleus. For example, there is a limit to the number of neutrons that can be added to a nucleus of a given proton number (the nucleus of a given element). A similar stability limit for nuclei is reached if the number of protons is increased relative to a fixed neutron number.

Experiments have established which combinations of protons and neutrons can form a nucleus only for the first eight of the more than 100 known elements, but little is known about the limits of stability for the heaviest nuclei. The coming decade in nuclear physics may reveal nuclear phenomena and structure unlike anything known in the stable nuclei making up the world around us. New theoretical tools will be developed to describe nuclear many-body phenomena, with important applications to condensed matter and nuclear astrophysics. Our strategy includes the following emphases:

- Investigate new regions of nuclear structure and develop the nuclear many-body theory to predict nuclear properties.
- Develop a next-generation facility with forefront experimental instrumentation that will use beams of rare isotopes to study nuclei at the very limits of stability. This facility will provide the tools for understanding nuclear structure evolution across the entire landscape of the chart of the nuclides.



Quark-gluon plasmas—matter at the birth of our universe: The RHIC (above) at the Office of Science's Brookhaven National Laboratory is the world's newest and largest particle accelerator for nuclear physics research. It is designed to recreate and study the "quark-gluon plasma," an elusive form of hot, dense matter thought to have existed in bulk at the birth of our universe. As gold nuclei zip along the collider's two 2.4-mile-long rings at nearly the speed of light, 1740 of these magnets guide and focus the particle beams until they collide (offset right).

BNL

Gamma rays as windows to rare and exotic nuclear processes: Gammasphere (one-half shown here) is a spectrometer of unparalleled detection sensitivity to gamma rays due to its high resolution, granularity, and efficiency. It consists of a spherical shell of 110 large-volume, high-purity germanium detectors, each enclosed in a bismuth-germanate shield for increased sensitivity. This detector is the ideal device to study rare and exotic nuclear processes that are key to understanding the many facets of nuclear structure. Shown here, in the middle, is a plunger apparatus that can be used to measure extremely short nuclear lifetimes (1 to 1000 picoseconds).

5.3 Search for quark-gluon plasma.

The quarks and gluons that compose each proton and neutron are normally confined within these nucleons. However, if nuclear matter is heated sufficiently, quarks will become deconfined and individual nucleons will melt into a hot, dense plasma of quarks and gluons. Such plasma is believed to have filled the universe about a millionth of a second after the "Big Bang." The discovery and characterization of this new state of matter formed at extreme conditions never before available in the laboratory will yield new insight into the early phases of the universe. Our strategy includes the following emphases:

- Use colliding beams of atomic nuclei at RHIC to explore new states of matter at high-energy density, recreating brief, small samples of quark-gluon plasma and characterizing its properties.
- Increase the beam luminosities at RHIC and upgrade the detectors to allow more detailed studies of this primal state of matter. Investigate the emission of particles at high transverse momentum to better understand the behavior of jet transmission through the plasma, using the Large Hadron Collider.

5.4 Investigate nuclear astrophysics.

Nuclear physics research is essential if we are to solve important problems in astrophysics—the origin of the chemical elements, the behavior of neutron stars, core-collapse supernovae and the associated neutrino physics, and galactic and extragalactic gamma-ray sources. Almost all the chemical elements in the universe were generated by nuclear reactions in stars or in cataclysmic stellar explosions. Given the high temperatures and particle densities in stellar objects and explosions, the relevant nuclear reactions typically occur among radioactive or exotic nuclei. Our strategy includes the following emphases:

- Using exotic beams of nuclei that have many neutrons, study interactions in nuclear matter like those that occur in neutron stars and those that create the nuclei of most atomic elements inside stars and supernovae.
- Develop computer simulations for the behavior of supernovae, including core collapse and explosion, which incorporate the relevant nuclear reaction dynamics.

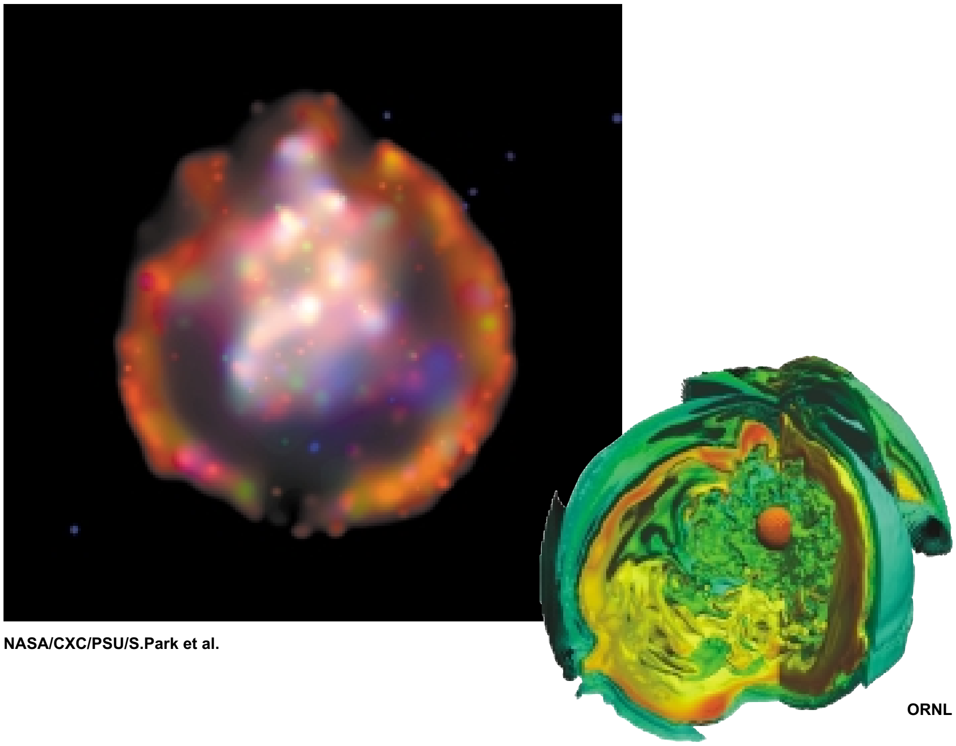
- Develop a unique next-generation facility with forefront experimental instrumentation that will provide new species of exotic beams at unprecedented intensities to advance science at the intersection of nuclear physics and astronomy. This facility is similarly described in section 5.2.

5.5 Investigate the fundamental symmetries that form the basis of the Standard Model.

Neutrinos are produced by nuclear reactions in the sun, in supernovae, and in reactors. Understanding their properties is essential for understanding stellar dynamics and supernova explosions. Studies with neutrinos generated in nuclear reactors are complementary to those produced by high-energy accelerators. Similarly, precise measurements of the weak (radioactive) decay of the neutron are complementary to measurements of weak interaction properties at high energies using particle accelerators. Both could require refinements of the Standard Model.

Our strategy includes the following emphasis:

- Further investigate neutrino mixing using neutrinos from the sun, cosmic-ray interactions, and nuclear reactors.
- Measure the decays of tritium nuclei and search for neutrinoless double beta decay to provide essential information about the absolute scale of neutrino masses.
- Using new cold and ultra-cold neutron facilities at the Manuel Lujan Jr. Neutron Scattering Center and the Spallation Neutron Source, improve on existing measurements of the decay properties of the neutron and search for the electric dipole moment of the neutron.
- Using advanced laser trapping techniques, search for the electric dipole moment of radium-225.



NASA/CXC/PSU/S.Park et al.

ORNL

Understanding an exploding star: The striking Chandra image of a supernova remnant SNR 0103-72.6 reveals a nearly perfect ring about 150 light years in diameter surrounding a cloud of gas enriched in oxygen and shock heated to millions of degrees Celsius. The ring marks the outer limits of a shock wave produced as material ejected in the supernova explosion plows into the interstellar gas. When such a star explodes, its core collapses to form either a neutron star, or if massive enough, a black hole, and the material surrounding the core is propelled into interstellar space. The image on the right is a computer simulation of an exploding star (supernova). Obtaining a detailed understanding of supernovae explosions and the formation of new elements is a goal of the Terascale Supernova Initiative at the DOE Office of Science's Oak Ridge National Laboratory.

Our Timeline and Indicators of Success

Our commitment to the future, and to the realization of **Goal 5: Explore Nuclear Matter—from Quarks to Stars**, is not only reflected in our strategies, but also in our Key Indicators of Success, below, and our Strategic Timeline for Nuclear Physics (NP), at the end of this chapter.

The NP Strategic Timeline charts a collection of important, illustrative milestones, representing planned progress within each strategy. These milestones, while subject to the rapid pace of change and uncertainties that belie all science programs, reflect our latest perspectives on the future—what we hope to accomplish and when we hope to accomplish it—over the next 20 years and beyond. Following the science milestones, toward the bottom of the timeline, we have identified the required major new facilities. These facilities, described in greater detail in the DOE Office of Science companion report, *Facilities for the Future of Science: A Twenty-Year Outlook*, reflect time-sequencing that is based on the general priority of the facility, as well as critical-path relationships to research and corresponding science milestones.

Additionally, the Office of Science has identified Key Indicators of Success, designed to gauge our overall progress toward achieving Goal 5. These select indicators, identified below, are representative long-term measures against which progress can be evaluated over time. The specific features and parameters of these indicators, as well as definitions of success, can be found on the web at **www.science.doe.gov/measures**.

Key Indicators of Success:

- Progress in realizing a quantitative understanding of the quark substructure of the proton, neutron, and simple nuclei by comparison of precision measurements of their fundamental properties with theoretical calculations.
- Progress in searching for, and characterizing the properties of, the quark-gluon plasma by recreating brief, tiny samples of hot, dense nuclear matter.
- Progress in investigating new regions of nuclear structure, study interactions in nuclear matter like those occurring in neutron stars, and determining the reactions that created the nuclei of atomic elements inside stars and supernovae.
- Progress in determining the fundamental properties of neutrinos and fundamental symmetries by using neutrinos from the sun and nuclear reactors and by using radioactive decay measurements.

Strategic Timeline for Nuclear Physics

Strategic Timeline-

2003 2005 2007 2009 2011 20

The Science

Heavy Ion

- Begin studies of rare processes in the formation of hot, dense nuclear matter (2004)
- Determine if quark-gluon plasma, the matter of the infant universe, can be made in the laboratory using colliding beams of atomic nuclei (2007)
- Begin measurements of the behavior of high-transverse-momentum particles through hot, dense, nuclear matter that is dominated by gluons (2011)

Medium Energy

- Obtain first polarized high-energy proton-proton data studying the proton spin (2006)
- Determine the strange quark content of the proton
- Begin search for an electric dipole moment of Radium-225 (2007)
- Determine gluon contribution to proton spin (2010)
- Establish basic properties of the proton, neutron, and simple nuclei using high-intensity polarized electron beams at 6 GeV (2012)

Low Energy

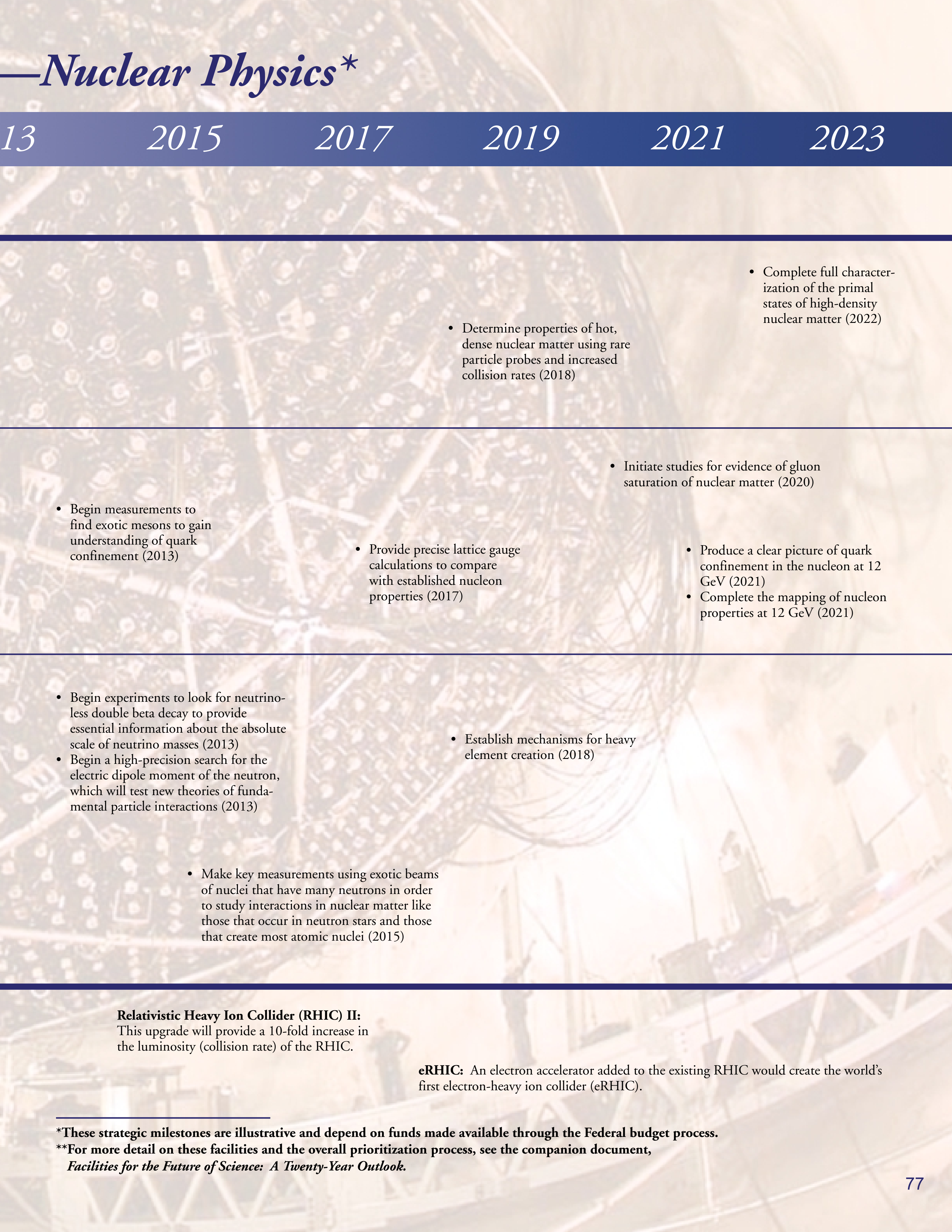
- Begin making precise measurements of the decay properties of the neutron to test the Standard Model of fundamental particles (2004)
- Quantify neutrino mixing using neutrinos from the sun, cosmic-ray interactions, and nuclear reactors (2006)
- Establish reaction rates for understanding how light elements are created in supernovae (2006)
- Develop three-dimensional computer simulations for the behavior of supernovae, including core collapse and explosion, which incorporate the relevant nuclear reaction dynamics (2006)
- Complete measurements in new regions of nuclear structure and develop the nuclear many-body theory to predict nuclear properties (2008)
- Begin studies of nuclei at the limits of stability using the new GRETINA gamma-ray detector, revolutionizing detector technology (2010)
- Launch next-generation neutron experiments studying decay of the neutrons (2010)
- Establish an electron neutrino mass (2011)

Future Facilities**

Rare Isotope Accelerator (RIA): The RIA will be the world's most powerful research facility dedicated to producing and exploring new rare isotopes that are not found naturally on Earth.

Continuous Electron Beam Accelerator Facility (CEBAF) Upgrade: The upgrade to the CEBAF at Thomas Jefferson National Accelerator Laboratory is a cost-effective way to double the energy of the existing beam.

Double Beta Decay Underground Detector: The underground double beta decay detector will enable measurements of neutrino masses and determination of whether the neutrino and its anti-particle are identical.



—Nuclear Physics*

13 2015 2017 2019 2021 2023

- Complete full characterization of the primal states of high-density nuclear matter (2022)
- Determine properties of hot, dense nuclear matter using rare particle probes and increased collision rates (2018)

- Initiate studies for evidence of gluon saturation of nuclear matter (2020)
- Begin measurements to find exotic mesons to gain understanding of quark confinement (2013)
- Provide precise lattice gauge calculations to compare with established nucleon properties (2017)
- Produce a clear picture of quark confinement in the nucleon at 12 GeV (2021)
- Complete the mapping of nucleon properties at 12 GeV (2021)

- Begin experiments to look for neutrinoless double beta decay to provide essential information about the absolute scale of neutrino masses (2013)
- Begin a high-precision search for the electric dipole moment of the neutron, which will test new theories of fundamental particle interactions (2013)
- Establish mechanisms for heavy element creation (2018)
- Make key measurements using exotic beams of nuclei that have many neutrons in order to study interactions in nuclear matter like those that occur in neutron stars and those that create most atomic nuclei (2015)

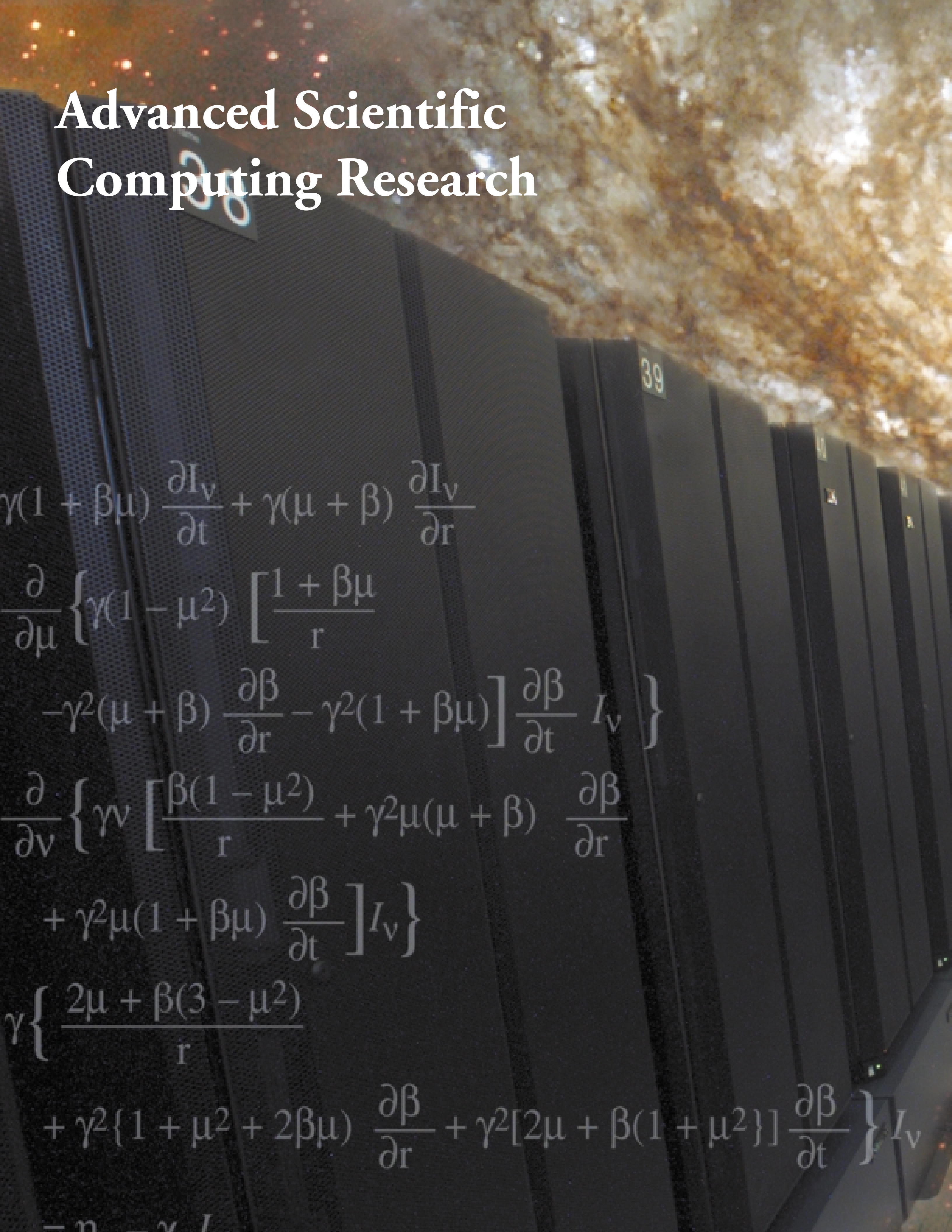
Relativistic Heavy Ion Collider (RHIC) II: This upgrade will provide a 10-fold increase in the luminosity (collision rate) of the RHIC.

eRHIC: An electron accelerator added to the existing RHIC would create the world's first electron-heavy ion collider (eRHIC).

***These strategic milestones are illustrative and depend on funds made available through the Federal budget process.**

****For more detail on these facilities and the overall prioritization process, see the companion document, *Facilities for the Future of Science: A Twenty-Year Outlook.***

Advanced Scientific Computing Research



6

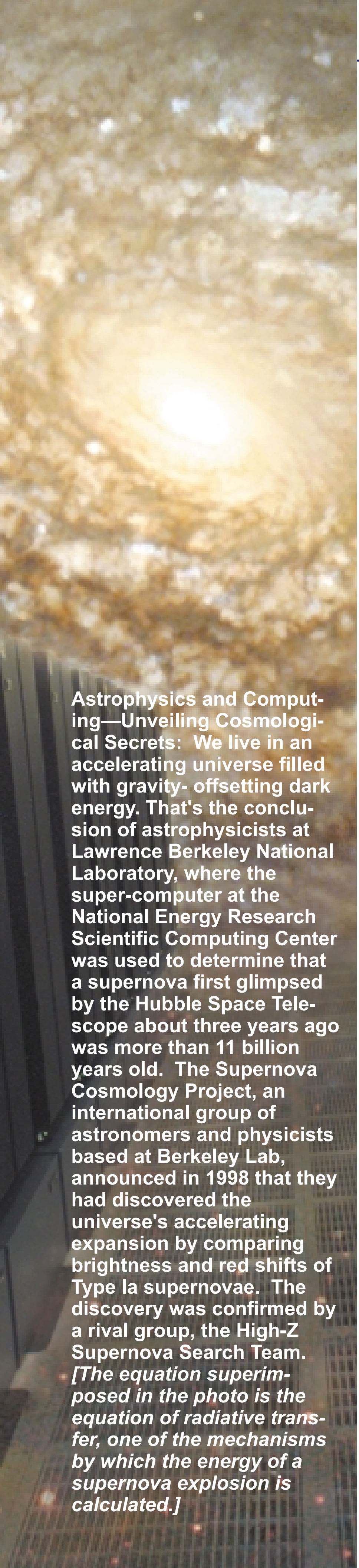
Deliver Computing for the Frontiers of Science

Deliver forefront computational and networking capabilities to scientists nationwide that enable them to extend the frontiers of science, answering critical questions that range from the function of living cells to the power of fusion energy.

Computer-based simulation enables us to predict the behavior of complex systems that are beyond the reach of our most powerful experimental probes or our most sophisticated theories. Computational modeling has greatly advanced our understanding of fundamental processes of Nature, such as fluid flow and turbulence or molecular structure and reactivity. Through modeling and simulation, we will be able to explore the interior of stars and learn how protein machines work inside living cells. We can design novel catalysts and high-efficiency engines. Computational science is increasingly central to progress at the frontiers of almost every scientific discipline and to our most challenging feats of engineering.

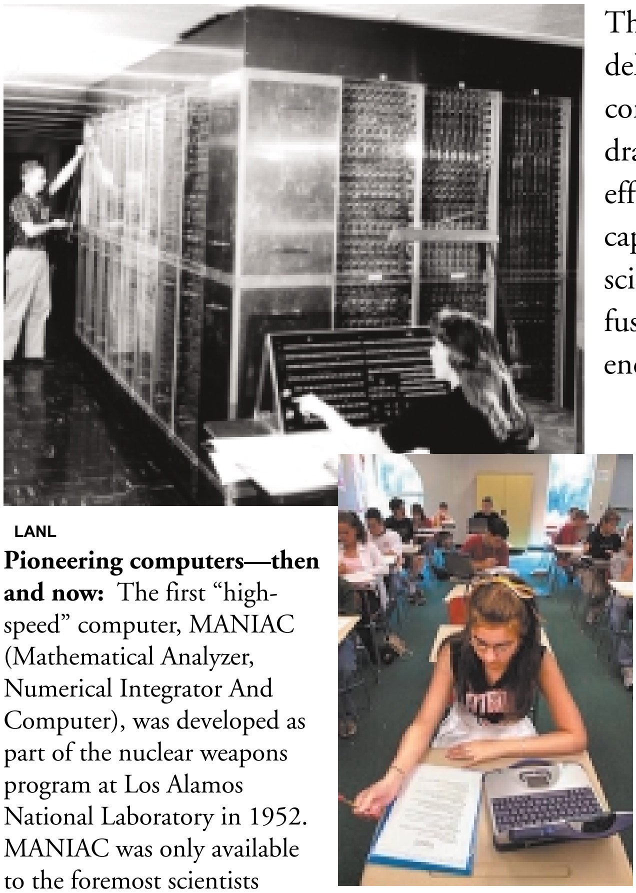
The science of the future demands that we advance beyond our current computational abilities. Accordingly, we must address the following challenges:

- What new mathematics are required to effectively model systems such as the Earth's climate or the behavior of living cells that involve processes taking place on vastly different time and/or length scales?
- Which computational architectures and platforms will deliver the most benefit for the science of today and the science of the future?
- What advances in computer science and algorithms are needed to increase the efficiency with which supercomputers solve problems for the Office of Science?
- What operating systems, data management, analysis, model development, and other tools are required to make effective use of future-generation supercomputers?
- Is it possible to overcome the geographical distances that often hinder science by making all scientific resources readily available to scientists, regardless of whether they are at a university, national laboratory, or industrial setting?



Astrophysics and Computing—Unveiling Cosmological Secrets: We live in an accelerating universe filled with gravity- offsetting dark energy. That's the conclusion of astrophysicists at Lawrence Berkeley National Laboratory, where the super-computer at the National Energy Research Scientific Computing Center was used to determine that a supernova first glimpsed by the Hubble Space Telescope about three years ago was more than 11 billion years old. The Supernova Cosmology Project, an international group of astronomers and physicists based at Berkeley Lab, announced in 1998 that they had discovered the universe's accelerating expansion by comparing brightness and red shifts of Type Ia supernovae. The discovery was confirmed by a rival group, the High-Z Supernova Search Team. *[The equation superimposed in the photo is the equation of radiative transfer, one of the mechanisms by which the energy of a supernova explosion is calculated.]*

LBNL



LANL

Pioneering computers—then and now: The first "high-speed" computer, MANIAC (Mathematical Analyzer, Numerical Integrator And Computer), was developed as part of the nuclear weapons program at Los Alamos National Laboratory in 1952. MANIAC was only available to the foremost scientists around the country to help solve the critical scientific problems of that era. It occupied a large room and was the first computer programmed to play chess, possessing enough memory to store up to 5000 words. It is hardly a comparison to the laptops of today, each with gigabytes of memory and available now to children in grade schools. Many technologies from Office of Science programs have contributed to the present generation of computers, and the Office of Science operates the premier supercomputer available for civilian research and development within DOE at NERSC.

The Office of Science will deliver models, tools, and computing platforms to dramatically increase the effective computational capability available for scientific discovery in fusion, nanoscience, high-energy and nuclear physics, climate and environmental science, and biology. We will develop new mathematics and computational methods for modeling complex systems; work with the scientific community and vendors to develop computing architectures tailored to simulation and modeling; develop improved networking resources; and support interdisciplinary teams of scientists, mathematicians, and computer scientists to build sophisticated computational models that fully exploit these capabilities. Our role complements and builds on the National Nuclear Security Administration's Accelerated Strategic Computing Initiative, delivering forefront modeling capabilities for stockpile stewardship, the basic computer science and mathematics research programs conducted by the National Science Foundation, and mission-focused programs of other agencies.

As an integral part of this Strategic Plan, and in *Facilities for the Future of Science: A Twenty-Year Outlook*, we have identified the need for three future facilities to realize our Advanced Scientific Computing Research vision and to meet the science challenges described in the following pages. All three of the facilities are near-term priorities: the **UltraScale Scientific Computing Capability (USSCC)**, the **Energy Sciences Network (ESnet) Upgrade**, and the **National Energy Research Scientific Computing Center (NERSC) Upgrade**. The USSCC, located at multiple sites, will increase by a factor of 100 the computing capability available to support open (as opposed to classified) scientific research—reducing from years to days the time required to simulate complex systems, such as the chemistry of a combustion engine, or

Our History of Discovery…Select Examples

1970s
Established the first national unclassified computer center, the Controlled Thermonuclear Research Center, the forerunner to today's National Energy Research Scientific Computing Center.

1980s
Built ESnet to link research facilities and supercomputers to users and the emerging Internet.

1991
Pioneered the transition to massively parallel supercomputing, enabling 1000 or more processors to work together.

1970

1980

1990

1970s
Determined the emergence of chaotic behavior in systems thought to be stable.

1990s
Installed the first supercomputer available to the civilian research community that broke the peak performance barrier of 1 teraflop computing speed.

weather and climate—and providing much finer resolution. The ESnet upgrade will enhance the network services available to support Office of Science researchers and laboratories and maintain their access to all major DOE research facilities and computing resources, as well as fast interconnections to more than 100 other networks. The NERSC upgrade will ensure that DOE's premier scientific computing facility for unclassified research continues to provide high-performance computing resources to support the requirements of scientific discovery. All three facilities are included in our Advanced Scientific Computing Research Strategic Timeline at the end of this chapter and in the facilities chart in Chapter 7 (page 93), and they are discussed in detail in the *Twenty-Year Outlook*.

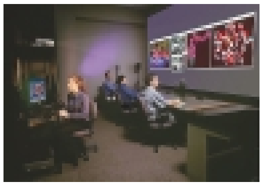
Our Strategies

6.1 Advance scientific discovery through research in the computer science and applied mathematics required to enable prediction and understanding of complex systems.

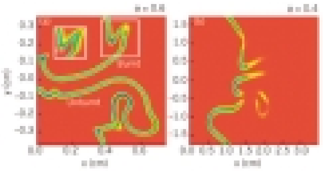
New computational methods are needed to make possible the simulation of the most complex physical and biological systems and to gain efficiency on multiprocessor terascale computers. Effective application of supercomputers requires sophisticated, scalable, operating systems; large-scale data management tools; and other computer science tools. We will support individual investigators and teams to develop new methods and tools, and encourage their transition to advanced computational science applications.

Our strategy includes the following emphases:

- Develop new and improved mathematical methods for addressing the challenges of multi-scale problems.
- Create methods and capabilities to address large-scale data management.
- Develop and apply middleware tools that enable researchers to focus on science while obtaining effective computational performance.



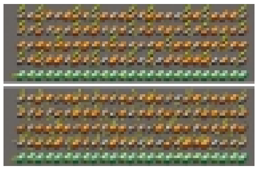
1992
Launched the first Internet videoconference.



1998
Simplified the development of scientific simulations in complex geometrics such as diesel engines.

1998
Wrote the first application code that surpassed one teraflop.

2000



1995
Developed a "spin dynamics" computational method to accurately model magnetic materials.

1998
Announced the discovery from the Supernova Cosmology Project that the universe is expanding.

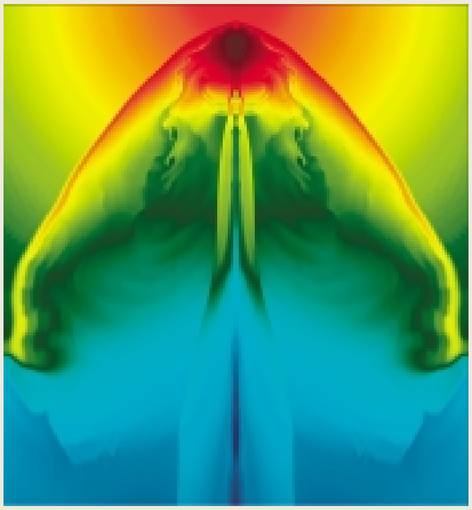
2001
Launched Scientific Discovery through Advanced Computing (SciDAC), a program that accelerates advances in computing and information technologies as tools for scientific discovery.

Scientific Discovery Through Advanced Computing (SciDAC)

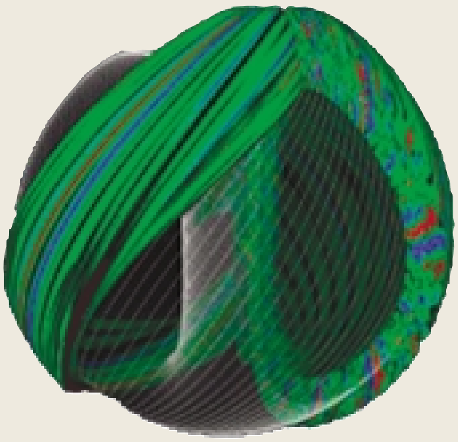
SciDAC is a research program with the goal to achieve breakthrough scientific advances through computer simulation. SciDAC has established a new model for collaboration among the scientific disciplines, computer scientists, and mathematicians. The SciDAC program is creating a new generation of scientific simulation codes and developing collaboratory software to enable geographically separated scientists to use scientific instruments and computers remotely, enabling distant colleagues to share data and function together as a team.

Current projects involve collaborations among 13 DOE laboratories and more than 50 colleges and universities in a broad spectrum of projects such as:

- Climate simulation and prediction
- Quantum chemistry and fluid dynamics
- Plasma systems to advance fusion energy science
- High energy and nuclear physics
- Software infrastructure
- Applied Mathematics Integrated Software Infrastructure Centers
- Computer Science Integrated Software Infrastructure Centers
- National collaboratory, middleware, and network research.



Model of a Supernova Blast



Plasma Microturbulence Simulation

6.2 Extend the frontiers of scientific simulation through a new generation of computational models that fully exploit the power of advanced computers and collaboratory software that makes scientific resources available to scientists anywhere, anytime.

Scientific discovery in many areas requires computational models that incorporate more complete and realistic descriptions of the phenomena being modeled than are possible today.

Our strategy includes the following emphases:

- Create, in partnerships across the Office of Science, new generations of models for fusion science, biology, nanoscience, physics, chemistry, climate, and related fields that provide high-fidelity descriptions of the underlying science.
- Incorporate the new models into scientific simulation software that achieves substantially greater performance from terascale supercomputers than we can achieve today.
- Build on the successes of the SciDAC program.

6.3 Bring dramatic advances to scientific computing challenges by supporting the development, evaluation, and application of supercomputing architectures tailored to science.

Major improvements in scientific simulation and analysis can be obtained through advances in the design of supercomputer architectures. Most of today's supercomputers were designed for commercial applications. However, computational science places stringent requirements on supercomputer designs that are often quite different from what arise in commercial applications. To meet the need for effective computing performance in the 100-teraflop range and beyond, we will support the evaluation, installation, and application of new very high-end computing architectures for computational science.

Our strategy includes the following emphases:

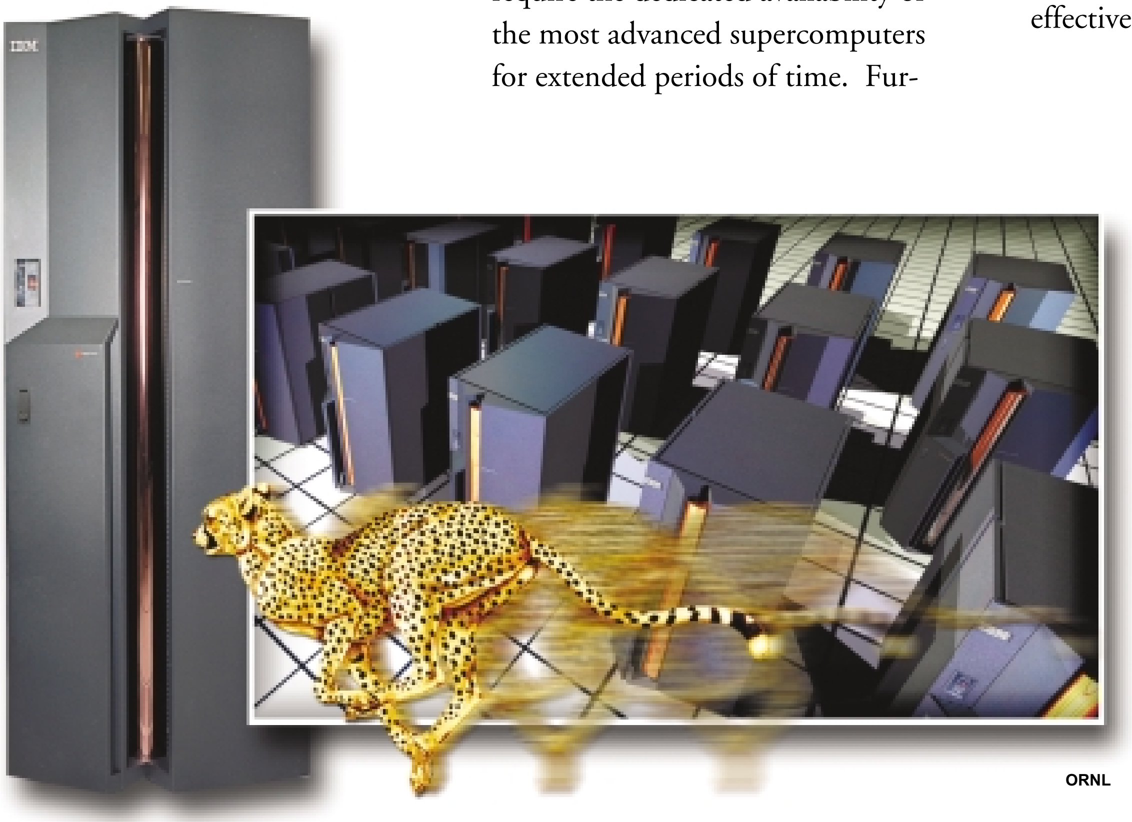
- Develop partnerships with U.S. industry in the near term to adapt current and next-generation products to more fully meet the needs of visionary computational science.
- Develop partnerships with the Department of Defense, the Defense Advanced Research Projects Agency (DARPA), and other Federal agencies to evaluate long-term architecture developments at the scale needed for Office of Science computation.
- Advance the focused research and development of systems software for radical increases in performance, reliability, manageability, and ease of use.

6.4 Provide computing resources at the petascale and beyond, network infrastructure, and tools to enable computational science and scientific collaboration.

Work at the forefront of science can require the dedicated availability of the most advanced supercomputers for extended periods of time. Furthermore, it is likely that at least a few different supercomputer designs will offer significant advantages for different classes of problems.

Our strategy includes the following emphases:

- Provide sustained, high-bandwidth access to the highest possible performance computers for the most demanding applications at the scientific frontiers.
- Upgrade the network and data management infrastructure supporting these resources to enable computational scientists to manage the extraordinarily large volumes of data often generated by large-scale scientific computing and modern experiment.
- Create supporting resources, grid nodes, and tools that enable teams of scientists to collaborate effectively at a distance.



ORNL

Computing test beds: Advanced Computing Research test beds evaluate new computing hardware and software, such as Oak Ridge National Laboratory's IBM Power4 Cheetah (pictured left) and Cray Xl, and Argonne National Laboratory's IBM/Intel/ Cluster.

"It is unworthy of excellent men to lose hours like slaves in the labor of calculation which could be relegated to anyone else if machines were used."

—Gottfried Wilhelm von
Leibnitz (1646-1716),
German philosopher
and mathematician

Our Timeline and Indicators of Success

Our commitment to the future and to the realization of **Goal 6: Deliver Computing for the Frontiers of Science** is not only reflected in our strategies, but also in our Key Indicators of Success, below, and our Strategic Timeline for Advanced Scientific Computing Research (ASCR), at the end of this chapter.

The ASCR Strategic Timeline charts a collection of important, illustrative milestones, representing planned progress within each strategy. These milestones, while subject to the rapid pace of change and uncertainties that belie all science programs, reflect our latest perspectives on the future—what we hope to accomplish and when we hope to accomplish it—over the next 20 years and beyond. Following the science milestones, toward the bottom of the timeline, we have identified the required major new facilities. These facilities, described in greater detail in the DOE Office of Science companion report, *Facilities for the Future of Science: A Twenty-Year Outlook*, reflect time-sequencing that is based on the general priority of the facility, as well as critical-path relationships to research and corresponding science milestones.

Additionally, the Office of Science has identified Key Indicators of Success, designed to gauge our overall progress toward achieving Goal 6. These select indicators, identified below, are representative long-term measures against which progress can be evaluated over time. The specific features and parameters of these indicators, as well as definitions of success, can be found on the web at **www.science.doe.gov/measures**.

Key Indicators of Success:

- Progress toward developing the mathematics, algorithms, and software that enable effective scientifically critical models of complex systems, including highly nonlinear or uncertain phenomena, or processes that interact on vastly different scales or contain both discrete and continuous elements.
- Progress toward developing, through the Genomics: GTL partnership with the Biological and Environmental Research program, the computational science capability to model a complete microbe and a simple microbial community.

Strategic Timeline for Advanced Scientific Computing Research

Strategic Timeline—Advanced

2003 *2005* *2007* *200*

The Science

Computer Science and Applied Mathematics Research

- Complete ASCR roadmap that defines national approach to the challenges of mathematics for complex systems (2003)
- Deliver operating systems for scientific computers that incorporate fault tolerance (2005)
- Deliver algorithms that scale to tens of thousands of processors for key mathematical libraries (2007)

Extending Science through Computation and Collaboration

- Simulate gyrokinetic transport of fusion plasma without detailed electron dynamics (2004)
- Enable secure, remote operation of fusion facilities (2004)
- Complete computational model of gene regulation (2005)
- Calculate enhanced optical properties at the nanoscale (2007)
- Simulate the catalyst action in automobile exhaust (2007)
- Perform full three-dimensional supernova simulation (2008)
- Simulate soot formation in diesel engines (2008)
- Enable real-time collaborative remote teams at the Spallation Neutron Source (2008)

Supercomputing Architectures for Science

- Complete evaluation of Cray X1 (2003)
- Complete evaluation of first computer with more than 50,000 processors (2005)
- Initiate evaluation of systems from DARPA High Productivity Computing Systems program (2007)

Computational and Network Infrastructure and Tools

- Deliver computing facilities for open science with a 50-fold increase in capability (2005)
- Complete expansion of ESnet to deliver core bandwidth of 10 gigabytes per second (2005)
- Deliver computing facilities for open science with 100-fold increase in capability relative to 2004 (2007)
- Increase ESnet core capability by 400% (2008)

*Future Facilities***

UltraScale Scientific Computing Capability (USSCC): The USSCC, located at multiple sites, will increase by a factor of 100 the computing capability available to support open (as opposed to classified) scientific research—reducing from years to days the time required to simulate complex systems.

***These strategic milestones are illustrative and depend on funds made available through the Federal budget process.**

****For more detail on these facilities and the overall prioritization process, see the companion document, *Facilities for the Future of Science: A Twenty-Year Outlook.***

Scientific Computing Research*

09 2011 2013 2015

- Complete programming model that enables scientists to use 100,000 processors (2009)
- Deliver mathematics of complex systems that enables accurate linkage of multiple time and length scales (2011)
- Deliver mathematics of complex systems that enables simulations of microbes (2013)
- Revolutionize computing in U.S. industry through research results from applied mathematics and computer science (2015)

- Achieve seamless integration of astrophysics simulation and data (2009)
- Perform climate simulations that incorporate biological carbon sequestration (2011)
- Deliver virtual catalogue that enables access to all climate data worldwide (2012)
- Complete simulation of tokamak disruptions that enable design of active control system to avoid disruptions (2013)
- Enable computational design of microbe for energy production (2014)
- Compete first integrated burning plasma simulation (2014)
- Deliver hundreds of petabytes per year of data to scientists, routinely (2015)

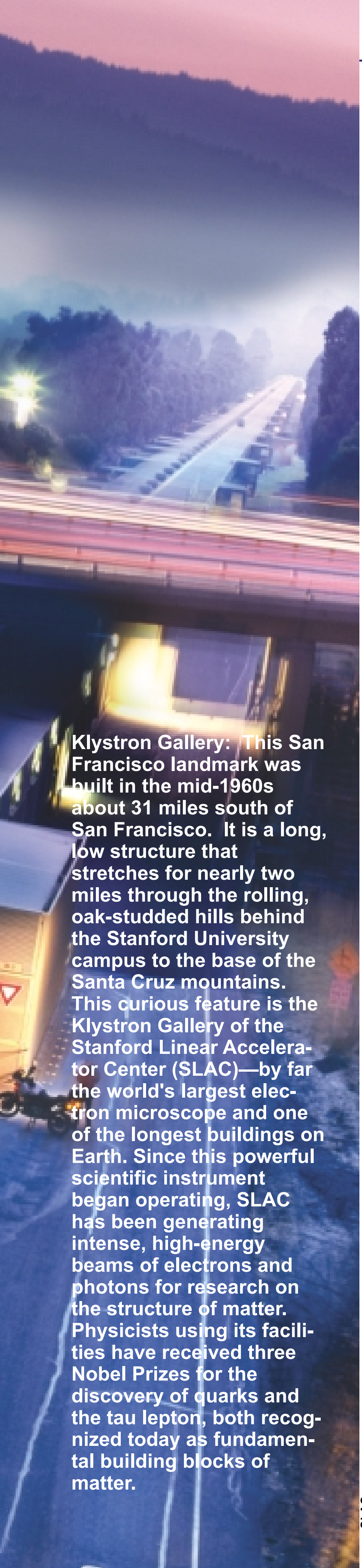
- Complete tests of computer systems that lead to the first system with sustained application performance over 10 petaflops (2011)

- Achieve computational capability for open science that reaches one petaflop (2012)
- Expand ESnet core capability to exceed 100 gigabytes per second (2013)

Energy Sciences Network (ESnet) Upgrade: The ESnet upgrade will enhance the network services available to support Office of Science researchers and laboratories and maintain their access to all major DOE research facilities and computing resources.

National Energy Research Scientific Computing Center (NERSC) Upgrade: This upgrade will ensure that NERSC continues to provide high-performance computing resources to support the requirements of scientific discovery.

Foundations



Klystron Gallery: This San Francisco landmark was built in the mid-1960s about 31 miles south of San Francisco. It is a long, low structure that stretches for nearly two miles through the rolling, oak-studded hills behind the Stanford University campus to the base of the Santa Cruz mountains. This curious feature is the Klystron Gallery of the Stanford Linear Accelerator Center (SLAC)—by far the world's largest electron microscope and one of the longest buildings on Earth. Since this powerful scientific instrument began operating, SLAC has been generating intense, high-energy beams of electrons and photons for research on the structure of matter. Physicists using its facilities have received three Nobel Prizes for the discovery of quarks and the tau lepton, both recognized today as fundamental building blocks of matter.

SLAC

7

Provide the Resource Foundations that Enable Great Science

Create and sustain the discovery-class tools, 21st Century scientific and technical workforce, research partnerships, and management systems that support the foundations for a highly productive, world-class national science enterprise.

Great leaps in the health and well being of our Nation require solid foundations of science. More than half of our national economic growth since 1945 is directly attributable to advances in energy production, energy efficiency, medicine, computation, and other technologies that have their basis in fundamental research. The Office of Science has played a major role in this national success story, contributing scientific advances in nuclear energy, nuclear medicine, advanced computation, genomics, materials science, chemistry, physics, and other areas that have resulted in 35 Nobel Prizes and thousands of industrial patents since DOE's inception in 1977. Modern science, not to mention the scientific endeavor of the future, is different from the science of our past. Increasingly, revolutionary scientific discoveries will involve:

- A complex interplay between scientists from different disciplines
- Scientific tools of incredible power and scope
- The ability to draw from a large pool of scientific and technical talent
- A modern research infrastructure and work environment
- Management practices that deliver outstanding science for each taxpayer dollar.

The Office of Science is uniquely positioned to address many of these challenges, and thus to strengthen the foundations of U.S. science and help lead our Nation into a new era of scientific discovery. No other organization in the world builds and operates such a diverse array of large-scale, discovery-class scientific tools. Furthermore, our track record of envisioning, designing, building, and operating large-scale scientific facilities on time and on budget is unmatched by any other Federal agency, the private sector, or the university community.

These facilities and the 10 DOE Office of Science national laboratories that we manage have become national crucibles for interdisciplinary research. In them, our programs can bring the power of thousands of researchers together in multidisciplinary teams to solve large-scale scientific challenges. The Office of Science specializes in scientific challenges that require such facilities and approaches, challenges that are high-risk and high-payoff.

Furthermore, our laboratories are an ideal training ground for young researchers eager to work alongside Nobel laureates and other world-class scientists in multidisciplinary settings. We take pride in managing for excellence in science through rigorous peer and advisory committee reviews of our research, our construction projects, and the way we operate.

Our Strategies

7.1 Provide the discovery-class tools required by the U.S. scientific community to answer the most challenging research questions of our era.

Scientific advancements cannot be made without similar advances in the tools used to make discoveries. Just as the telescope enabled Galileo to see the stars and planets in an entirely new way, new tools being developed by the Office of Science will enable researchers to view our physical world at its extremes—from the tiniest bits of matter to the limits of the cosmos. We call these tools "discovery-class" because they are the best of their kind—they attract the greatest scientific minds in the world and enable the type of discoveries that truly change the face of science.

For more than half a century, the Office of Science has envisioned, designed, constructed, and operated many of the premier scientific research facilities in the world. Today, more than 18,000 researchers and their students from universities, other government agencies, private industry, and abroad use these facilities each year—and this number is growing. For example, the light sources built and operated by the Office of Science now serve more than three times the total number of users they served in 1990. An indication of the ability of these research tools to build bridges between disciplines and open new vistas for research is seen in the dramatic increase—more than 20-fold in the last decade—of life science users at the light sources, once the sole domain of materials and physical science researchers.

Our strategy includes the following emphases:

- Work with the Office of Science programs' advisory committees and the broader scientific community to implement the recommendations of the companion document, *Facilities for the Future of Science: A Twenty-Year Outlook,* and continue to identify and champion those critical facilities that will ensure the U.S. position at the forefront of scientific discovery.

Discovery-Class Scientific Tools

The Office of Science has an unparalleled history of creating discovery-class tools that are available free of charge to the general scientific community and have led to Nobel Prizes and enormous scientific achievement. In the broadest sense, the Office of Science is skilled at creating the following types of scientific tools:

Particle Accelerators and Detectors: These devices are used to study the smallest bits of matter, subatomic particles, and their interactions, and are also used for medical diagnosis and treatment and myriad other applications. Using accelerators, researchers supported by the Office of Science and its predecessors have discovered 10 of the 12 basic constituents of matter (quarks and leptons).

Advanced Light Sources: High-intensity photon and x-ray sources build on core accelerator technology and are used by scientists worldwide to probe materials that cannot otherwise be analyzed. These light sources have led to new medicines, lightweight materials, and a host of other technological innovations.

Neutron Beam Sources: Once the Spallation Neutron Source becomes operational in 2006, the U.S. will regain world leadership in this vital scientific field. Neutron science uses powerful beams of neutrons to probe matter in ways that no other tool can do, opening the door to exciting discoveries in energy production, environmental restoration, and many other areas.

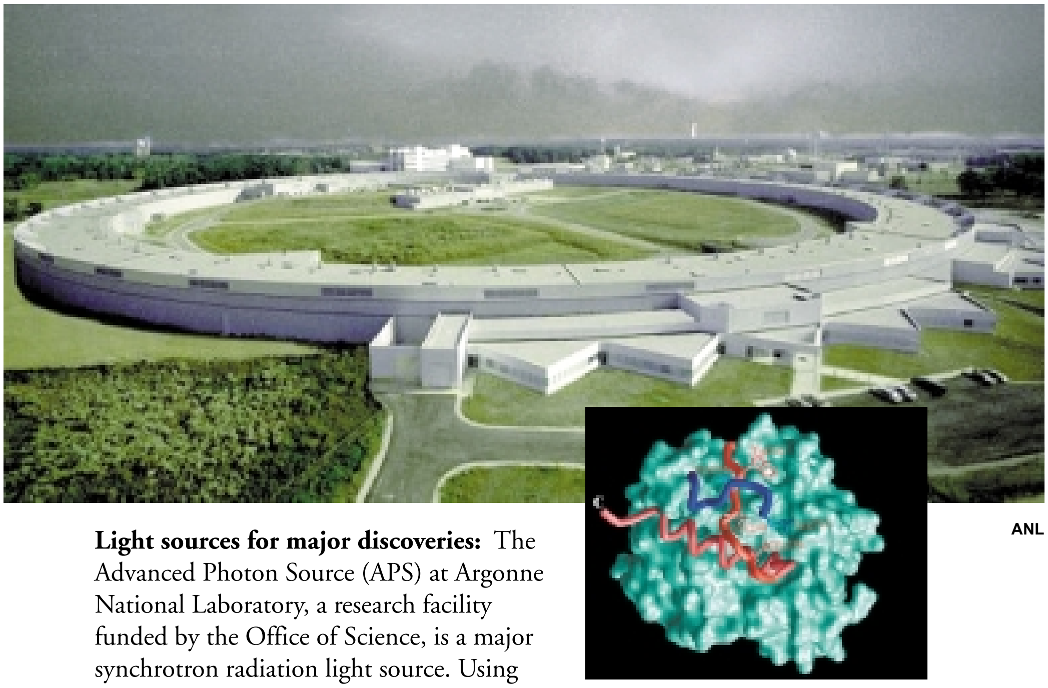
Plasma Science: The Office of Science leads the Nation in the development of tools used to understand plasma phenomena in all its forms. These tools have resulted in a greater understanding of the technology that will be required for a commercial fusion reactor, as well as more immediate uses such as fluorescent lighting and exotic new materials.

Genome Sequencing Facilities: The Office of Science pioneers many of the underlying technologies and high-throughput capabilities in DNA sequencing, incorporating these developments into its own leading-edge facilities for sequencing living organisms—from primitive microbes and new forms of life to the complex blueprint of human beings.

Specialized Facilities: The Office of Science builds and operates a large number of specialized facilities, including advanced computational centers, computational networking systems, electron-beam microcharacteriza-tion centers, combustion research facilities, centers for materials, and atmospheric radiation monitoring sites.

"It seems to me—and I am not the first to point this out—that we are in the early stage of a revolution in science nearly as profound as the one that occurred early in the last Century with the birth of quantum mechanics. . . . The revolution I am describing is one in which the notion that everything is made of atoms finally becomes operational. For the first time we have tools that give an edge to this sweeping reductionist vision. We can actually see how the machinery of life functions, atom-by-atom. We can actually build atomic-scale structures that interact with biological or inorganic systems and alter their functions. We can design new tiny objects "from scratch" that have unprecedented optical, mechanical, electrical, chemical, or biological properties that address needs of human society. . . . This revolution is caused by two developments: one is the set of instruments such as electron microscopy, synchrotron x-ray sources, lasers, scanning microscopy, and nuclear magnetic resonance devices; the other is the availability of powerful computing and information technology. Together these have brought science finally within reach of a new frontier, the frontier of complexity."

—Presidential Science Advisor John H. Marburger, III, Director of the Office of Science and Technology Policy, Executive Office of the President, at the meeting of the American Association for the Advancement of Science, Boston, Massachusetts, February 15, 2002



ANL

Light sources for major discoveries: The Advanced Photon Source (APS) at Argonne National Laboratory, a research facility funded by the Office of Science, is a major synchrotron radiation light source. Using high-brilliance x-ray beams from the APS, members of the international research community conduct forefront basic and applied research in the fields of materials science; biological science; physics; chemistry; environmental, geophysical, and planetary science; and innovative x-ray instrumentation. The first knotted protein (inset), from a microorganism called *Methanobacterium thermoautotrophicum*, was discovered by researchers using the APS. Protein folding theory previously held that forming a knot was beyond the ability of a protein. This organism is of interest to industry for its ability to break down waste products and produce methane gas.

- Build and operate the next generation of large-scale, discovery-class national research facilities to support the vitality and excellence of U.S. science, which will attract and retain top students and lead to new discoveries.
- Develop partnerships with other Federal agencies, universities, and the U.S. scientific community to fully exploit the extraordinary capabilities and interdisciplinary nature of our user facilities.
- Fully integrate scientific computation and other information technology tools into the fabric of scientific discovery.

Our Timeline for Future Facilities

In the Fall of 2002, the DOE's Office of Science began a major effort to evaluate facility needs and priorities. The process and results are contained in the companion document, the *Twenty-Year Outlook.*

Choosing major facilities is one of the most important activities of the DOE's Office of Science. It requires prioritization across fields of science, a difficult and unusual process. The set of facilities must be phased to conform to scientific opportunities, and to a responsible funding strategy. The largest facilities will often be international in character, requiring both planning and funding from other countries and organizations, together with the U.S.

The 28 proposed facilities are listed by priority in the chart on page 93. Some are noted individually; however, others for which the advice of our advisory committees was insufficient to discriminate among relative priority are presented in "bands." In addition, the facilities are roughly grouped into near-term priorities, mid-term priorities, and far-term priorities (and color-coded red, blue, and green respectively) according to the anticipated research and development timeframe of the scientific opportunities they would address.

Each facility listing is accompanied by a "peak of cost profile," which indicates the onset, years of peak construction expenditure, and completion of the facility. Because many of the facilities are still in early stages of conceptualization, the timing of their construction and completion is subject to the myriad considerations that come into play when moving forward with a new facility. Furthermore, it should be

U.S. Department of Energy Office of Science 20-Year Facility Outlook Peak of Cost Profile

Term	Priority	Program	Facility
Near-Term	1	FES	ITER
	2	ASCR	UltraScale Scientific Computing Capability
	Tie for 3	HEP	Joint Dark Energy Mission
		BES	Linac Coherent Light Source
		BER	Protein Production and Tags
		NP	Rare Isotope Accelerator
	Tie for 7	BER	Characterization and Imaging
		NP	CEBAF Upgrade
		ASCR	Esnet Upgrade
		ASCR	NERSC Upgrade
		BES	Transmission Electron Achromatic Microscope
	12	HEP	BTeV
Mid-Term	13	HEP	Linear Collider
	Tie for 14	BER	Analysis and Modeling of Cellular Systems
		BES	SNS 2-4 MW Upgrade
		BES	SNS Second Target Station
		BER	Whole Proteome Analysis
	Tie for 18	NP/HEP	Double Beta Decay Underground Detector
		FES	Next Step Spherical Torus
		NP	RHIC II
Far-Term	Tie for 21	BES	National Synchrotron Light Source Upgrade
		HEP	Super Neutrino Beam
	Tie for 23	BES	Advanced Light Source Upgrade
		BES	Advanced Photon Source Upgrade
		NP	eRHIC
		FES	Fusion Energy Contingency
		BES	HFIR Second Cold Source and Guide Hall
		FES	Integrated Beam Experiment

Peak Cost ■ Near-term 🟥 Mid-term 🟦 Far-term 🟩

Programs:

ASCR = Advanced Scientific Computing Research
BES = Basic Energy Sciences
BER = Biological and Environmental Research
FES = Fusion Energy Sciences
HEP = High Energy Physics
NP = Nuclear Physics

remembered that construction of these cost profiles was guided by an ideal funding scenario. Appropriate caveats and explanation are provided in the *Twenty-Year Outlook*.

This facility plan represents the DOE Office of Science's best guess today at how the future of science and the need for scientific facilities will unfold over the next two decades. We know, however, that science changes. Discoveries, as yet unimagined, will alter the course of research and the facilities needed in the future. Additionally, we recognize that the breadth and scope of the vision encompassed by these 28 facilities reflects an aggressive and optimistic view of the future of the Office. Nevertheless, we believe that it is necessary to have and discuss such a vision. Despite the uncertainties, it is important for organizations to have a clear understanding of their goals and a path toward reaching those goals. The *Twenty-Year Outlook*, and more broadly, this Office of Science Strategic Plan, offer just such a vision.

Science and Technology Workforce Development—A National Crisis

Our Nation is failing to produce both a scientifically literate citizenry and the kind of workforce we will need in the 21st Century. Consider the following:

- Test scores placed U.S. students near the bottom of the 16 nations that administered physics and advanced math tests.
- U.S. engineering majors declined by 35% between 1975 and 1998.
- Only 19,000 degrees in the physical sciences were granted in the U.S. in 1999, compared with 130,000 social science degrees.

The disturbing statistics go on and on, but this decline can no longer be tolerated by a Nation that aspires to lead the world in science and technology. As the U.S. Commission on National Security in the 21st Century reported, "Inadequacies of our systems of research and education pose a greater threat to U.S. national security over the next quarter century than any potential conventional war that we might imagine."

7.2 Contribute to a vital and diverse national scientific workforce by providing national laboratory research opportunities to students and teachers.

Our national laboratories offer a unique setting for mentor-intensive training opportunities, helping to ensure that DOE and the Nation have a highly skilled and diverse scientific and technical workforce. These capabilities strongly complement the career development opportunities provided by the National Science Foundation and other Federal agencies. Our national laboratories provide an environment where, under the mentorship of world-class scientists, students and teachers have unparalleled opportunities to perform exciting research with the most advanced instrumentation available. This combination of mentor talent and advanced instrumentation greatly serves to attract, develop, and retain a diverse and capable workforce. Our strategy includes the following emphases:

- Provide undergraduate internships for students entering science, technology, engineering, and math (STEM) careers, including K-12 science and math teaching careers.
- Provide graduate/faculty fellowships for STEM teachers and faculty.
- Develop partnerships with other Federal agencies to address the long-term decline in undergraduate and graduate degrees in the physical sciences.

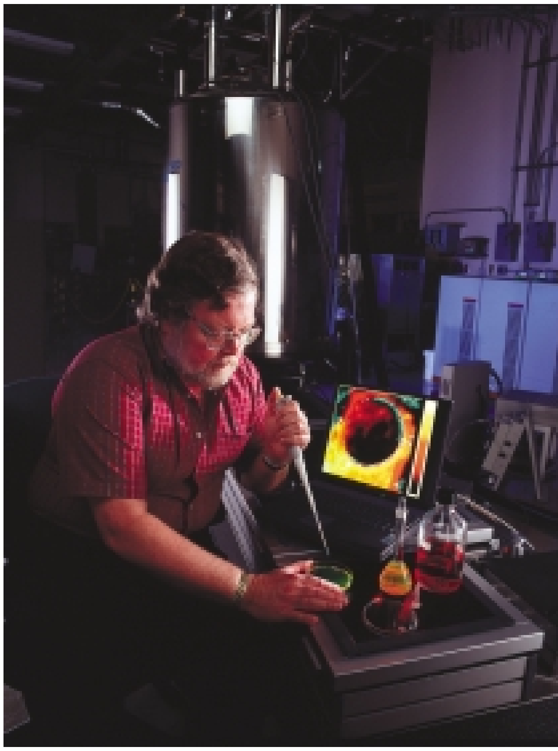
7.3 Strengthen national laboratory, university, and industry partnerships to work on the science challenges facing our Nation.

The Office of Science manages 10 DOE national laboratories, home to many of the premier scientists and facilities the United States has to offer, and makes direct investments in over 280 universities located across the Nation through research grants and other activities. We also work with high-technology companies, such as General Motors and Cray, to explore advanced technologies and solutions that quickly find their way into the marketplace. As one of the few organizations in the world that manages such a diverse portfolio of research performers, the Office of Science has a unique opportunity to bring the power of these research teams to work at the extreme frontiers of science.

Researchers at the national laboratories will benefit from these partnerships through increased access to scientific talent and capabilities that are only found in universities, while universities will benefit through greater training opportunities for students, access to scientific tools unavailable at universities, and participation in multidisciplinary teams of researchers. Industry, increasingly, is seeing the benefit of tapping into the Federal government's deep reservoir of scientific resources to maintain U.S. economic competitiveness.

In addition, the Office of Science works closely with other Federal agencies and major DOE applied research programs to fully leverage the Federal investment in science. We work with the National Institutes of Health to develop new medical technologies; with NASA to explore the cosmos; with the National Science Foundation on fundamental physics, advanced computation, and nanoscience; and with other DOE programs to develop new energy options and solutions. Overall, key scientific disciplines will be strengthened through this interchange of people and ideas.

We recognize that the very nature of science and the exchange of ideas within the scientific community benefits greatly from open communications and collaborations. In the future, it will be necessary to preserve and protect the openness and



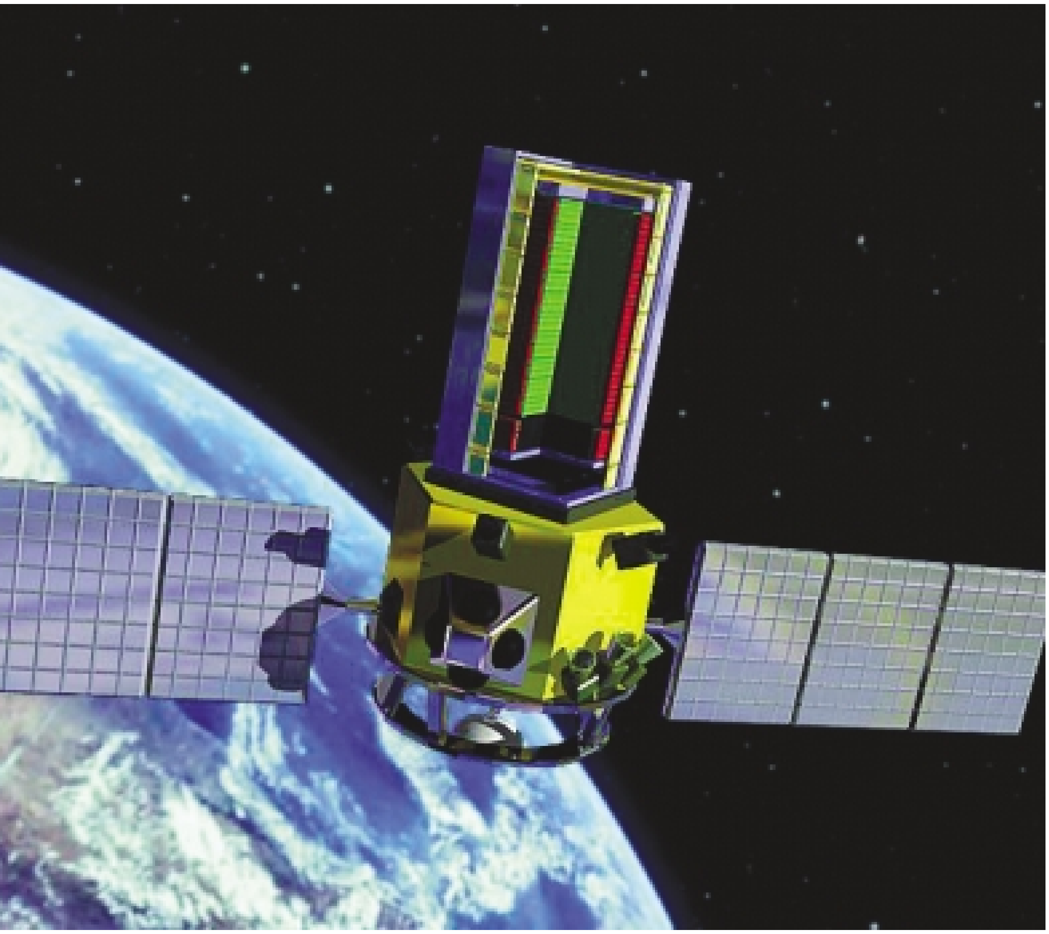
PNNL

Partnership for a new science imaging technology: Scientists from the Pacific Northwest National Laboratory and the Massachusetts Institute of Technology developed a system that images "live" cellular systems using both optical microscopy and nuclear magnetic resonance (NMR) microscopy. The NMR image works like a magnetic resonance imaging unit at a modern hospital, except that it examines down to a single cell and its nucleus. This noninvasive technique will enable scientists to monitor how live cells respond as they are exposed to environmental changes, such as heat, chemicals, and radiation. Scientists will also be able to see what happens when cells are exposed to multiple contaminants at the same time, and ultimately, to relate these responses to large-scale efforts.

strength of our scientific institutions, while at the same time exercising greater control of the free dissemination of scientific information that has important national security implications. This delicate balance will be developed carefully and in consultation with the science community to ensure that a "do no harm" philosophy is followed.

Our strategy includes the following emphases:

- Encourage the creation of partnerships among national laboratory, university, and industrial researchers to tackle major multidisciplinary scientific challenges, such as development of new materials through nanoscience and high-end computational simulation.
- Expand access and operating time at key scientific user facilities to enable national partnerships that address significant national challenges.
- Strengthen relationships with minority institutions to increase the diversity of science and performers available within the U.S. scientific enterprise.
- Establish high-speed information connections among teams of researchers located at diverse locations, while improving remote access to scientific user facilities.
- Strengthen ties between our science programs and DOE-led national initiatives in nuclear energy, hydrogen fuel, bio-based fuels, climate change, carbon management, and nonproliferation through sustained, coordinated programs.
- Foster cooperation among Federal science agencies to enhance the impact and benefit of our jointly held assets, particularly in emerging areas of national need, such as advanced computation, nanoscience, climate change, and genomics.
- Build international partnerships where national resources can achieve global benefits and gain leverage from participation of collaborating nations.



The Gamma-Ray Large Area Space Telescope (GLAST): NASA and DOE's Office of Science are teaming to bring the astrophysics and particle physics communities together to map the high-energy gamma ray sky. These gamma rays come from sources like active galactic nuclei, supernovae remnants, black holes, and neutron stars. GLAST can also search for dark matter candidate particles and other high mass relics from the early universe. Launch is expected in 2006.

- Participate in the development of national policies for the sharing of scientific and technical information, achieving a careful balance between the need for scientific openness and security interests.

7.4 Manage the Office of Science's research enterprise to the highest standards, delivering outstanding science and new discoveries that improve our Nation's health and economy.

Extraordinary discoveries depend strongly on the extraordinary management of the Nation's science enterprise. Our management agenda is designed to ensure that the national scientific enterprise benefits as broadly and fully as possible from the decisions we make and the work we do. This means carefully managing not only the science we produce, but also the institutions and other resources that support our science programs.

The Office of Science has a large workforce, a national scientific enterprise that spans state and national borders, and five decades of experience managing national scientific programs. We manage an annual budget comparable to the gross domestic product of many countries. Our national laboratory complex has no peer in the world in the size and diversity of its research. We sponsor research at universities and other institutions throughout the country. Our research programs have been very successful, yielding major advances in human knowledge, with substantial benefits to the Nation's economy.

The outstanding success of our research hinges on two key principles:

1) *Long-term strategic investments in people, partnerships, and high-risk research:* The Office of Science takes big scientific risks and expects

Integrated Management in the Office of Science

The Office of Science's integrated management philosophy can be summed up as follows:

"Anticipate and manage the full range of issues that affect our ability to deliver excellent science and scientific services to the Nation."

Operationally, this means that we ensure that all of the non-research activities at the 10 DOE Office of Science national laboratories are managed to the highest standards of efficiency, safety, and productivity. In this way, we know that all available resources are focused on our primary goal—delivering great science that supports DOE's missions and enables our Nation to meet major national challenges.

We are adopting a comprehensive approach to integrated management that builds on the success of a major initiative in the late 1990s that integrated safety management practices into all facets of work planning and execution at our national laboratories. This included business practices, infrastructure, maintenance, safeguards and security, safety, and stakeholder relations.

We will expand upon our past successes by integrating all other aspects of operations into our scientific programs at the laboratories. A good example of how this is already being done is through contract performance measures. Our laboratory contractors are evaluated annually for their management of science and operational programs. Their performance in these areas, taken together, determines the overall performance rating they receive from the Office of Science.

We are now exploring which management systems, if any, need to change; where integration should take place; and what level of integration is required. Major initiatives underway that will lead to a full implementation of integrated management within the Office of Science include restructuring, strategic planning, a Model Contract Initiative, contractor self-assessment programs, and development of better performance metrics.

SLAC

State-of-the-art instrumentation critical for great science: Technicians manufacture complex copper structures for use as accelerator components that operate under high electric fields and high vacuum conditions. These components must be fabricated in state-of-the-art facilities, requiring the modern infrastructure and corresponding work environment that leads to high precision equipment, and ultimately, to great science. These copper structures are intended for use in the two-mile-long linear accelerator (linac) at the Stanford Linear Accelerator Center, a premier user facility available to scientists worldwide. The linac contains over 80,000 copper discs and cylinders that must be brazed together.

and achieves high payoffs. We make long-term investments in people and research programs, while responding with agility to rapid changes at the frontiers of science. We balance our support for big science and interdisciplinary teams with a broad portfolio of projects conducted by leading university and laboratory investigators and collaborative groups. Underpinning these efforts is an uncompromising commitment to scientific excellence and integrity. We are in the business of discovery and, therefore, we value bright minds and new ideas as much as efficiency and productivity.

2) *Systematic assessment of major projects, programs, and institutions:* Every research activity that we support with U.S. taxpayer dollars is assessed to ensure that the quality, relevance, and performance of DOE Office of Science programs meet the highest standards. Each major construction project, all of our scientific user facilities and national laboratories, and significant elements of each Office of Science research portfolio are reviewed regularly according to established procedures, frequently with the help of external experts to ensure that we achieve our goals.

Consistent with these two principles, we have adopted two distinct kinds of management practices. First, we invest in people and institutions, so we follow established business practices such as integrated safety management that would be recognized by any U.S. corporate executive as current and effective.

Second, we sponsor basic research, which requires an entirely different set of management practices designed to ensure that the best scientific opportunities are pursued. These practices include the extensive use of peer and merit review to monitor the quality and relevance of the science we sponsor; a reliance on the advice and guidance of the U.S. scientific community through six independent advisory committees; and the employment of highly skilled program managers who nurture critical scientific disciplines and provide the multi-year continuity of support that is often needed to meet difficult technical challenges. These practices help ensure that the U.S. taxpayer receives the highest possible return on the science investment that our Nation makes.

The intersection between traditional management practices and those that are unique to the scientific community is clearest in the way that we construct and operate the large discovery-class scientific user facilities that are a signature feature of the Office of Science. Constructing scientific facilities pushes the envelope of science and technology to the frontiers, and they are considered huge engineering projects by any standard.

Improve our overall performance.

The Office of Science is committed to performance. We have embarked on a comprehensive restructuring of our organization that is designed to increase performance-based management practices, reduce management layering, enhance integration, guarantee line accountability, simplify internal processes, and increase worker productivity. All of these management strategies, however, are being carefully implemented to reflect the unique nature of basic research and the long-term nature of our investments. Our strategy includes the following emphases:

- Consolidate and streamline financial, budgetary, procurement, personnel, program, and performance information to communicate faster and at less cost.
- Use new information management technologies to streamline project funding, facilitate a portfolio view of R&D, and enhance communication across Federal offices and organizations.
- Re-engineer laboratory management contracts to improve contractor performance, enhance line management accountability, and give the Office of Science and its contractors the flexibility needed to manage for results.
- Develop an integrated approach to planning, program execution, and performance management that sets the benchmark for a Federal basic research organization.
- Employ a highly competent Federal workforce capable of continuing the Office of Science's tradition of discovery into the future.

Establish a modern laboratory system, fully capable of delivering the science our Nation requires.

The DOE Office of Science laboratory system includes hundreds of research labs, offices, and specialized scientific facilities distributed over eight states and accessed by more than 25,000 scientists worldwide. The loss to the science community would be immense if we stopped upgrading, operating, and providing access to this incredible research complex. However, 24% of the buildings in the Office of Science laboratory system have reached or are reaching the end of their serviceable lives.

In addition to making targeted investments that maximize our rehabilitation efforts, our strategy includes examining our total portfolio of facilities and seeking to expand their utility. Our strategy includes the following emphases:

- Size our facilities to scientific demand, including investing in new replacement support facilities where needed and removing excess facilities.
- Increase our annual laboratory maintenance investment to a level consistent with nationally recognized standards (i.e., generally 2 to 4% for conventional facilities).
- Increase the overall functionality of general-purpose facilities by significantly increasing our annual capital investment.
- Support greater flexibility in the use of funds for maintenance and modernization.

Appendix A

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Appendix B

Our Presence—Map Details (for more information, go to www.science.doe.gov)

DOE National Laboratories [Blue dots]

Office of Science [10]

1. Ames Laboratory (Ames)
2. Argonne National Laboratory (ANL)
3. Brookhaven National Laboratory (BNL)
4. Fermi National Accelerator Laboratory (FNAL or FermiLab)
5. Lawrence Berkeley National Laboratory (LBNL)
6. Thomas Jefferson National Accelerator Facility (TJNAL)
7. Oak Ridge National Laboratory (ORNL)
8. Pacific Northwest National Laboratory (PNNL)
9. Princeton Plasma Physics Laboratory (PPPL)
10. Stanford Linear Accelerator Center (SLAC)

DOE National Laboratories (other Offices) [11]

1. Environmental Measurements Laboratory (EML)
2. Idaho National Engineering and Environmental Laboratory (INEEL)
3. Knolls Atomic Power Laboratory (KAPL)
4. Lawrence Livermore National Laboratory (LLNL)
5. Los Alamos National Laboratory (LANL)
6. National Energy Technology Laboratory (NETL)
7. National Renewable Energy Laboratory (NREL)
8. New Brunswick Laboratory (NBL)
9. Radiological & Environmental Sciences Laboratory (RESL)
10. Sandia National Laboratories (SNL)
11. Savannah River Site (SRS)

Office of Science User Facilities [41] [Orange dots]

1. Atmospheric Radiation Measurement Program (ARM), North Slope of Alaska - SNL, Barrow, AK
2. Advanced Light Source (ALS) - LBNL, Berkeley, CA
3. B-Factory - SLAC, Stanford, CA
4. Combustion Research Facility (CRF) - SNL, Livermore, CA
5. DIII-D (General Atomics), San Diego, CA
6. Energy Sciences Network (ESnet) - LBNL, Berkeley, CA
7. Joint Genome Institute (JGI) - LANL, LBNL, LLNL, ORNL, PNNL, Walnut Creek, CA
8. Linac Coherent Light Source (LCLS) - SLAC, Stanford, CA
9. Molecular Foundry - LBNL, Berkeley, CA
10. National Center for Electron Microscopy (NCEM) - LBNL, Berkeley, CA
11. National Energy Research Scientific Computing Center (NERSC)- LBNL, Berkeley, CA
12. Stanford Synchrotron Radiation Laboratory (SSRL) - SLAC, Stanford, CA
13. Advanced Photon Source (APS) - ANL, Argonne, IL
14. Argonne Tandem Linac Accelerator System (ATLAS) - ANL , Argonne, IL
15. BTeV - FNAL, Chicago, IL
16. Center for Microanalysis of Materials at University of Illinois (CMM), Urbana-Champaign, Urbana, IL
17. Center for Nanoscale Materials (CNM) - ANL, Argonne, IL

18. Electron Microscopy Center for Materials Research (EMCMR) - ANL, Argonne, IL
19. Intense Pulsed Neutron Source (IPNS) - ANL, Argonne, IL
20. Neutrinos at Fermilab's Main Injector/Main Injector Neutrino Oscillation Search (NuMI/MINOS) - FNAL, Chicago, IL
21. Tevatron - FNAL, Chicago, IL
22. Pulse Radiolysis Facility - University of Notre Dame, Notre Dame, IN
23. Materials Preparation Center (MPC) - Ames, Ames, IA
24. Bates Linear Accelerator Center (MIT), Middleton, MA
25. National Spherical Torus Experiment (NSTX) - PPPL, Princeton, NJ
26. Manuel Lujan Jr. Neutron Scattering Center (Lujan Center) - LANL, Los Alamos, NM
27. Center for Functional Nanomaterials (CFN) - BNL, Upton, NY
28. National Synchrotron Light Source (NSLS) - BNL, Upton, NY
29. Relativistic Heavy Ion Collider (RHIC) - BNL, Upton, NY
30. Atmospheric Radiation Measurement Program (ARM), Southern Great Plains - ANL, Lamont, OK
31. Atmospheric Radiation Measurement Program Archive (ARM), Oak Ridge, TN
32. Center for Nanophase Materials Sciences (CNMS) - ORNL, Oak Ridge, TN
33. High Flux Isotope Reactor (HFIR), Oak Ridge, TN
34. Holifield Radioactive Ion Beam Facility (HRIBF) - ORNL, Oak Ridge, TN
35. Laboratory for Comparative and Functional Genomics - ORNL, Oak Ridge, TN
36. Shared Research Equipment (SHaRE) - ORNL, Oak Ridge, TN
37. Spallation Neutron Source (SNS) - ORNL, Oak Ridge, TN
38. Continuos Electron Beam Accelerator Facility (CEBAF), TJNAF, Newport News, VA
39. Environmental Molecular Sciences Laboratory (EMSL) - PNNL, Richland, WA
40. Free Air CO_2 Enrichment Research Facility (FACE), (ORNL, Rhinelander, WI, Nevada Test Site)
41. Atmospheric Radiation Measurement Program Archive (ARM) Tropical Western Pacific- LANL, (Manus Province, Papua New Guinea; Darwin, Australia, and Republic of Nauru)
42. Center for Integrated Nanotechnologies (CINT) - SNL AND LANL, Albuquerque and Los Alamos, NM

Office of Science University Research User Facilities [27] [Green dots]

Field Research Centers to study ecosystem responses to changes in atmospheric chemistry [4]

1. San Diego State University, San Diego, CA
2. Michigan Technological University, Houghton, MI
3. University of Nevada, Reno, NV
4. Duke University, Durham, NC

Field Research Centers to study ecosystem atmosphere exchanges of CO_2 [17]

1. University of California at Berkeley, Berkeley, CA
2. University of California at Davis, Davis, CA
3. University of California at Irvine, Irvine, CA
4. University of Colorado at Boulder, Boulder, CO
5. Yale University, New Haven, CT
6. Smithsonian Institution, Washington, DC
7. University of Florida, Gainesville, FL
8. Indiana University, Bloomington, IN
9. Pulse Radiolysis Facility (Notre Dame), Notre Dame, IN
10. Kansas State University, Manhattan, KS
11. University of Maine, Orono, ME
12. Harvard University, Cambridge, MA
13. University of Michigan, Anne Arbor, MI
14. University of Minnesota, Minneapolis, MN

15. University of Nebraska, Lincoln, NE
16. Duke University, Durham, NC
17. Oregon State University, Corvallis, OR

Nuclear Physics Program University Facilities [4]

1. AW Wright Nuclear Structure Laboratory (Yale University), New Haven, CT
2. Triangle University Nuclear Laboratory (Duke University, Carolina State University, University of North Carolina), Durham, NC
3. Cyclotron Institute (Texas A&M University), College Station, TX
4. Center for Nuclear Physics and Astrophysics (University of Washington), Seattle, WA

Basic Energy Sciences and Fusion Energy Sciences Program Facilities [2]

1. James McDonald Laboratory (Kansas State University) Manhattan, KS
2. Alcator C-Mod (Massachusetts Institute of Technology) Cambridge, MA

Office of Science University-Based Research [283] [Yellow dots]

1. University of Alaska, Fairbanks, AK
2. Alabama A&M University, Normal, AL
3. Auburn University, Auburn, AL
4. Spring Hill College, Mobile, AL
5. University of Alabama at Birmingham, AL
6. University of Alabama at Tuscaloosa, AL
7. University of South Alabama, Mobile, AL
8. University of Arkansas, Fayetteville, AR
9. University of Arkansas, Little Rock, AR
10. Arizona State University, Tempe, AZ
11. University of Arizona, Tucson, AZ
12. California Institute of Technology, Pasadena, CA
13. California State University Fullerton, CA
14. California State University Northridge, CA
15. California State University, Los Angeles, CA
16. Keck Graduate Institute, Claremont, CA
17. Loma Linda University, Loma Linda, CA
18. San Diego State University, San Diego, CA
19. San Francisco Sate University, San Francisco, CA
20. San Jose State University Foundation, San Jose, CA
21. Society For Molecular Imaging, Stanford, CA
22. Stanford University, Stanford, CA
23. University of California at Berkeley, CA
24. University of California at Davis, CA
25. University of California at Irvine, CA
26. University of California at Los Angeles, CA
27. University of California at Oakland, CA
28. University of California at Riverside, CA
29. University of California at San Diego, La Jolla, CA
30. University of California at San Francisco, CA
31. University of California at Santa Barbara, CA
32. University of California at Santa Cruz, CA
33. University of Southern California, Los Angeles, CA
34. Colorado School of Mines, Golden, CO
35. Colorado State University, Fort Collins, CO

36. University of Colorado, Boulder, CO
37. Fairfield University, Fairfield, CT
38. University of Connecticut, Storrs, CT
39. Yale University, New Haven, CT
40. American University, Washington, DC
41. Catholic University of America, Washington, DC
42. George Washington University, Washington, DC
43. Georgetown University, Washington, DC
44. Howard University, Washington, DC
45. Bartol Research Institute University of Delaware, Newark, DE
46. University of Delaware at Lewes, DE
47. University of Delaware at Newark, DE
48. Florida A&M University, Tallahassee, FL
49. Florida Atlantic University, Boca Raton, FL
50. Florida International University, Miami, FL
51. Florida State University, Tallahassee, FL
52. Rollins College, Winter Park, FL
53. University of Central Florida, Orlando, FL
54. University of Florida, Gainesville, FL
55. University of Miami, Miami, FL
56. University of South Florida at St. Petersburg, FL
57. University of South Florida at Tampa, FL
58. Clark Atlanta University, Atlanta, GA
59. Emory University, Atlanta, GA
60. Georgia State University, Atlanta, GA
61. Georgia Tech Research Corporation, Atlanta, GA
62. Medical College of Georgia, Augusta, GA
63. Morehouse College, Atlanta, GA
64. North Georgia College & State University, Dahlonega, GA
65. University of Georgia, Athens, GA
66. University of Hawaii, Honolulu, HI
67. Iowa State University at Ames, IA
68. Iowa State University at Iowa City, IA
69. University of Idaho, Moscow, ID
70. Illinois Institute of Technology, Chicago, IL
71. Northern Illinois University, DeKalb, IL
72. Northwestern University, Evanston, IL
73. Southern Illinois University, Carbondale, IL
74. University of Chicago, Chicago, IL
75. University of Illinois at Chicago, IL
76. University of Illinois at Urbana-Champaign, Champaign, IL
77. University of Illinois at Urbana-Champaign, Urbana, IL
78. Indiana University, Bloomington, IN
79. Purdue Research Foundation, West Lafayette, IN
80. University of Notre Dame, Notre Dame, IN
81. Valparaiso University, Valparaiso, IN
82. Kansas State University, Manhattan, KS
83. University of Kansas, Lawrence, KS
84. Wichita State University, Wichita, KS

85. University of Kentucky, Lexington, KY
86. University of Louisville, Louisville, KY
87. Louisiana State University at Baton Rouge, LA
88. Louisiana State University at New Orleans, LA
89. Louisiana Tech University at Ruston, LA
90. Southeastern Louisiana University, Hammond, LA
91. Southern University & A&M College, Baton Rouge, LA
92. Southern University, Baton Rouge, LA
93. Tulane University, New Orleans, LA
94. University of New Orleans, New Orleans, LA
95. University of Southwestern Louisiana, Lafayette, LA
96. Xavier University, New Orleans, LA
97. Boston College, Chestnut Hill, MA
98. Boston University, Boston, MA
99. Brandeis University, Waltham, MA
100. Clark University, Worcester, MA
101. Hampshire College at Amherst, MA
102. Harvard College at Cambridge, MA
103. Harvard Medical School, Boston, MA
104. Harvard University, Cambridge, MA
105. Massachusetts Institute of Technology, Cambridge, MA
106. Merrimack College, North Andover, MA
107. Mount Holyoke College, South Hadley, MA
108. Northeastern University, Boston, MA
109. Smith College, Northampton, MA
110. Tufts University at Boston, MA
111. Tufts University at Medford, MA
112. University of Massachusetts at Amherst, MA
113. University of Massachusetts at Boston, MA
114. University of Massachusetts at Lowell, MA
115. University of Massachusetts-Dartmouth, North Dartmouth, MA
116. Worcester Polytechnic Institute, Worcester, MA
117. Johns Hopkins University, Baltimore, MD
118. Morgan State University, Baltimore, MD
119. University of Maryland at Baltimore, MD
120. University of Maryland at College Park, MD
121. University of Maryland Baltimore County, Baltimore, MD
122. University of Maryland Biotechnology Institute, Baltimore, MD
123. University of Maine, Orono, ME
124. Michigan State University, East Lansing, MI
125. Michigan Technological University, Houghton, MI
126. University of Michigan, Ann Arbor, MI
127. Wayne State University, Detroit, MI
128. Western Michigan University, Kalamazoo, MI
129. University of Minnesota at Duluth, MN
130. University of Minnesota at Minneapolis, MN
131. University of Minnesota, St. Paul, MN
132. University of Missouri at Columbia, MO
133. University of Missouri at Kansas City, MO
134. University of Missouri at Rolla, MO

135. Washington University, St. Louis, MO
136. Jackson State University, Jackson, MS
137. Mississippi State University, Mississippi State, MS
138. University of Mississippi, University, MS
139. Montana State University, Bozeman, MT
140. University of Montana, Missoula, MT
141. Duke University Medical Center, Durham, NC
142. Duke University, Durham, NC
143. East Carolina University, Greenville, NC
144. Elizabeth City State University, Elizabeth City, NC
145. Fayetteville State University, Fayetteville, NC
146. North Carolina Central University, Durham, NC
147. North Carolina State University, Raleigh, NC
148. University of North Carolina, Chapel Hill, NC
149. North Dakota State University, Fargo, ND
150. University of North Dakota, Grand Forks, ND
151. Creighton University, Omaha, NE
152. University of Nebraska at Lincoln, NE
153. University of Nebraska at Omaha, NE
154. Dartmouth College, Hanover, NH
155. University of New Hampshire, Durham, NH
156. Institute for Advanced Study, Princeton, NJ
157. New Jersey Institute of Technology, Newark, NJ
158. Princeton University, Princeton, NJ
159. Rutgers-State University of New Jersey at New Brunswick, NJ
160. Rutgers-State University of New Jersey at Piscataway, NJ
161. Stevens Institute of Technology, Hoboken, NJ
162. University of Medicine and Dentistry of New Jersey at Newark, NJ
163. University of Medicine and Dentistry of New Jersey at Piscataway, NJ
164. Mind Institute-Mental Illness & Neuroscience Discovery, Albuquerque, NM
165. New Mexico Highlands University, Las Vegas, NM
166. New Mexico Institution of Mining & Technology, Socorro, NM
167. New Mexico State University, Las Cruces, NM
168. University of New Mexico School of Law, Albuquerque, NM
169. University of New Mexico, Albuquerque, NM
170. University of Nevada at Las Vegas, NV
171. University of Nevada at Reno, NV
172. Albert Einstein College of Medicine, Bronx, NY
173. Alfred University, Alfred, NY
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175. City University of New York, New York, NY
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179. Hunter College of City University of New York, New York, NY
180. Lehman College of City University of New York, New York, NY
181. New York University Medical Center, New York, NY
182. New York University, New York, NY
183. Pace University, New York, NY

184. Rensselaer Polytechnic Institute, Troy, NY
185. Rochester Inst. of Technology, Rochester, NY
186. Rockefeller University, New York, NY
187. State University of New York at Albany, NY
188. State University of New York at Binghamton, NY
189. State University of New York at Buffalo, NY
190. State University of New York at Old Westbury, Albany, NY
191. State University of New York at Stony Brook, NY
192. State University of New York, Syracuse, NY
193. Syracuse University, Syracuse, NY
194. University of Rochester, Rochester, NY
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197. Miami University, Oxford, OH
198. Ohio State University Research Foundation, Columbus, OH
199. Ohio University, Athens, OH
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254. University of Texas at Austin, TX
255. University of Texas at Dallas, TX
256. University of Texas at Richardson, TX
257. University of Texas at San Antonio, TX
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259. University of Texas of MD Anderson Cancer Center, Houston, TX
260. Brigham Young University, Provo, UT
261. University of Utah, Salt Lake City, UT
262. Utah State University, Logan, UT
263. College of William and Mary, Williamsburg, VA
264. George Mason University, Fairfax, VA
265. Hampton University, Hampton, VA
266. Norfolk State University, Norfolk, VA
267. Old Dominion University, Norfolk, VA
268. University of Richmond, Richmond, VA
269. University of Virginia, Charlottesville, VA
270. Virginia Commonwealth University, Richmond, VA
271. Virginia Institute of Marine Science, Gloucester Point, VA
272. Virginia Polytechnic Institute and State University, Blacksburg, VA
273. University of Vermont, Burlington, VT
274. Gonzaga University, Spokane, WA
275. University of Washington, Seattle, WA
276. Washington State University, Pullman, WA
277. Lawrence University, Appleton, WI
278. Marquette University, Milwaukee, WI
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Office of Science
U.S. DEPARTMENT OF ENERGY

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