PHYSICS IN A NEW ERA

If physics is to flourish at the threshold of the 21st century, the physics community must respond to the needs of a rapidly changing society.

Thomas Appelquist and Donald Shapero

Physics has entered a new era of expanding opportunities and is having an increasing impact on science, technology, and the national economy. So concluded the National Research Council's Physics Survey Overview Committee (PSOC) after reviewing the NRC's most recent decadal survey of physics.

The NRC published its previous decadal survey, *Physics through the 1990s*, in 1986. In the early 1990s, the Board on Physics and Astronomy continued the NRC's tradition of periodically reviewing physics by initiating a new survey. In this new survey, volumes on the various branches of physics were to be completed serially. The first such volume was completed in 1994 and the last in 1999. The series was dubbed *Physics in a New Era*.

As the last volumes were being completed, the NRC appointed the PSOC, whose members are listed in the box on page 35. The PSOC held its first meeting in February 1999. It consulted widely within the international physics community and among scientific and academic leaders throughout the US. Experts chosen by the NRC reviewed the committee's work.

In June 2001, the National Academy Press published the PSOC's report, entitled *Physics in a New Era: An Overview*. The *Overview* assessed the overall state of physics, identified six research areas of especially high priority, and offered nine specific recommendations collectively designed not only to strengthen physics in the US, but also to solidify the ability of physicists to serve important national needs.

A new era for physics

The advances and breakthroughs of 20th-century physics have enriched all the sciences and opened a new era of discovery. They have touched nearly every part of our society, from health care to national security to our understanding of Earth's environment. They have led us into the information age and fueled broad technological and economic development. The pace of discovery in physics has quickened over the past two decades. New instruments of great sensitivity and reach are being created and used, and new microscopic devices are being developed with a host of applications. Stronger links are being formed across sciences, in particular with the biological sciences.

Physics is becoming a thoroughly global enterprise. This transformation reflects the increasing need for facilities too large, complex, and expensive for any single nation to build, and is largely a consequence of modern information technology, the heart of our present age of change.

We are in the midst of an information revolution that, we believe, is every bit as profound as the two great technological revolutions of the past—the agricultural and industrial revolutions. Information technology, drawing on several fields of physics, is transforming society and changing the economy. The World Wide Web, originally intended as a global coordination tool for high-energy physics, is now a pervasive communication tool, reshaping education and commerce. Information technology revenues are estimated to account for 5–15% of the US gross domestic product (GDP), and 40% of US industry's capital spending today is for information technology.

The tools of physics continue to grow in power and breadth of application. Synchrotron light sources developed by accelerator physicists originally for condensed-matter physics studies are now in great demand for structural biology research. The next generation of particle colliders will reveal the new, unknown physics of the TeV scale. Much better computer hardware and architectures combined with improved modeling techniques have enabled, for example, the simulation of turbulent plasmas in tokamaks and the modeling of atmospheric dynamics. At the microscopic scale, ion traps and atomic cooling techniques enable the creation of ensembles of atoms so free of thermal agitation that quantum mechanics takes over to create atomic Bose–Einstein condensates. Atomic-force microscopes make it possible to map the surface of materials atom by atom. Condensed matter physicists have begun to shrink the materials they study to sizes in which discrete quantum excitations play a central role. A second quantum revolution is under way, bringing condensed matter and atomic physics together at the nanoscale.

The intellectual reach of physics has never been greater, and the questions being asked are more ambitious than ever. High-energy physicists are proposing attractive mechanisms to generate the masses of elementary particles and ways to test these mechanisms experimentally. Many of their ideas have been drawn from condensed matter physics, where those same ideas are applied to deep problems such as the understanding of high-temperature superconductors. Cosmologists are making great progress in understanding the birth of the universe and in testing their theories with detailed measurements of the cosmic microwave background radiation and the abundance of primordial elements. String theorists are developing a framework in which elementary-particle physics and gravitational physics may be joined in a "theory of everything."

With increasing frequency, though, the work of physicists cannot be considered as being confined to one subfield of physics, or even within the discipline of physics. As mentioned earlier, condensed matter and atomic physicists have found common ground. The questions posed in cosmology bring astronomy and physics together. For example, the inflation that explains the homogeneity of the early universe may have been driven by the same kind of field that confers mass on elementary particles.

Understanding the molecular machines that govern

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IBM RESEARCH

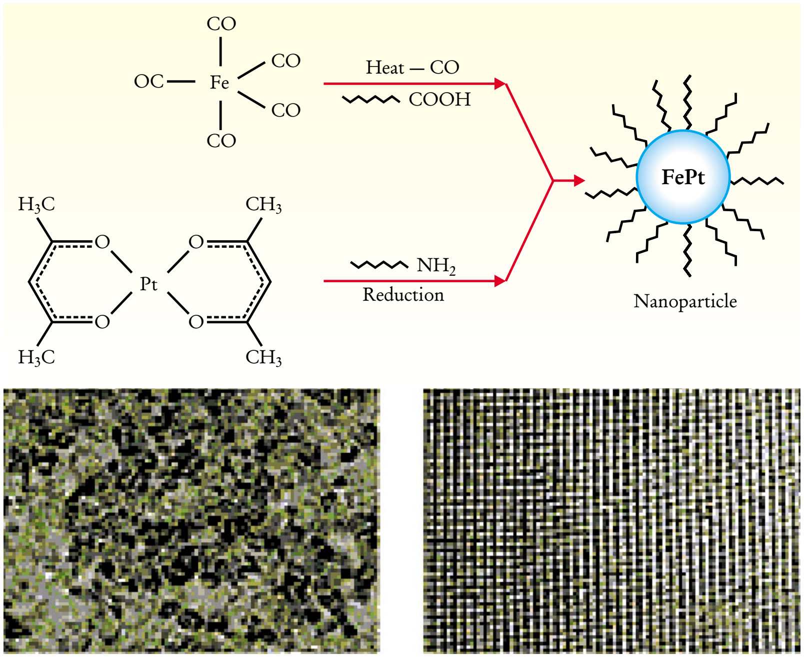

FIGURE 1. NANOSCALE BUILDING blocks may be organized into structures with novel optical, electronic, or magnetic properties. The lower right panel shows a FePt superlattice in which each nanocrystal is 4 nm in diameter. Compare this lattice with the state-of-the-art CoPtCrB magnetic recording medium shown at the same magnification in the lower left panel. The smaller, more uniform grains of the FePt system will enable more detailed studies of the limits of magnetic recording and the production of ultrahigh-density recording media. The schematic above the panels shows the combination of organoplatinum, iron carbonyl, and surfactant species used in the production of the FePt nanocrystals.

life processes brings biology, chemistry, and physics together. Powerful techniques such as optical tweezers enable scientists to measure the spring constant of DNA molecules. Physics, chemistry, mathematics, and computer science have provided new discoveries about life processes and fueled a host of new insights that have helped contribute to the "big bang" of progress now being enjoyed by the life sciences.

One of the great challenges for the life sciences is decoding the human genome and understanding how living cells compile that code into the stuff and processes of life. Leading biologists such as Harold Varmus, former director of the National Institutes of Health, have pointed out that the physical science underpinnings of biology must continue to develop if this challenge is to be met.

Society's needs

The profound nature of the developments just discussed inspired the title *Physics in a New Era* for the NRC survey series. The title was meant to suggest not only that physics itself has reached new levels of accomplishment and impact, but also that the wider society in which the physics community functions is rapidly changing. For physics to flourish and enter the new era with renewed vigor, the physics community must be sensitive to these changes and respond effectively to society's needs, in particular the needs for a scientifically literate populace and for a strong defense.

Understanding the basics of the physical sciences is becoming ever more important to the average citizen. Issues ranging from how much one is willing to pay for an energy-efficient air conditioner to legislation concerning nuclear power plants routinely confront the public. Almost all technology is based on scientific principles, and providing people with appropriate levels of scientific literacy and technical knowledge is one of the most important missions of the physics community. Higher education in physics is essential for developing an outstanding technical workforce, and continued progress in adapting higher education to this need will pay great dividends. More than ever, the physics community is now mobilizing to improve undergraduate physics education.

The defense posture of the US is in a period of evolution, given extra urgency by the events of 11 September 2001. Reconnaissance, new forms of cryptography, the aging of the nuclear stockpile, communications electronics, counterterrorism, and ballistic missile defense are now among the most important concerns of the partnership between the government and the physics community. (See the special issue of PHYSICS TODAY devoted to national security, December 2000.)

Physicists are directly involved in defense technologies such as laser guidance and satellite technology. They also indirectly contribute to defense through the many areas of basic research that underpin modern materials, electronics, and sensing systems. Scientists engaged in basic research also play a crucial role in evaluating new

Membership of the Physics Survey Overview Committee

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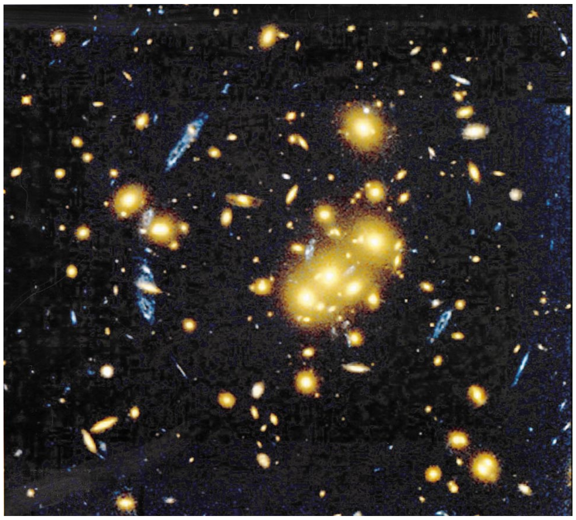


FIGURE 2. DARK MATTER warps the space-time around it, and so images of galaxies surrounding dark matter concentrations are distorted. Here, the distortion is manifested by the fact that the galaxies (light blue) are not oriented randomly, but rather appear reminiscent of compass needles in the vicinity of a current-carrying wire. Images such as this may be analyzed to reconstruct a map of the mass distribution of the dark matter over large areas on the sky. This distribution can provide insight as to the nature of the dark matter. (Courtesy of J. Anthony Tyson, Bell Labs, Lucent Technologies; Wesley N. Colley, Harvard–Smithsonian Center for Astrophysics; and Edwin L. Turner, Princeton University and NASA.)

threats and opportunities arising from technical advances. Both in Department of Defense (DOD) research and in Department of Energy (DOE) laboratories, the traditional emphasis on core competencies and long-term basic research has weakened—this unfortunate development must be reversed.

Priorities and opportunities

The accomplishments of physics, the increasing power of its instruments, and its expanding reach into the other sciences have generated an unprecedented set of scientific opportunities. The PSOC concluded that some are so promising that their pursuit should be a matter of high national priority. It identified six "grand challenges," which range across all of physics and overlap other areas of science and engineering. They are developing quantum technologies, creating new materials, understanding complex systems, unifying the forces of nature, exploring the universe, and applying physics to biology. The choices of these challenges were based on intrinsic scientific importance, potential for broad impact and application, and promise for major progress during the next 10 years. In each of the six areas, recent theoretical advances have opened up new questions and set the stage for further syntheses. And in each case, the promise seen for the near future hinges on the emergence of a new generation of instruments providing great precision, very high energy, or powerful computational capability.

Deep understanding, important applications

The ability to manipulate individual atoms and molecules will lead to new quantum technologies with applications ranging from the development of new materials to the analysis of the human genome. The manipulation of individual atoms with, for example, laser trapping and evaporative cooling, has yielded intriguing Bose–Einstein condensates, a state of matter in which many atoms are in the same quantum mechanical state, with a high probability of spatial overlap and entanglement. In gaseous Bose–Einstein condensates, quantum overlap can sometimes extend over distances very large compared to a single atom. A new generation of technology will be developed, with construction and operation entirely at the quantum level. Extraordinarily sensitive measurement capabilities, quantum computation, quantum cryptography, and quantum-controlled chemistry are likely possibilities.

Novel materials will be discovered, understood, and used widely in science and technology. The discovery of materials such as high-temperature superconductors and new crystalline structures such as the FePt nanocrystals shown in figure 1 has stimulated new theoretical understanding and led to technological applications. Several themes and challenges are apparent: the synthesis, processing, and understanding of complex materials comprising more and more elements; the role of molecular geometry and motion in only one or two dimensions; the incorporation of new materials and structures in existing technologies; the development of new techniques for materials synthesis, in which biological processes such as self-assembly can be mimicked; and the control of a variety of poorly understood, nonequilibrium processes (for example, turbulence, cracking, and adhesion) that affect material properties on scales ranging from the atomic to the macroscopic.

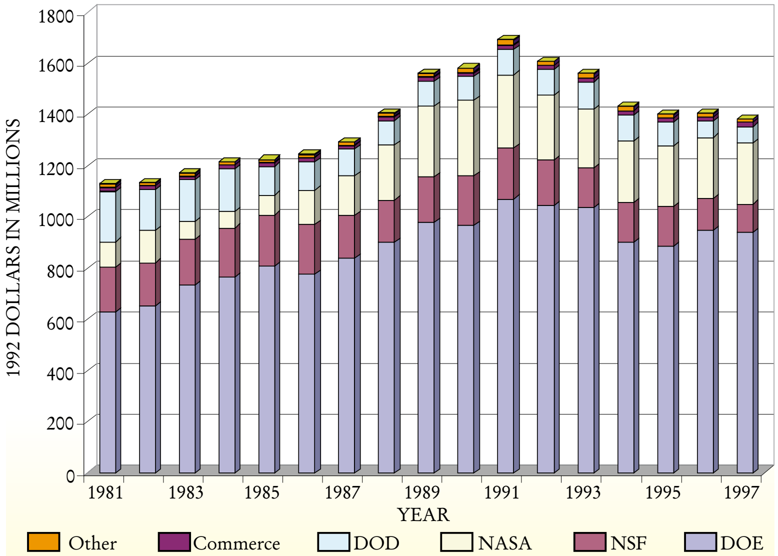
Theoretical advances and large-scale computer modeling will enable phenomena as complicated as the explosive death of stars, the reversing of Earth's magnetic field, and the properties of complex materials to be understood at a depth that, only a few years ago, was unachievable. The rapid advances of massively parallel computing, coupled with equally impressive developments in theoretical analysis, have had an extraordinary impact on our ability to model and predict complex and nonlinear phenomena and to visualize the results. Problems that may soon be rendered tractable include the strong nuclear force, turbulence and other nonlinear phenomena in fluids and plasmas, the origin of large-scale structure in the universe, and a variety of quantum many-body challenges in condensed matter, nuclear, atomic, and biological systems. The study of complex systems is inherently of great breadth: Improved understanding of radiation transport, for example, will advance both astrophysics and cancer therapy.

Rich interplays

Theory and experiment together will provide a new understanding of the basic constituents of matter. The mystery of the nature of elementary particles has deepened in the past 10 years. The extraordinarily heavy top quark was discovered in the mid-1990s, and continuing observations of oscillations in neutrinos from the Sun and the upper atmosphere provide strong evidence that neutrinos have extremely tiny masses. During the next decade, experiments at a new generation of high-energy colliders will begin to reveal the currently unknown physics responsible for elementary-particle masses and various other particle properties. Possibilities range from new, unique elementary particles to fundamental changes in our notions of space and time.

Whatever this new physics may be, its determination

FIGURE 3. FEDERAL OBLIGATIONS in physics, by federal department or agency. Most of the funds labeled "other" come from the Department of Health and Human Services. Data from NSF's *2000 Science and Engineering Indicators*. (Adapted from *Physics in a New Era: An Overview*.)



will be an important step toward the historic goal of discovering a unified theoretical description of all the fundamental forces of Nature—the strong nuclear force, the electroweak forces, and gravity. Quantum chromodynamics has successfully unified the strong and electroweak forces, but so far gravity has resisted being incorporated into a unified framework. The most promising and exciting framework for unifying gravity with the other forces proposes that, at very tiny distances, elementary particles behave not like points, but like higher-dimensional surfaces such as strings or membranes. Theorists working within this framework have created new and vibrant intersections between physics and pure mathematics.

New instruments through which stars, galaxies, dark matter, and the Big Bang can be explored in unprecedented detail will revolutionize our understanding of the universe, including its origin and destiny. The universe itself is now a laboratory for the study of fundamental physics, because its structure and evolution depend in detail on just what constitutes the dark matter and dark energy that make up 95% of its mass-energy. (Figure 2 shows a cluster of galaxies whose images are distorted by intergalactic dark matter.) Continuing measurements will test the foundations of cosmology and help determine the nature of the dark matter and dark energy. Gravitational waves may be directly detected, and the predictions that Einstein's general theory of relativity makes about the structure of black holes may be checked against data for the first time. The origin of the chemical elements, the nature of extremely energetic cosmic accelerators, and many other puzzles will be understood more deeply. The quest to understand the universe has given birth to a rich, new interplay of physics and astronomy.

There's a rich, new interplay between physics and biology too. Ultimately all essential biological mechanisms depend on physical interactions between molecules, so physics lies at the heart of many profound insights into biology. Current challenges include the biophysics of cellular electrical activity underlying the functioning of the nervous, circulatory, and respiratory systems; the biomechanics of the motors responsible for biological movement; and the mechanical and electrical properties of both DNA and the enzymes essential for cell division and cellular processes. In the near future, central problems in biology such as the way molecular chains fold to yield the specific biological properties of proteins will become accessible to analysis through basic physical laws. Tools developed in physics, particularly for the understanding of highly complex systems, are vital for progress in all these areas. Theoretical physics approaches are also important, and are being applied to bioinformatics, biochemical and genetic networks, and computation by the brain.

Recommendations

The PSOC developed a set of nine recommendations designed to strengthen all of physics and to ensure the continued international leadership of the US. Of those recommendations, five address the support of physics by the federal government and the scientific community, physics education, and the role of basic physics research in national security. We quote and discuss these five principal recommendations in detail, and conclude with abbreviated versions of the remaining four recommendations, which focus on the enterprise of physics research.

The federal government must take primary responsibility for the support of basic research in science. This vital research is often too broad and distant from commercial development to be a sensible industrial investment.

The results of basic physics research bear fruit for technology and the economy more rapidly now than they did in the past. Still, 10–20 years is the typical interval between a fundamental physics discovery and its impact on society. Examples that bear this assertion out include the laser, magnetic resonance imaging, and the optical fiber transmission line. Much of today's high-tech economy is being driven by the technology that grew out of physics research in the early 1980s.

Federal support for physics research declined in constant dollars during the 1990s, as seen in figure 3. This decline, coming after the modest growth of the 1980s, means that growth in the past 20 years has averaged only about 2% per year. Figure 4 shows that, relative to the size of the economy as measured by the GDP, federal support has dropped by more than 20% from 1980 to the present. This trend, in the view of the PSOC, has made it more difficult for federal science agencies to support outstanding proposals, which, in turn, has made the field of physics less attractive to the highly skilled professionals it needs. The drop in federal support relative to the size of the economy does not cut across all the sciences: Figure 4 shows that the federal government's support of basic research in the life sciences has grown more rapidly than the GDP during the past 20 years.

Recommendation 1. To allow physics to contribute strongly to areas of national need, the federal government and the physics community

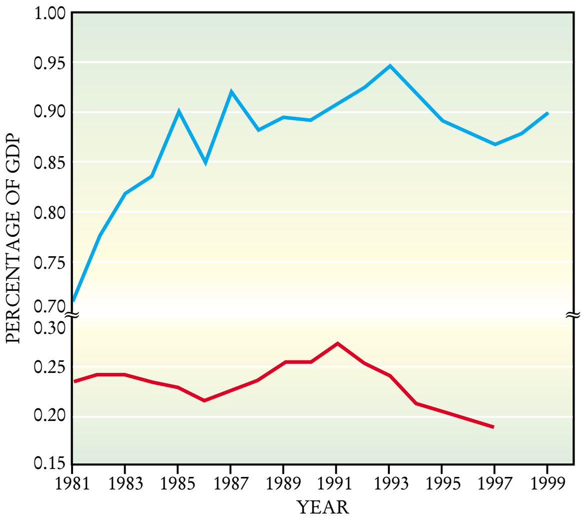


FIGURE 4. FEDERAL FUNDING FOR BASIC RESEARCH in physics (red) and the life sciences (blue) as a percentage of the gross domestic product (GDP). Data from NSF's *2000 Science and Engineering Indicators*. (Adapted from *Physics in a New Era: An Overview*.)

> should develop and implement a strategy for long-term investment in basic physics research. Key considerations in this process should include the overall level of this investment necessary to maintain strong economic growth driven by new physics-based technologies, the needs of other sciences that draw heavily on advances in physics, the expanding scientific opportunities in physics itself, the cost-effectiveness of stable funding for research projects, the characteristic time interval between the investment in basic research and its beneficial impact, and the advantages of diverse funding sources. The Physics Survey Overview Committee believes that to support strong economic growth and provide essential tools and methods for the biomedical sciences in the decade ahead, the federal investment in basic physics research relative to GDP should be restored to the levels of the early 1980s.

A first critical goal for physics education in our high schools and universities must be scientific literacy—a broad knowledge of basic physical principles on the part of the population at large. Another key goal is providing the more extensive understanding of physics that is so important for members of a technical workforce. And students, like those seen in figure 5, must be instilled with an excitement about physics if enough of them are to be drawn into science careers. Physics education, in the view of the PSOC, is failing in all three of these critical roles.

> **Recommendation 2.** Physics departments should review and revise their curricula to ensure that they are engaging and effective for a wide range of students and that they make connections to other important areas of science and technology. The principal goals of this revision should be (1) to make physics education do a better job of contributing to the scientific literacy of the general public and the training of the technical workforce and (2) to reverse, through a better-conceived, more outward-looking curriculum, the long-term decline in the numbers of US undergraduate and graduate students studying physics. Greater emphasis should also be placed on improving the preparation of K–12 science teachers.

Physics departments should take an active role in training science teachers, and administrators should provide departments with adequate release time for this purpose.

Big physics, small physics

A large, diverse, and well-supported program of research by single investigators and small groups is essential for generating important technological advances and new ideas in physics. Discoveries such as nuclear magnetic resonance, the laser, the transistor, and superconductivity have come out of investigations carried out by groups of one or two senior scientists often working with a few students. The small-group or single-investigator research environments, which provide many outlets for creativity and opportunities for independence, are particularly well suited to the training of students. The growing interest in such environments among graduate students is reflected in the recruiting efforts of many physics departments. Funding for small-group and single-investigator research has become dangerously inadequate and important opportunities for the nation have been lost as a result.

> **Recommendation 3.** Federal science agencies should assign a high priority to providing adequate and stable support for small groups and single investigators working at the cutting edge of physics and related disciplines.

Large facilities and a coordinated effort among many collaborators are essential to address many of the most important problems in physics. As the scale of the research increases, it becomes ever more important to carefully assess scientific opportunities and to develop priorities nationally and internationally. Large-scale physics requires extensive R&D, and the federal government must be prepared to support such work well in advance of the start-up of specific facilities. Once initiated, large-scale projects must be managed carefully by the responsible federal agencies and the scientists involved. And mechanisms must be in place so that such projects are terminated once they are no longer at the forefront of research.

> **Recommendation 4.** While planning and priority setting are important for all of physics, they are especially critical when large facilities and collaborations are necessary. To do this successfully, the community of physicists in the US and abroad must develop a broadly shared vision and communicate this vision clearly and persuasively. Planning and implementation for the very largest facilities should be international. The federal government should develop effective mechanisms for US participation and leadership in international scientific projects, including clear criteria for entrance and exit.


LIGO

FIGURE 5. ASPIRING SCIENTISTS willing to trade their summer vacations for the opportunity to do research receive support from the NSF Research Experience for Undergraduates (REU) program. Begun more than a decade ago, REU helps university departments, government laboratories, industrial research groups, and others recruit undergraduates to participate in research projects that are guided by senior investigators. The students shown here are at the Laser Interferometer Gravitational-Wave Observatory in Hanford, Washington.

National security

DOD supports basic research in physics and other sciences, work that is crucial for national defense interests. Even with recent funding increases, the department's support of basic research in physics has declined by approximately 10% in constant dollars since 1993. Over the past decade, there has been a substantial decline in the amount and quality of physics research being carried out at DOD laboratories and a corresponding loss of talented people to serve as in-house expert advisers. The laboratories need to be restored or alternative sources of expertise must be developed.

DOE's Office for Defense Programs' national laboratories—Los Alamos, Lawrence Livermore, and Sandia—have the congressionally mandated duty of verifying the readiness and reliability of the US nuclear arsenal. In the absence of nuclear testing, these laboratories must carry out this duty through a challenging program of component testing and numerical simulation. This work demands the highest quality of scientific personnel, including a vital core of physicists.

Security is essential at the laboratories. Yet, they must be able to respond to problems in ways that will maintain the creative and scientifically rigorous environment that has served them so well throughout their existence.

> **Recommendation 5.** Congress and the Department of Energy should ensure the continued scientific excellence of the Department of Energy's Office of Defense Programs' national laboratories by reestablishing the high priority of long-term basic research in physics and other core competencies important to laboratory missions.

Other recommendations. The PSOC concluded with four additional recommendations. First, the federal government, universities and their physics departments, and industry should develop partnerships. Second, federal science agencies should assign a high priority to the broad support of core physics research, providing a healthy balance with special initiatives in focused research directions. (See page 170 of the *Overview*.) Third, peer review should be maintained as the principal factor in determining how federal research funds are awarded. Fourth, the federal government and physics community together should develop a coordinated approach for the support of bibliographic and experimental databases and data-mining tools. In particular, there should be support for the bibliographic archive long housed at Los Alamos National Laboratory and recently moved to Cornell University.

Further reading

NRC *Overview*:

▷ Physics Survey Overview Committee, NRC, *Physics in a New Era: An Overview*, National Academy Press, Washington, DC (2001).

Discipline volumes in the *Physics in a New Era* series:

▷ Panel on the Future of Atomic, Molecular, and Optical Sciences, NRC, *Atomic, Molecular, and Optical Science: An Investment in the Future*, National Academy Press, Washington, DC (1994).

▷ Panel on Opportunities in Plasma Science and Technology, NRC, *Plasma Science: From Fundamental Research to Technological Applications*, National Academy Press, Washington, DC (1995).

▷ Committee on Elementary-Particle Physics, NRC, *Elementary-Particle Physics: Revealing the Secrets of Energy and Matter*, National Academy Press, Washington, DC (1998).

▷ Committee on Nuclear Physics, NRC, *Nuclear Physics: The Core of Matter, the Fuel of Stars*, National Academy Press, Washington, DC (1999).

▷ Committee on Condensed-Matter and Materials Physics, NRC, *Condensed-Matter and Materials Physics: Basic Research for Tomorrow's Technology*, National Academy Press, Washington, DC (1999).

▷ Committee on Gravitational Physics, NRC, *Gravitational Physics: Exploring the Structure of Space and Time*, National Academy Press, Washington, DC (1999).

Other key NRC reports:

▷ Committee on Cosmic-Ray Physics, NRC, *Opportunities in Cosmic-Ray Physics and Astrophysics*, National Academy Press, Washington, DC (1995).

▷ Panel on Cosmology, NRC, *Cosmology: A Research Briefing*, National Academy Press, Washington, DC (1995).

▷ Panel on Neutrino Astrophysics, NRC, *Neutrino Astrophysics: A Research Briefing*, National Academy Press, Washington, DC (1995).

▷ Solid State Sciences Committee, NRC, *The Physics of Materials: How Science Improves our Lives*, National Academy Press, Washington, DC (1997).

▷ Committee on Optical Science and Engineering, NRC, *Harnessing Light: Optical Science and Engineering for the 21st Century*, National Academy Press, Washington, DC (1998).

▷ Committee on the Physics of the Universe, NRC, *Connecting Quarks with the Cosmos: Eleven Science Questions for the New Century*, National Academy Press, Washington, DC (2001). ■