Materials in a New Era: Proceedings of the 1999 Solid State Sciences Committee Forum

Solid State Sciences Committee, National Research Council

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Materials in a New Era

Proceedings of the 1999 Solid State Sciences Committee Forum

Solid State Sciences Committee
Board on Physics and Astronomy
Commission on Physical Sciences, Mathematics, and Applications

National Research Council

NATIONAL ACADEMY PRESS
Washington, D.C.

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Acknowledgment of Reviewers

These proceedings have been reviewed by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the National Research Council's (NRC's) Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the authors and the NRC in making the published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The contents of the review comments and the draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their participation in the review of this report:

Gordon A. Baym, University of Illinois at Urbana-Champaign,
David Campbell, University of Illinois at Urbana-Champaign,
Charles W. Clark, National Institute of Standards and Technology,
Denis McWhan, Brookhaven National Laboratory,
James J. Rhyne, University of Missouri, and
Nicholas P. Samios, Brookhaven National Laboratory.

Although the individuals listed above have provided many constructive comments and suggestions, the responsibility for the final content of this proceedings rests solely with the authoring committee and the NRC.

Contents

I: Materials and the Federal Role

II: Materials R&D in a Changing World

III: Materials Education and Infrastructure

IV: Materials R&D—A Vision of the Scientific Frontier

List of Participants

Materials in a New Era

Proceedings of the 1999 Solid State Sciences Committee Forum

Abstract

The 1999 Solid State Sciences Committee Forum, entitled "Materials in a New Era," was held at the National Academy of Sciences in Washington, D.C., on February 16-17, 1999. The forum was designed to launch the report entitled *Condensed-Matter and Materials Physics: Basic Research for Tomorrow's Technology.* That report, part of the decadal survey series, *Physics in a New Era*, reviews some of the outstanding accomplishments in materials research over the last decade. It indicates some emerging areas and conveys the true excitement in the field from a perspective of basic science and potential societal impact. The forum was designed to showcase the main themes of that report.

The tone of this forum was considerably more upbeat than that of the forum held 3 years ago. In the interim, the federal funding picture for scientific research has stabilized and improved, there is increased awareness of the value of sustained investment in research in Washington, and industrial support for physical science has stabilized. With such relatively good news, it is tempting for the community to become complacent about being recognized as an invaluable contributor to the U.S. and world economy. However, the message of this forum is that the condensed-matter and materials physics community must continue to be proactive in bringing the field to a more broadly based audience, including politicians and lay persons not versed in science.

These proceedings provide a written record of the 2-day event for forum attendees and other interested scientists, program managers, policymakers, and members of the general public. The sources of the articles herein are written material provided by the speaker and notes taken by members of the Solid State Sciences Committee. Unless otherwise specified, the articles were prepared from notes taken by a member of the Solid State Sciences Committee.

Executive Summary

Thomas P. Russell
Chair, Solid State Sciences Committee

The 1999 Solid State Sciences Committee Forum, entitled "Materials in a New Era," was held at the National Academy of Sciences in Washington, D.C., on February 16-17, 1999. The forum was designed to coincide with the release of the decadal report *Condensed-Matter and Materials Physics: Basic Research for Tomorrow's Technology*. The report, part of the series *Physics in a New Era*, reviews some of the outstanding accomplishments in materials research over the last decade and indicated some of the emerging areas where there is excitement in the field from a perspective of basic science as well as potential societal impact. The program for the forum was designed to highlight these accomplishments and emerging areas.

The 1st day of the forum focused on the national political environment surrounding materials science, the funding constraints under which materials scientists must operate, and the changing roles of government laboratories, industry, and academic institutions in promoting materials science. The 2nd day focused on education, infrastructure, and emerging areas in condensed-matter physics and materials science.

The tone of this forum was considerably more upbeat than that of the forum held 3 years ago. In the interim, the federal funding picture for scientific research has stabilized and improved, there is increased awareness of the value of sustained investment in research in Washington, and industrial support for physical science has stabilized. With such relatively good news, it is tempting for the community to become complacent about being recognized as an invaluable contributor to the U.S. and world economy. However, the message from the forum is clear—we, as a community, cannot afford to be complacent but must act proactively in bringing condensed-matter and materials physics to a more broadly based audience, including politicians and lay persons not versed in science. Doing so will require active participation by scientists in educating students on all levels and getting young students interested in materials physics. In addition, scientific research is becoming much more interdisciplinary. Some of the key advances in science are occurring at the interface between different disciplines. It is imperative that active dialogs be established between different communities to bring the knowledge and advances made in materials physics to other disciplines.

Summary of Articles

Keynote Address: Unlocking Our Future

Laura Lyman Rodriguez, a staff member in the office of Representative Vernon Ehlers (R-MI), set the stage from a national perspective with the keynote presentation on the recently issued study *Unlocking Our Future: Toward a New National Science Policy*. This report, the result of a House of Representatives study headed by Representative Ehlers, was aimed at developing a national science policy appropriate for the 21st century. The study finds that the federal government, scientists, and educators must address several issues, as follows: (1) Our science policy is outdated, (2) the American public does not understand science and its practice, and (3) scientists are politically clueless. It is evident that our nation needs to improve its science, mathematics, engineering, and technology education; to develop a new concise, coherent, and comprehensive science policy; and to make its scientists socially responsible and politically aware. The report makes the following four major recommendations:

1. Continue to push the boundaries of the scientific frontier by supporting interdisciplinary research, maintaining a balanced research portfolio, and funding more innovative "risk-taking" projects.
2. Support private research efforts, an essential component of a healthy U.S. R&D portfolio, by encouraging young, startup companies, making the R&D tax credit permanent, streamlining regulations, and pursuing and developing effective partnerships.
3. Increase efforts in education at all levels including preschool to graduate school; conduct research on curricula and education; address issues of teacher training, recruitment, and retention; provide for a more diversified graduate experience; and increase public outreach.
4. Strengthen the relationship between science and the society that supports it through improved communication among scientists, journalists, and the public and by engaging the scientific community in helping society make good decisions.

Materials and the Federal Role

The interdependence of different fields of research was emphasized by a number of representatives of federal agencies.

Office of Science and Technology Policy

Arthur Bienenstock, Associate Director for Science in the Office of Science and Technology Policy (OSTP), emphasized the Clinton administration's unequivocal commitment to maintaining leadership across the frontiers of scientific knowledge. Technology and the underlying science in many fields are responsible for more than 50 percent of the increases in productivity that we have enjoyed over the last 50 years. The various branches of science are truly interdependent—progress in one field depends on advances in many other areas. As an example, Bienenstock pointed to computerized axial tomography (CAT) scans, one of the mainstays of medical diagnostics, asking why it took so long after the discovery of x-rays for the technology to develop. Progress in many fields was needed to make the technology a reality—solid state physics and engineering to enable the computers that control the instrument and collect and analyze the data, materials science to provide the x-ray detectors, and mathematics and computer science for the algorithms to reconstruct the image from the raw data. CAT scans would not exist today if any of these were missing.

National Institutes of Health

Marvin Cassman, Director, National Institute of General Medical Sciences, further embroidered the theme of interdependence by discussing the multidisciplinary nature of research at major facilities such as synchrotrons and neutron sources. In the United States, most such facilities are funded by agencies with major responsibilities for condensed-matter and materials research. Biological research, however, is finding an increasing need for these facilities and now accounts for a significant fraction of all work being carried out at these national sources. Appropriate cooperation among these communities and the agencies that fund them will be essential to the continued viability of these important and extremely costly facilities. An interagency working group has been formed under the auspices of OSTP to facilitate such cooperation.

U.S. Department of Energy

Martha Krebs, Director of the Department of Energy Office of Science, presented the view from her office. The fiscal year 2000 budget request for the Office of Science is $189 million greater than that for the fiscal year 1999 budget. This increase is largely for construction of the Spallation Neutron Source and for the Scientific Simulation Initiative, an interagency initiative that will bring teraflop-scale computing to bear on a number of problems including global systems, combustion, and basic science (which may include materials). Krebs identified a number of future directions and opportunities in materials research including neutron scattering, materials at high magnetic fields, sp^2-bonded materials, granular materials, complex materials, and high-temperature superconductors.

U.S. Department of Defense

Hans Mark, Director for Defense Research and Engineering in the Department of Defense (DOD), began his presentation by noting the basic axiom that possession of superior technology leads to victory in war. However, what has not been recognized is that fundamental scientific research is the link between superior technology and basic knowledge. He outlined four new science and technology topics that the Defense Science Board should be considering and invited the community to suggest others. The ones he suggested were:

1. "Strange" molecules, i.e., fullerenes, carbon nanotubes, or hyperbranched molecules;
2. Predictive chaos theory/nonlinear dynamics and its applicability to national security;
3. Software development, especially new techniques for producing software such as genetic algorithm development and application and automation of software development; and
4. High-power electrical devices.

He emphasized that it is essential for the U.S. military to receive the best possible scientific information and, to this end, the DOD will continue to support basic research.

National Institute of Standards and Technology

Raymond Kammer, Director of the National Institute of Standards and Technology (NIST), outlined the impact that NIST has had in materials science including the high quality of research performed in its laboratories, the research facilities that are provided to the scientific community, and the Advanced Technology Program that has an impact on the industrial sector of research in the United States. With the growth of industrial interest in soft materials, including biomaterials, the drive toward nanoscale structures, and the importance of magnetic materials, it is essential that NIST remain on the forefront of research in these fields. NIST will continue to develop, build, and operate the best possible research facilities where NIST will play a special role.

National Science Foundation

Robert A. Eisenstein, the Assistant Director for Mathematical and Physical Sciences of the National Science Foundation (NSF), surveyed the broad range of research currently supported by the NSF that spans length scales from the subatomic to the astronomic. Although Mathematical and Physical Sciences supports such a broad range of research, over the past 10 years its budget has only increased by 60 percent, an increase that can be compared with the nearly doubled budget of the National Science Foundation. Mathematical and Physical Sciences is not keeping pace, with greater budgetary increases going to Engineering, Biology, Education, and Computer Science. Can this be changed? Only if the direct impact of Mathematical and Physical Sciences research on these other fields and on society in general is demonstrated and argued convincingly. Quoting Neal Lane, "It is necessary to involve materials scientists in a new role, undoubtedly an awkward one for many, that might be called the 'civic scientist.' This role is one in which science shares in defining our future."

Materials R&D in a Changing World

Report of the Committee on Condensed-Matter and Materials Physics

The focal point of the forum was the report of the Committee on Condensed-Matter and Materials Physics (CMMP), *Condensed-Matter and Materials Physics: Basic Research for Tomorrow's Technology*. **Venkatesh Narayanamurti**, Dean of Engineering and Applied Science, Harvard University, chaired this committee and summarized the report.

Over the past decade, CMMP has been marked by the unexpected. If one looks at the last decadal study by Brinkman (*Physics Through the 1990s*, National Academy Press, Washington, D.C., 1986) , the majority of major findings were far from expectations. One need only look at the discoveries of fullerenes, giant magnetoresistance, the fractional quantum Hall effect, and atomic force microscopy, to name a few, to see the impact that the unforeseen has had on science and society in general.

CMMP, however, faces stringent challenges in the future to ensure its intellectual vitality and transfer of knowledge to practical applications. In general, science is becoming multidisciplinary in that advances in different fields are brought about by the integration of the expertise existent in specific subfields. For the scientific effort to succeed, facilities infrastructure needs to be in place so that research by a broad community can be enabled in an efficient and effective manner. New modes of cooperation between the academic, industrial, and government communities must be established to ensure a connectivity of CMMP with society and to preserve the innovative climate. The future of science lies with students who are currently being trained or will be trained at our universities. Yet, with the multidisciplinary nature of research, academic institutions need to evaluate and, perhaps, modify the curriculum to train students in the best way.

Narayanamurti went on to describe several actions that must be taken to maintain and enhance the productivity of CMMP. The different government funding agencies need to nurture the core research effort, modernize the CMMP research infrastructure, and invest in state-of-the-art equipment.

Concerning larger facilities, the current gap between the United States and the rest of the world in neutron science needs to be closed by construction of the Spallation Neutron Source and by upgrading existing reactor and spallation-based sources. Support of operating, and upgrading existing, synchrotron sources and investment in the next generation of synchrotron sources should be strengthened.

Incentives should be provided for partnerships among academic, industrial, and government laboratories. Universities need to enhance the students' understanding of both the role of knowledge integration and transfer and also knowledge creation.

Can we predict where advances will be made? Absolutely not. Nonetheless, it is abundantly clear that the success achieved in CMMP has had an impact that transcends many disciplines and has led to marked advances in completely unexpected areas.

Materials R&D in Industry

Cherry A. Murray, Director of Research at Bell Laboratories, Lucent Technologies, discussed materials R&D in the industrial sector. The development of corporate research in the United States since the 1970s has evolved from "just in case" to "just in time" to "just indispensable." Without question, industrial research is becoming more tightly coupled to products, and the opportunities to conduct "blue sky" research (i.e., research completely disconnected from the bottom line) are very limited. However, the technological advances that have been witnessed during the past decade now place technology in the position of pushing fundamental limits. As a consequence, many companies are now increasing their support of long-term research. To maintain a competitive edge, companies must maintain "in-house" competencies, stimulate innovation, fuel growth, and broaden the product portfolios. But why the need for research? Inventions, technological expertise, and strong intellectual property positioning are the answer. Murray concluded with the remark that ". . . physical sciences research is as essential as ever for leading-edge high-technology companies."

Changing Roles for Research Universities

J. David Litster of the Massachusetts Institute of Technology described the current funding transition in which research universities are involved. Using his home institution as an example, Litster noted the enormous pressure that universities are facing in terms of overhead recovery rates with the flat or declining budgets. During the 1980s federal funding for student financial aid showed a significant decrease, from 50 percent to 20 percent, with the universities being left to make up the difference. To make up these large financial burdens, universities have turned to industrial support for research. However, a delicate balance must be struck, because industry is sensitive to intellectual property and ownership, whereas universities must be free to publish.

Changing Roles for Government Laboratories

John McTague, recently retired Vice President of Ford Motor Company and Co-chair of the Secretary of Energy's Laboratory Operations Board, addressed the challenges that face government laboratories. How can the national laboratories operate as a truly integrated system working more efficiently to address the problems of national importance?

McTague cited the four specific examples: the Center for Excellence for Synthesis and Processing of Advanced Materials, the Partnership for a New Generation of Vehicles, the Spallation Neutron Source, and the Information Technology for the 21st Century. Each of these examples is based on interactive, collaborative efforts among several national laboratories, which will require them to operate in a concerted manner from the management level down to the laboratory bench level.

McTague concluded by noting that he was cautiously optimistic that the national laboratories will be able to meet this challenge. The laboratories may evolve beyond being simply a collection of isolated institutions.

Panel Discussion of the Future of Materials R&D

The first day concluded with a panel discussion including **Cherry A. Murray, Venkatesh Narayanamurti, Thomas Weber** of the National Science Foundation, **William Oosterhuis** of the Department of Energy, **Skip Stiles**, a member of the House Science Committee Minority Staff, and **Harlan Watson**, a member of the House Science Committee Majority Staff.

Although the members of the panel fully agreed that CMMP has a compelling case for support, that the impact of CMMP in society has been significant, and that the importance of CMMP in industry has been and will continue to be great, these facts are not sufficient to ensure the health and prosperity of the field. Specifically, scientists need to continually "beat the stump" with local and national politicians, educating them on the manner in which CMMP has had significant impact on their constituents and why future funding is essential. Although all these arguments have been made in the past, the transmission of this message has not been effective. Even with convincing arguments, the funding of the scientific enterprise is still faced with the reality that spending caps will be in place over the next 2 years and that no new money will materialize unless these caps are lifted. The Frist-Rockefeller bill (S. 1305) authorizing a doubling of research funding is a good organizational tool but will not produce more funding and does not bind future Congresses.

Materials Education and Infrastructure

Materials Education for the 21st Century

Robert P.H. Chang of Northwestern University presented several sobering facts concerning the current state of education in the United States and stated the imminent need for educational reform in materials science if the field is to remain vibrant. From the low number of American students attending college and advancing on to higher degrees to the overall poor performance of American children in international testing and the dearth of teachers trained in materials science, the outlook for the future of materials science must be of concern to every materials scientist at all institutions—academic, industrial, and government. Materials science, essential in our everyday lives and vital to our future, still has a very low profile in secondary education. Materials science is an ever-changing discipline with new areas continually emerging, and it is necessary for academic institutions to shift in a commensurate time frame. Although easily said, this is difficult to realize given the slow rate at which academic institutions can change. Consequently, existing resources, such as the Materials Research Science and Engineering Centers and Science and Technology Centers funded by the National Science Foundation, must be used to best advantage. Outreach programs of the centers serve K-12 education needs. Although these programs are effective, they are simply not enough. Chang's studies indicate that the middle school and high school years are a particularly crucial time in the educational development of children. At this age, many students lose interest in materials science, and we must ask ourselves why this occurs and how materials science education can bridge the gap between high school and college.

Chang concluded that all materials science initiatives must undertake to foster greater awareness of the importance of materials science education, introduce materials science at the high school level to enhance mathematics and science education, and get teachers involved in materials science education.

Meeting the Challenge in Neutron Science

Thom Mason, Science Coordinator for the Spallation Neutron Source at Oak Ridge National Laboratory, outlined the status of this $1.3 billion project that involves an integrated effort from the five national laboratories. The history of neutron sources has been marked by several key threshold points.

In particular, for neutron scattering, the development of the graphite reactor at Oak Ridge, the National Research Universal reactor in Canada, and the development of neutron waveguides marked significant breakthroughs in the use of neutrons for materials research.

We stand now on another threshold with the planned construction of the Spallation Neutron Source at the Oak Ridge National Laboratory. This will be the world's most powerful pulsed neutron source. It will enable qualitatively new and different science in disciplines ranging from materials science to biological sciences. The Spallation Neutron Source will offer nearly one order of magnitude enhancement in the neutron flux on the sample over existing spallation sources and will open new areas of materials science.

Is the pathway straightforward and without obstacles? Any effort that involves five different national laboratories and that requires each component constructed at the different laboratories to operate perfectly and to mesh with exceptional precision will not be straightforward. The construction of the Spallation Neutron Source is technically difficult. And the coordination of five different laboratories operating under severe budget constraints poses a significant managerial challenge. Nonetheless, the future of materials science based on neutrons rests on the Spallation Neutron Source. It is absolutely imperative for the scientific well-being of the nation that the Spallation Neutron Source be successfully completed on time and within budget.

Toward a Fourth-Generation Light Source

David E. Moncton, Director of the Advanced Photon Source, Argonne National Laboratory, described the advances that have been made in the x-ray flux with the developments in synchrotron radiation sources and the science that these sources have enabled. The developments of these sources have been driven by the urgent and compelling needs of science. In turn, the massive increases in flux have also opened unexpected areas of science.

Fourth-generation sources offer spectacular gains in flux and brilliance; large quantitative improvements in beam coherence, timing, and dynamics; and large qualitative improvements in photon degeneracy over current sources. Such sources hold opportunities in atomic and molecular physics, biology, chemical physics, materials science, high-field physics, and soft matter physics.

Smaller Facilities—Opportunities and Needs

J. Murray Gibson, University of Illinois, addressed an often overlooked, yet essential component of materials science research, namely, the smaller facilities that include, for example, electron microscopy facilities, ion beam facilities, and mass spectrometry facilities. These facilities lie in the intermediate funding range, being too expensive for any single investigator to consider for funding, yet too small to capture the attention on a national level. However, these facilities perform an exceptionally vital role in materials science research, enabling a tremendous amount of research across the nation, and provide capabilities far beyond that afforded by the laboratory of an individual researcher.

Maintaining and upgrading these facilities is by no means inexpensive. Operating costs upwards of $1 million with replacements costs of over $2 million annually is not uncommon. Yet, the number of mechanisms that such centers have for obtaining the necessary funding is limited. Many are situated at NSF-supported Materials Research Science and Engineering Centers, Science and Technology Centers, and Engineering Research Centers or Department of Energy-supported Materials Research Laboratories. Although such centers have proven to be important, opening different avenues for support and maintenance of these centers is critical.

Materials R&D—A Vision of the Scientific Frontier

The Science of Modern Technology

This topic was discussed by **Paul Peercy** of SEMI/SEMATECH. Although the scientific discoveries over the past decade have been both unexpected and impressive, equally impressive have been the technological advances based on our increased understanding of the physics, chemistry, and processing of materials. These insights have enabled modern technology to keep pace with, if not exceed, the expectations set by Moore's Law. Scientific understanding has not only demonstrated the feasibility of advances in technology but also led the way to producing devices in a high-volume, low-cost manner.

Today's technological revolution would not be possible without this basic understanding. This fact holds true for industries across the board, ranging from semiconductors to communications to commodity polymers. To keep pace, continued research in the optical, electrical, and magnetic properties of materials must continue. As size scales shrink, nanostructured materials, artificially structured materials, self-assembled systems, and biologically based systems will become increasingly important for future advances.

Novel Quantum Phenomena in Condensed-Matter Systems

Steven M. Girvin from Indiana University presented a lecture focused on novel quantum phenomena. He dispelled the notion that few surprises or intellectual challenges are left when one considers the physics of well-known objects, such as atoms, that interact via well-defined and well-understood electromagnetic forces. Superconductivity, superfluidity, and the fractional quantum Hall effect are three recent examples of surprises lurking in familiar systems. These phenomena underscore the fact that the quantum mechanics of large collections of objects can be unusual and unexpected. Emergent phenomena, such as phase transitions and broken symmetries, often appear in large collections of objects. These pose significant theoretical and experimental challenges to condensed-matter and materials physicists, because materials constructed from a large collection of atoms routinely have completely unexpected properties.

Nonequilibrium Physics

James S. Langer of the University of California, Santa Barbara, treated the subject of nonequilibrium physics—the physics of materials not in mechanical or thermal equilibrium with their surroundings. Although the Brinkman report recognized the importance of nonequilibrium behavior, some of the most important areas where nonequilibrium behavior is critical were completely overlooked. Areas that have emerged include topics ranging from friction and fracture to granular materials to ductility. Each of these rather familiar areas provides a prime example in which nonequilibrium physics plays a key role. One goal of nonequilibrium physics is to quantify the relationship between precision and predictability. Nonequilibrium phenomena continually come to the foreground in the understanding of the response of a material to an applied external field or its ultimate properties. With increasing interactions between different disciplines, it is evident that nonequilibrium phenomena will increase in importance.

Soft Condensed Matter

V. Adrian Parsegian of the National Institutes of Health underscored the importance of condensed-matter and materials physics to the biological community and the general importance of cross-disciplinary research. One can look at the advances that have been made with high-powered synchrotron and neutron sources where advances in one field have a significant impact on another. As discussed previously by Cassman, the number of protein structures that are being solved has increased by a large factor through advances developed by the synchrotron community. However, it is not sufficient simply to offer the most sophisticated instrumentation. At present, physicists are simply off the radar screen of most biologists, where the former are considered as being insular and parochial. It is necessary to establish a dialog between the different communities. Doing so, however, will require an education of both physicists and biologists that will increase the awareness of the two communities of each other and, thereby, stimulate interactions.

Fractional Charges and Other Tales from Flatland

Horst Störmer of Bell Laboratories and Columbia University, who recently shared the 1998 Nobel Prize in physics with D.C. Tsui and Robert Laughlin for their discovery of the fractional quantum Hall effect, addressed the forum with his “Tales from Flatland” where electrons can move along a two-dimensional surface, being confined in the third dimension, and carry a fractional charge. Fractional charges arise when a two-dimensional gas of electrons becomes highly correlated. In an animated presentation, Störmer took the forum attendees through the initial discovery of the quantum Hall effect to experiments performed under very high magnetic fields where fractionally charged excitations are observed.

Keynote Address: Unlocking Our Future

Laura Lyman Rodriguez
Office of Representative Vernon Ehlers

In 1945, Vannevar Bush outlined the national science policy under President Franklin Roosevelt with the publication of "Science—The Endless Frontier." The policy outlined by Bush was comprehensive. Among other things, it addressed the status of science in the nation and defined areas of national need in science. Subsequent Administrations followed this policy without major modifications.

Although the policy has lasted more than 50 years, there have been sweeping changes in its social context. The Cold War is over, the Soviet Union no longer exists, and we are in the midst of an unprecedented revolution in technology. To address science policy in light of these changes, the Speaker of the House requested a study in mid-1997. The report of this study was released on September 24, 1998, and was approved by the full House of Representatives on October 8, 1998.

Representative Vernon Ehlers, the first research physicist elected to Congress, was chosen to lead the study. During his investigation, Representative Ehlers received input from over 10,000 scientists nationwide. This wide base of expertise enabled him to produce a dramatic new vision for science and technology. Although some of the points made in the report may seem obvious to the practitioners of scientific research, it was written for Congress and serves as a framework for future funding and policy discussions. The report is not meant as an end.

Congressman Ehlers' goal and vision is for the United States to maintain its preeminent status in science and technology—not just to provide opportunity for U.S. scientists but to improve the lives, health, and freedom for people everywhere. He believes it is our responsibility, as the sole remaining superpower, to use our leadership in science and engineering for the betterment of the world. However, for science to continue to benefit society, the scientific enterprise must stay strong and be sustainable. The recommendations in the report are meant to provide a framework in which the continued strength and sustainability can be achieved.

Four main theses were developed in the report:

1. Our science policy is outdated.
2. The U.S. public does not understand science or its practice.
3. Scientists are politically clueless.
4. Our nation needs:
    - Better science, mathematics, engineering and technology education;
    - A new concise, coherent, and comprehensive science policy; and
    - Socially responsible and politically aware scientists.

The report identified the following four major areas as needing attention:

1. Continued discoveries at the scientific frontier;
2. Research advances in the private sector;
3. Integration of science and decisionmaking through both the regulatory and judicial systems; and
4. Improvement of science education.

Fundamental research is of primary significance because it will drive many of the innovations that can make the vision of better and healthier lives a reality. This research depends largely on funding from the federal government—funding that must be stable, substantial, and of high priority. The report strongly endorses the need for a major federal role in funding individual investigators for pursuit of fundamental research in the sciences, mathematics, and engineering. The goal of the report is to strengthen the basic research enterprise in the country.

The Federal Level

Interdisciplinary research is becoming increasingly important and must be supported at the federal level. Because interdisciplinary research does not fit neatly into a specific funding category, it can fall through the cracks in our current system of funding. Therefore, mechanisms should be established to support this research as an im-

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NOTE: This article was prepared from written material provided to the Solid State Sciences Committee by the speaker.

portant part of the federal basic research portfolio.

The balance of funding between different disciplines must also be addressed. Prosperity, health, and security are the result of breakthroughs in a diversity of disciplines. Moreover, advances in one area of science often depend on advances in completely different research areas.

Exploratory research ideas that are creative and truly represent a leap in thinking must be supported. As research funding becomes more competitive, strictly funding "safe" incremental research at the expense of more risky ideas must be avoided. A fraction of the federal research funds must be set aside for this purpose.

The discretionary budget, the source of all federal science funding, is shrinking. Controlling this reduction or turning it around requires controlling entitlement spending. Entitlement programs, such as Social Security and Medicare, need reformation because they can consume any surplus that is generated. In 1962, entitlements used 25 percent of the budget, whereas now the amount is 50 percent. Without control, this percentage will increase, such that, by 2010, all revenues will be spent on entitlements and interest, leaving nothing for defense and domestic discretionary spending. The current surplus of federal funds adds a twist to the overall budget strategy but does not alter the fact that discretionary restraints must be incorporated.

The Private Sector

Research in industry is important for harvesting the fruits of basic research that benefit society. New findings can rarely, if ever, be brought directly from the laboratory bench to a salable item. The gap between basic research and industry-driven applied research or product development is referred to as the "valley of death." As academic research becomes more basic, applied research is shifting more and more toward product development, thus broadening the gap between the two worlds. It is in this netherworld where discoveries that may be very beneficial for society are lost or forgotten. The bridges or pathways between the two do not follow a straight trajectory but have a complex, interactive relationship. Consequently, truly innovative research in industry is absolutely necessary and must be encouraged. To attain this goal, the following policies should be pursued:

- Young startup companies must be encouraged, because they often pursue research that is far more basic than applied. Capitalization of these companies is critical and tax policies must be enacted that support this.
- R&D tax credit should be made permanent. The uncertainty about the existence of a tax credit from year to year inhibits innovative, long-term, multiyear research in the industrial sector.
- Regulations that are needlessly burdensome must be streamlined.
- Partnerships between government, academic, and industrial laboratories must be promoted.

Education

Development of the nation's intellectual capital in science and mathematics is vitally important to ensure a bright future for the United States. The report recommends changes at all levels of education—from K-12 through graduate school. Teacher training, the retention of qualified teachers, curricula, and research at the K-12 level are addressed in the report. The report also stresses the need for a diversified education. In particular, at the graduate level, students can no longer be trained exclusively for careers as academic researchers because the majority of Ph.D. graduates will pursue careers outside of academia. Communication between the scientific establishment and the lay public must also be improved. Although the freedom of the individual researcher is necessary to bring about ground-breaking discoveries, it is crucial that the scientific and engineering communities strengthen their ties to society and to the taxpayers who ultimately support their research.

The report recognizes and underscores the idea that science helps us make everyday decisions—as a society, as a government, as individuals, and as voters. The ability to draw on science and engineering to facilitate the decision-making process must be strengthened. If a more civic-minded mentality is adopted and if policymakers reach out to communities, the quality of decisions and policies related to scientific research can be improved.

General Remarks

Congressman Ehlers set out to write a document that was concise, coherent, and comprehensive. Because of these constraints, in-depth treatments of specific aspects of the scientific enterprise were not possible. Rather, the report is a "broad brush" view of the entire science and engineering landscape. It is intended to be the beginning of a process and not the end of one. For example, the report is the first step in a long-term process in which Congress will focus on the national science policy with reviews at least every 5 years. The work to address specific science policy issues must emerge from the continuing review. Representative Ehlers intends to begin the congressional dialog on science policy during the 106th Congress.

In the words of the Ehlers report:

> We must ensure that the well of scientific discovery does not run dry, by facilitating and encouraging advances in fundamental research.
>
> We must see that this well of discovery is not allowed to stagnate.
>
> We must strengthen both the educational system we depend upon to produce the diverse array of people . . . who draw from and replenish the well of discovery, as well as the lines of communication between scientists and engineers and the American people.

I. Materials and the Federal Role

Perspectives from the Office of Science and Technology Policy

Arthur Bienenstock
Associate Director for Science, Office of Science and Technology Policy

Arthur Bienenstock provided a perspective on the Clinton administration's science policy and fiscal year 2000 science and technology budget submission, with particular emphasis on new initiatives and opportunities in the materials sciences. He reiterated the administration's commitment to the federal role in science, quoting from the 1997 Office of Science and Technology Policy report, *Science and Technology Shaping the 21st Century,* "The Administration is unequivocally committed to maintaining leadership across the frontiers of scientific knowledge."

The President and Vice President invoke two overarching themes in articulating their broad support for science:

- The fact that technology and the underlying science are responsible for over one-half of productivity increases over the past 50 years; and
- The importance of the interdependencies of the sciences (e.g., the dependence of the biomedical sciences on advances in natural science, mathematics, and engineering).

This support is seen in the Administration's fiscal year 2000 budget submission, which shows substantial increases for scientific research at the National Institutes of Health (NIH), National Science Foundation (NSF), Department of Energy (DOE) Office of Science, National Aeronautics and Space Administration (NASA), and U.S. Department of Agriculture. Included in these increases is $366 million for an Information Technology Initiative, $214 million for construction of the Spallation Neutron Source, and $50 million for an Interagency Education Research Initiative.

The Information Technology Initiative increases federal investments in fundamental information technology research, advanced computing for science and engineering, and research in the social and economic implications of the information revolution. Support is also provided for the education and training of the U.S. information technology work force. This initiative is led by NSF with significant involvement by the Department of Defense, DOE, and NASA.

Bienenstock reviewed progress toward implementing the goal of S. 1305, authorization legislation that calls for a doubling of the federal investment in science over the next 12 years. The NIH R&D budget increased significantly in fiscal year 1999 and is on a path toward achieving this goal in less than 12 years. The non-NIH civilian R&D budgets have not experienced such growth and have been essentially flat in recent years. One of the outstanding challenges is how to place federal investment in R&D on a growth curve within the current budget caps.

To demonstrate the interdependence of the sciences, Bienenstock reviewed the development of x-ray research leading to the modern computerized axial tomography (CAT) scan. X-rays were discovered in 1896, and their importance for diagnostic and therapeutic radiology was almost immediately recognized. X-ray crystallography was awarded the Nobel Prize in Physics in 1915, and many related Nobel prizes have followed, particularly in protein crystallography. Why, then, did it take so long to develop the CAT scan? Although the concept was understood, the CAT scan could not be realized until parallel advances in computers, detectors, and image processing were achieved. These advances required investments in solid state physics and engineering, materials science, and mathematics and computer science. The CAT scan is not an x-ray advance. It is the result of a broad integration of science across several disciplines—an integration that could not have been achieved without broad leadership "across the frontiers of science."

Bienenstock closed his presentation by stressing the importance of the federal role in supporting a broad range of research. The importance of recognizing the interdependence of research is clearly apparent in condensed-matter and materials physics, where advances often occur at interfaces with biology, chemistry, atomic physics, materials science, and the engineering disciplines. Bienenstock encouraged the condensed-matter and materials physics community to advocate support for a broad range of research. He also urged the community to become engaged in the emerging dialog concerning post-Social Security federal budget priorities. Competing priorities include broad tax cuts and investments in the future such as research and education. The R&D community has a large stake in the outcome.

Perspectives from the National Institutes of Health

Marvin Cassman
Director, National Institute of General Medical Sciences
National Institutes of Health

The interplay between the biological sciences and solid state sciences is clearly manifest in the rapid acceleration of the number of crystal structures of proteins that are being determined. Over the course of 10 years, 1987-97, for example, the number of protein crystallographic structures that have been deposited in the Protein Data Base has increased from tens to thousands. This rapid increase in the number of structures has been made possible, in part, by the improvements in x-ray synchrotron sources. Over this period, the x-ray brightness has increased by orders of magnitude—from first-generation sources, like the Stanford Synchrotron Radiation Laboratory, to second-generation sources, like the National Synchrotron Light Source at the Brookhaven National Laboratory, to third-generation sources, like the Advanced Photon Source (APS) at the Argonne National Laboratory. At present, within a 90-minute experiment at the Advanced Photon Source, sufficient data can be collected to determine a structure. The rate-limiting step in a structural determination is the ability to produce a high-quality crystal. Although x-ray brightness is a key element in the massive increase in the number of crystal structures determined, the need and desire to know the spatial distribution of chemical entities as well as the realization that distribution underpins the functionality of the protein have also been of critical importance to this growth.

This coupling of the need from the biological community with the advances in the x-ray sources, constructed primarily for solid state science research using traditional funding sources like the Department of Energy (DOE) and the National Science Foundation (NSF), has provided a synergy that is virtually unparalleled. The excitement over such advances comes at a cost. It is very apparent that biologists are becoming increasingly heavy users at the synchrotron sources, which draw their operational costs from the physics and materials sciences at the DOE and the NSF.

This raises an important question as to how funding from the National Institutes of Health (NIH), the primary funding agency of biological research, can be introduced effectively and efficiently into the picture. The recent report of the Basic Energy Sciences Advisory Committee on Department of Energy Synchrotron Radiation Sources (the Birgeneau/Shen Report) clearly states the desirability of restricting the operation of the sources to only one funding agency. Using multiple funding agencies to operate a single source would lead, in the opinion of the report, to duplication of effort, unnecessary complication of operations, and inefficiency. Yet, the dilemma stands as to the partitioning between different agencies of funding for these sources, for supporting staff scientists, and for instrumentation.

A study that was recently released from the Office of Science and Technology Policy addresses this issue. The working group that produced the report consisted of representatives from the NIH, DOE, the NSF, and the National Institute of Standards and Technology. Some of the more important findings of this study are discussed below.

How can this rapid expansion in protein crystallography be supported? It is clear that existing facilities are being stretched to their limit in terms of the staff scientists. It is inconceivable that current staff levels can support increased demand. Consequently, enhancing the number of the staff and the number of staff capable of interfacing with the biological community is imperative. In particular, it should be possible for a biologist, totally unfamiliar with diffraction methods, to determine the crystal structure of a newly isolated protein without having to spend years in developing an effort in crystallography. Along with this, improved access procedures to existing sources need to be established. Procedures need to be set in place where nonspecialists can perform experiments at the sources and walk away with a crystal structure in a easy and straightforward manner.

Although many advances have been made in the sources, advances in experimentation require parallel advances in the supporting equipment. This includes advances in the detectors, the diffractometers, and the ancillary equipment. If the efficiency in detecting diffracted x-rays does not keep pace with the advances made to the source, then what has been gained? Similarly, if the limiting step in data accumulation rests with the diffractometer, be this in the movement of stepping motors or in its alignment, then are the enhancements in the flux being used effectively? Consequently, there is a continued need to support R&D efforts for improvements to instrumentation.

With the large growth in biological activity in the United States and worldwide, the importance of the quantitative determination of protein crystal structure, and the demand that is being placed on current facilities, the expansion of existing crystallographic capabilities is critical to the further growth of the field. One needs only view the Advanced Photon Source, where there is a large percentage of remaining sectors in the ring dedicated to protein crystallography, to get a feeling for the demand. Even with the APS, crystallographic facilities at the different light sources across the country need to be increased. If current trends persist, even large increases may not be sufficient to satisfy the demand.

Perspectives from the U.S. Department of Energy

Martha Krebs
Director, Office of Science
U.S. Department of Energy

The Department of Energy (DOE) is the second largest source of federal support for basic and applied research with a total budget of $4.4 billion and is the largest provider of R&D facilities. The DOE is the top supporter of the physical sciences including materials R&D. The DOE share of materials research rose from 35 percent of total federal support in 1998 to 42 percent in 1999 with a total budget of $780.9 million.

Nondefense basic research is managed by DOE's Office of Science (SC), which accomplishes its mission primarily through support of multiprogram laboratories and research facilities and also through support of university research at a level of $478 million per year and industry at $126 million per year. Apart from a dramatic decrease of funding for major facilities in the period 1994-97, SC's research budget has roughly tracked the cost of living over the last decade. Facilities funding is at a historic high in the fiscal year 2000 budget request, which includes provisions for the Spallation Neutron Source.

In addition to the operation of major research facilities, the Materials Science Division supports a balanced portfolio of materials research including:

- Structure and dynamics of solids, liquids and surfaces;
- Electronic structure;
- Surfaces and interfaces;
- Synthesis and processing science;
- Predictive theory, simulation, and modeling;
- Structural characterization at the angstrom level; and
- Mechanical and physical behavior of materials.

It is difficult to enhance base support for research without a distinguishable national initiative. This political reality is particularly important for materials because there is no intuitively apparent credible national problem that requires a major initiative in materials research. DOE has played a major role in national initiatives regarding global climate change, the human genome project, and the new Scientific Simulation Initiative.

SC captures its research under four themes that reflect its basic research, energy, environmental, and facilities missions:

1. Exploring energy and matter;
2. Fueling the future;
3. Protecting our living planet; and
4. Using extraordinary tools for extraordinary science.

Given the high cost of construction and operation of national facilities, facilities initiatives necessarily stress the base research efforts. Nevertheless, these facilities have historically prevented erosion of the base research and have served as the basis for revitalization of DOE's mission as national priorities evolve.

Perspectives from the U.S. Department of Defense

Hans Mark
Director of Defense Research and Engineering
U.S. Department of Defense

The Connection Between Basic Science and Critical Technologies for War

That the possession of superior technology leads to victory in war has been a basic axiom ever since people started to fight wars and then to write history. What has not always been clear is the connection between this superior technology and basic knowledge that is the result of fundamental scientific research. This relationship was not fully recognized in Europe until the beginning of the 15th century. Perhaps the leading figure in establishing this all-important connection was Prince Henry of Portugal, who was the first to apply basic scientific knowledge to the technology of seafaring. In 1420, Henry established what today would be called a multidisciplinary, mission-oriented research center near Sagres in southern Portugal. There, he collected mathematicians, astronomers, and geographers who provided basic knowledge to navigators, sea captains, shipwrights, coopers, sailmakers, and other craftsmen. It was this work that made the rapid exploration of the world possible in the following century [1].

The French Experience

The contributions of French scientists have been especially important in the development of new knowledge through basic research, with a subsequent application to the enhancement of military strength. Napoleon Bonaparte, as an artillery officer, knew firsthand the valuable contribution of technology toward victory. What was more important, he cultivated friendships with the very best scientists of the day, including Jean Baptiste Joseph Fourier and Pierre Simon Laplace. Bonaparte also left a legacy that has had far-reaching consequences—a system of military education that resulted in the creation of a generation of distinguished scientists and mathematicians. Probably the most eminent early product of this system was Augustin Louis Cauchy.

France also led in the introduction of aeronautical technology to warfare. The Montgolfier Brothers invented the hot air balloon in the last years of the 18th century. At the battle of Fleurs in Maubeuge in 1794, the French used balloons for surveillance of the battlefield for the first time. Their employment proved decisive in this engagement, and since then air power has become a major factor in war [2].

New Areas of Basic Research

During a recent meeting with the Defense Science Board, which is a senior advisory committee to the Secretary of Defense on basic research and technology, I outlined the following four areas in which I thought that more research was needed.

1. Strange Molecules

In the past decade, a number of complex molecular structures have been discovered that were not anticipated. There is, for example, the molecule containing 60 carbon atoms in a spherical structure called the “bucky ball.” The discoverers of this molecule and others of this kind were awarded the Nobel Prize in Chemistry in 1996 [3]. Perhaps even more important than the bucky balls are nanotubes, long tubular structures of carbon atoms that have cage-like walls formed when two-dimensional sheets of carbon atoms (called graphene) are rolled into a tube. The tubes have diameters that range from 1 to 10 nm and can be either conductors or semiconductors, depending on that diameter. These structures may provide the way out of the quantum limits on silicon devices and allow components of one to two orders of magnitude smaller than present limits. This would have obvious military applications in guidance of small arms munitions, unmanned microaircraft, microspacecraft, and microsensors [4].

2. Chaos or Complexity Theory

About a century ago, the distinguished French mathematician Jules Henri Poincaré was the first to identify evidence of chaotic behavior in deterministic systems. He examined the proof given by Laplace of the stability of the solar system and found that it was not rigorous because Laplace had used a Fourier series that was

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NOTE: This article was prepared from written material provided to the Solid State Sciences Committee by the speaker.

only conditionally convergent. Poincaré went further and showed that even though the solar system was governed by deterministic equations, these sometimes had solutions that exhibited chaotic behavior [5]. Later, it was established that this is a general property of nonlinear systems, and we are just beginning to understand chaotic behavior. It is hoped that complete understanding will allow development of a theory with both descriptive and predictive power [6]. Because all systems are ultimately nonlinear, an understanding of this behavior will likely have the broadest possible application. In terms of military applications, these will probably range from improving weather predictions to guiding tactical decisions on the battlefield.

3. Software Development

Almost all advanced weapons systems depend on computers to guide and control them. These computers are in turn controlled by operating systems that depend on the construction of appropriate “software.” Problems in developing software for these computers have in recent years been responsible to a large extent for the delays and cost growths experienced in the development of advanced weapons. The question is whether new techniques for creating software could be developed to alleviate these problems. Developments are being studied today that might make it possible for large computers to partially program themselves in an evolutionary or Darwinian manner. It is possible that these techniques could lead to automation in the area of computer programming, just as the manufacturing of hard goods has been automated by the application of computer-controlled robots. Once again, the achievement of practical results of importance to the military will depend on fundamental research in this area [7]. The hope is that by automating software development, some of the costly problems that have been encountered in many complex weapons programs can be reduced or eliminated.

4. High-Power Electrical Devices

The computer revolution was generated by the application of quantum mechanics to solid state physics. Almost all of the applications that resulted from the detailed understanding of the solid state resulted in new devices that involved low electrical power levels. This situation has now changed; we are entering an era in which new understandings of high-temperature plasmas and nonlinear materials that can handle very-high power densities have opened up new vistas. This is the new knowledge that we are attempting to apply in the development of electromagnetic guns. There is every reason to believe, in my opinion, that such weapons will come into existence in the first decade or two of the next century and that they may have decisive military effects [8]. New high-energy laser weapons, both airborne and space based, require a detailed understanding of the behavior of high-density plasma flowing in supersonic jets. In addition, optical systems that can handle very-high intensity light beams and still retain extremely accurate dimensional tolerances are necessary. Weapons of this kind are now under development and will, I believe, also be decisive in future conflicts.

Role of the Universities in Basic Research

The modern research university, which evolved in Europe during the 19th century, is today the most effective institution for the creation of new knowledge. In the United States, the Department of Defense sponsors basic research in many universities. This work is supported by a system of grants and contracts that has been in place for almost half a century, with the research subject to normal academic review to assure quality. The classic example of work of this kind was the discovery of fission in 1938 by two German professors, Otto Hahn and Fritz Strassmann, working at the University of Berlin [9]. Seven short years later, this discovery led to the nuclear weapon used at Hiroshima that brought about the end of the Second World War. That this development was achieved in such a short time was due in large part to a number of American professors including J. Robert Oppenheimer and Ernest O. Lawrence of the University of California, Berkeley, who initiated fundamental research in nuclear physics during the 1930s.

Another good example of a decisive military development was radar, a British invention shared with U.S. scientists in 1940. A group of U.S. scientists at the Massachusetts Institute of Technology furthered the development of radar such that small and robust units could be placed on ships and airplanes. This proved to be decisive in many naval and air engagements during the Second World War.

Following the end of the war, U.S. research universities were encouraged by the Department of Defense to establish research institutes in order to concentrate resources and focus the research on topics that are most likely to be of interest to the military. Examples of these institutions include the Applied Physics Laboratory at Johns Hopkins University sponsored by the Navy, the Lincoln Laboratory at the Massachusetts Institute of Technology sponsored by the Air Force, and the Institute for Advanced Technology at the University of Texas at Austin sponsored by the Army. These research institutes are able to draw on the very best scientific talent in some of the most outstanding research universities in the United States. In addition, many of the brightest young people are drawn into scientific research that could affect our military posture.

The results that have been obtained in such institutions have had far-reaching consequences. Radar, lasers, solid state electronic devices, novel optical fire control systems, and various other technologies of this kind would not exist were it not for the work done at many U.S. universities. Thus, the system of university-based research that has been developed has been proven effective. It is a most important component that helps to ensure the national security of the United States.

Concluding Remarks

It is essential that the U.S. military continues to receive the best possible scientific advice. The Department of Defense will continue to support basic research and will encourage the Defense Research Board to concentrate on such issues in the future.

References

[1] C. Raymond Beazley, *Prince Henry the Navigator*, G.P. Putnam and Sons, New York, N.Y., 1911.

[2] Hans Mark, “Warfare in Space,” *America Plans for Space*, National Defense University Press, Washington, D.C., June 1986, pp. 13-32.

[3] The 1996 Nobel Prize in Chemistry was awarded to Robert F. Curl, Jr., Sir Harold W. Kroto, and Richard E. Smalley for their discovery of fullerenes.

[4] M. Meyyappan and Jie Han, “Buckytubes in a Nanoworld,” *Prototyping Technology International*, December 1998.

[5] Jules Henri Poincaré, *Les Méthodes Nouvelles de la Mécanique Céleste*, Gauthier-Villiers, Paris, 1892-99.

[6] Henri D.I. Abarbanel, *Analysis of Observed Chaotic Data*, Springer-Verlag Inc., New York, N.Y., 1996.

[7] Stephanie Forrest, “Genetic Algorithms,” *ACM Computing Surveys*, Vol. 28, No. 1, March 1996, pp. 77-80.

[8] Harry D. Fair, “Electromagnetic Launch: A Review of the U.S. National Program,” *IEEE Transactions on Magnetics*, Vol. 33, No. 1, January 1997.

[9] Otto Hahn and Fritz Strassman, “Concerning the Existence of Alkaline Earth Metals Resulting from the Neutron Irradiation of Uranium,” *Naturwissenschaften*, Vol. 27, No. 11, 1939.

Perspectives from the National Institute of Standards and Technology

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Materials and NIST: Today and Tomorrow

The primary mission of the National Institute of Standards and Technology (NIST) is to promote U.S. economic growth by working with industry to develop and apply measurements, standards and technology, and related scientific research areas. We do this through the Measurement and Standards Laboratories (MSLs, performing internal R&D), our Advanced Technology Program (ATP, which supports cost-shared work on high-risk technologies), the Manufacturing Extension Partnership (a series of local resources to support technology application in small manufacturers), and the Malcolm Baldrige National Quality Program. The MSL programs in areas relevant to condensed-matter and materials physics (CMMP) are funded at an annual level of $100 million out of a total budget of $285 million, while ATP awards in these areas have provided R&D funding of more than $200 million out of $1,390 million since the beginning of the program. Thus, NIST has a large investment in the area of CMMP, reflecting the central role that materials research plays in the future of the modern high-technology economy.

CMMP-related research at NIST is performed in virtually all areas of the MSLs, including the Physics, Chemical Science and Technology, Materials Science and Engineering, Building and Fire Research, and Electronics and Electrical Engineering Laboratories. The research projects are quite varied, covering a wide range of materials and dimensions, with an increasing emphasis on soft materials and materials-by-design efforts. Several NIST scientists have recently been recognized for their work in this area, including William Phillips who in 1997 was awarded a share of the Nobel Prize in Physics for his work on laser cooling of atoms (work instrumental in the production of Bose-Einstein condensation); John Cahn, who this year was awarded the National Medal of Science for his seminal work on quasi crystals and spinodal decomposition; and Charles Han who this year was awarded the High Polymer Prize of the American Physical Society. Some examples of NIST internal research will help to convey this breadth.

The NIST Polymers Division is the oldest and likely the best polymer research center in the federal government. The scientists of this division conduct a broad range of research in polymers, including measurements of the properties of polymer blends, which are the key to high-performance plastics with tailored properties. As one example, they study mixing, isotropic structure formation, and the effects of shear fields on phase equilibria in real time, using neutron, x-ray, and light-scattering and microscopy techniques. The information obtained is critical in understanding the industrial processing of these important materials. NIST researchers are also heavily involved in semiconductor metrology—an increasingly important activity as device size is decreased. In addition to producing Standard Reference Materials, we are developing atomic-scale measurements in which electrical measurements are conducted on test structures made in single crystal silicon, which are then referenced to atomic layers. This will allow development of extremely well-calibrated line width measurements, directly traceable to NIST standards. As a final example of an area of in-house research, NIST researchers are heavily involved in magnetic effects, especially at the nanometer scale. As magnetic storage density is pushed ever higher, the ability to perform such measurements will become increasingly important. For example, NIST has recently constructed a low-temperature (2 K) scanning tunneling microscope with both high magnetic field capability and in situ molecular epitaxy capability for metals and semiconductors. This instrument will allow autonomous atom-by-atom assembly of nanostructures for research use. On a larger scale, NIST also has a special role in materials for civil infrastructure, including concrete. For example, we have a strong competence in computational materials science of concrete and provide about 20 analytical software programs for concrete on a Web site that is visited by over 1,000 users per month. Among the computational models is one that is used to calculate the rate of migration of salt used on bridges to the reinforcing steel in the concrete.

In addition to this in-house work, the ATP, since its inception, has supported a number of important materials projects in industries (often with university participation). This support has always come with approximately equal contributions from the participants. With support from ATP, Non-Volatile Electronics, Inc., has developed and demonstrated giant magnetoresistance computer memory cells, which will form the basis for nonvolatile computer memories. Motorola and others are helping to commercialize this application. Texas Instruments has worked with Nanopore, Inc., a small New Mexico company, to incorporate xerogel insulation into an integrated chip and used that along with copper wires to develop a new microchip fabrication technology with very exciting possibilities. In yet another project supported by ATP, Aastrom Biosciences, Inc., of Ann Arbor, Michigan, has developed a desktop-sized bioreactor that grows stem cells rapidly, thus markedly reducing the number of stem cells that must be extracted (painfully) from the donors. This device is now in clinical trials and promises to cut costs as well as reduce donor pain.

NIST also provides a number of research tools for researchers and operates them as national facilities. The NIST Center for Neutron Research (NCNR) is the best and most cost-effective neutron facility in this country, serving more than one-half the total number of neutron users. In 1998, the facility had more than 1,500 participants (over 800 of whom actually came to NIST) from 50 companies, 90 universities, and 30 other government laboratories and agencies. CMMP-related measurements performed at the NCNR include the structures of superconductors and colossal magnetoresistance materials, the structures of lipid bilayers and chemical films, motions of molecules and macromolecules in catalysts and solutions, Standard Reference Material certification of zeolites and aerospace alloys, and phase transitions in polymer and magnetic thin films. NIST intends to continue to improve and operate the NCNR for at least the next 25 years to meet critical national measurement needs. NCNR scientists will also help in the development of the instrumentation at the new Spallation Neutron Source now being designed and constructed at the Oak Ridge National Laboratory.

For the future, NIST research will continue in many of the areas highlighted in the report on Condensed-Matter and Materials Physics that this forum of the Solid State Sciences Committee has introduced. We foresee a growing industrial use of and interest in soft materials, including biomaterials, for applications from medicine to computation. Another clear trend for the future is the move to the nanometer scale in many different areas of technology. Magnetic phenomena will continue to grow in importance. To ensure that the necessary measurement capabilities and standards are available when they are needed, we must remain at the forefront of research in all of these areas. Many of these new opportunities will require the best possible research facilities, both large and small, and NIST will continue to develop, build, and operate those where we have a special role. In planning our future, the insights contained in this report will inform and guide our choices.

Perspectives from the National Science Foundation

Robert A. Eisenstein
Assistant Director, Mathematical and Physical Sciences
National Science Foundation

Materials Research and Education at NSF: Materials in a New Era

Cautioning that many changes are currently being considered and are under way, Eisenstein listed the Directorates and Research Offices at the National Science Foundation (NSF). These include Biology; Computer and Information Science and Engineering; Education and Human Resources; Engineering; Geosciences; Mathematical and Physical Sciences (MPS), Social, Behavioral, and Economic Sciences; and the Office of Polar Programs. There are currently three NSF-wide budget themes: Knowledge and Distributed Intelligence, Life and Earth's Environment, and Education of the Future.

The Division of Materials Research (DMR), which funds a large portion of solid state science and materials research, is one of the divisions in MPS; the others are Astronomical Sciences, Chemistry, Mathematical Sciences, and Physics. MPS also contains an Office of Multidisciplinary Activities, which has been quite successful in promoting and dealing with cross-disciplinary research. The MPS $792 million request for fiscal year 1999 is the largest within NSF, with Education second at $683 million. NSF's responsibility in educational matters is large and growing. In an effort to better justify and explain its mission to the public, MPS has formulated a "portfolio" that includes Fundamental Mathematics, Origins of the Universe, the Quantum Realm, Molecular Connections, and Discovering Science, the last focused on education. Research within MPS spans an enormous range of length scales, from 10^{-28} cm during the "big bang" through protons, atoms, viruses, and astronomical systems to the universe at 10^{28} cm. A particularly important aspect of this, described by Moore's Law, is the exponentially increasing density of information storage with time and the concommitant reduction of length scales associated with current technologies. We are rapidly approaching fundamental limits set by quantum mechanics. This very exciting science has clear relevance to technology. So, what's the problem?

The NSF budget has doubled within the past decade, between 1988 and 1998. In contrast, the budget for MPS has increased only by 60 percent. Put differently, the share of the NSF budget devoted to mathematical and physical sciences plus materials research in engineering decreased from 29.1 percent in 1986 to 21.9 percent in 1998. Clearly, MPS has not kept up with the rest of the Foundation. Where has all the money gone? It has gone to engineering, biology, education, and computer science. It is essential that we show that MPS research has a direct impact on these fields. Eisenstein quoted Frederick Seitz, President Emeritus of the Rockerfeller University, who wrote in 1987 in *Advancing Materials Research,* "Perhaps what is most significant about materials research throughout its history is that . . . it tended to be a major limiting factor in determining the rate at which civilization could advance."

Eisenstein called attention to the National Science Foundation Web site, http://www.nsf.gov/, which contains extensive and detailed information about the NSF. He then quickly summarized some of it. Materials research at NSF is funded as follows: 63 percent through DMR, 14 percent each through other divisions within MPS and in the Engineering Directorate, and 9 percent elsewhere in the Foundation. The $300 million devoted to materials research is approximately 10 percent of the total NSF budget, $230 million of it awarded through the Directorate of MPS. Within DMR, 48 percent, or roughly one-half the budget goes to research projects, 31 percent to centers, and the remaining 21 percent to instrumentation and facilities. Eisenstein provided additional detailed information on the allocation of funds during fiscal year 1998 among subunits of DMR—namely, the various disciplinary subprograms, the Materials Research Science and Engineering Centers (MRSECs), the Science and Technology Centers, the national facilities, and the Instrumentation for Materials Research Program. He also provided a list of MRSECs as well as the winners of the most recent competition. Information was also provided regarding DMR partnerships with industry and business, other agencies, government, international projects, and professional societies. The Division of Materials Research supports a sizable number of people, ranging from senior scientists to undergraduate students, as well as teachers at the precollege level and students in educational outreach programs. DMR is involved in educational issues throughout its activities at all levels, including K-12. These activities range from those in the MRSECs to those in science and education modules.

Regarding the future, Eisenstein quoted Antoine de Saint-Exupery, "As for the future your task is not to foresee it but to enable it." He listed a number of interesting topical workshops that have been held, as well as international materials workshops involving participation in various combinations by U.S., Canadian, Mexican, European, Pan American, Asia-Pacific, and African representatives. Various facilities are under discussion; a major new facility, the Spallation Neutron Source, is currently under construction.

Neal Lane was quoted, "It is necessary to involve materials scientists in a new role, undoubtedly an awkward one for many of them, that might be called the 'civic scientist.' This role is one in which science shares in defining our future." Eisenstein closed with the following message, "Materials research has been and will continue to be an essential part of the MPS and NSF scientific and engineering enterprise."

II. Materials R&D in a Changing World

Report of the Committee on Condensed-Matter and Materials Physics

Venkatesh Narayanamurti
Harvard University
Chair, Committee on Condensed-Matter and Materials Physics

Condensed-matter and materials physics (CMMP) plays a central role in many of the scientific and technological advances that have changed our lives so dramatically in the last 50 years. CMMP gave birth to the transistor, the integrated circuit, the laser, and low-loss optical fibers so important to the modern computer and communication industries. The years ahead promise equally dramatic advances, making this an era of great scientific excitement for research in the field. Communicating this excitement and ensuring further progress are the main goals of the CMMP report.

Over the decade since the last major assessment of the field, important results and discoveries have come rapidly and often in unexpected ways. These advances range from development of new experimental tools for atomic-scale manipulation and visualization, to creation of new synthetic materials (such as bucky balls and high-temperature superconductors), to discovery of new physical phenomena such as giant magnetoresistance and the fractional quantum Hall effect.

An enormous increase in computing power has yielded qualitative changes in visualization and simulation of complex phenomena in large-scale many-atom systems. Progress in synthesis, visualization, manipulation, and computation will continue to have an impact on many areas of research spanning different length scales from atomic to macroscopic. Strong impact may also be expected in "soft" condensed-matter physics, particularly at the interfaces with biology and chemistry.

The priorities of society are shifting from military security to economic well-being and health. Changing societal priorities, in turn, create shifting demands on CMMP. Among these growing demands are improving public understanding of science, allowing better education of scientists and engineers for today's employment marketplace, and making new contributions to the nation's industrial competitiveness.

The key challenges facing condensed-matter and materials physics are the following:

- Nurturing the intellectual vitality of the field—particularly the facilitation of the research of individual investigators and small teams in areas that cross disciplinary boundaries;
- Providing the facilities infrastructure for research—for example, creation of laboratory-scale microcharacterization facilities at universities and large-scale facilities at national laboratories;
- Enhancing efforts in research universities to improve integration of CMMP education and research, particularly at the boundaries of disciplines, and to prepare flexible and adaptable physicists for the future; and
- Developing new modes of cooperation among universities, colleges, government laboratories, and industry to ensure the connectivity of the field with the needs of society and to preserve the fertile, innovative climate of major industrial laboratories, which have played a dominant role in CMMP research.

The different modes of research—benchtop experiments, larger collaborations, and so on—are evolving steadily. The work that is carried on in these varied venues is complex and diverse, and the committee has paid special attention to describing the forefronts of research in terms of a small number of research themes. These themes, listed in Box 1, are discussed in some detail in the Overview of the CMMP report and reappear in each of the chapters of the report.

One of the themes that has captured the imagination of theorists and experimenters alike is the structure and properties of materials at reduced dimensionality—for example, in planar structures. Large-scale integrated circuits depend on understanding the behavior of semiconductors in such configurations, so the potential for impact is apparent.

NOTE: This article was prepared from written material provided to the Solid State Sciences Committee by the speaker.

BOX 1: Research Themes in CMMP

- The quantum mechanics of large, interacting systems
- The structure and properties of materials at reduced dimensionality
- Materials with increasing levels of compositional, structural, and functional complexity
- Nonequilibrium processes and the relationship between molecular and mesoscopic properties
- Soft condensed matter and the physics of large molecules, including biological structures
- Controlling electrons and photons in solids on the atomic scale
- Understanding magnetism and superconductivity

A number of actions are required to maintain and enhance the productivity of the field of condensed-matter and materials physics. These actions involve each level of the hierarchy of research modalities and the interactions among the various levels and the various performers. The principal recommendations of the cmmittee are summarized as follows:

- The National Science Foundation (NSF), the Department of Energy (DOE), and other agencies that support research should continue to nurture the core research that is at the heart of condensed-matter and materials physics. The research themes listed in Box 1 provide a guide to the forefronts of this work.
- The agencies that support and direct research in CMMP should plan for increased investment in modernization of the CMMP research infrastructure at universities and government laboratories.
- The NSF should increase its investment in state-of-the-art instrumentation and fabrication capabilities, including centers for instrumentation R&D, nanofabrication, and materials synthesis and processing at universities. The DOE should strengthen its support for such programs at national laboratories and universities.
- The gap in neutron sources in the United States should be addressed in the short term by upgrading existing neutron-scattering facilities and in the longer term by moving forward with the construction of the Spallation Neutron Source.
- Support for operations and upgrades at synchrotron facilities, including research and development on fourth-generation light sources, should be strengthened.
- The broad utilization of synchrotron and neutron facilities across scientific disciplines and sectors should be considered when agency budgets are established.
- Federal agencies should provide incentives for formation of partnerships among universities and government and industry laboratories that carry out research in condensed-matter and materials physics.
- Universities should endeavor to enhance their students' understanding of the role of knowledge integration and transfer as well as knowledge creation. In this area, experience is the best teacher.

Action on these issues will allow us to capture the opportunities for intellectual progress and technological impact that continue to emerge in condensed-matter and materials physics.

Materials R&D in Industry

Cherry A. Murray
Bell Laboratories, Lucent Technologies

The Changing Role for Physical Science Research in Industry in the "Information Age"

Today industry funds about two-thirds of total U.S. R&D, amounting to nearly $130 billion in 1997. The U.S. government supplies the remaining one-third of the funds spent on R&D in the United States (nearly $65 billion). Of federal funding in 1997, about 35 percent (roughly $23 billion) went directly to industry, 28 percent to national laboratories, 22 percent to universities, and the remainder to federally funded R&D centers and nonprofit organizations. Today, total federal funding of industrial R&D has declined to about three-fifths of its high point of a decade ago. "Blue sky" corporate research has declined sharply in this decade in all economic sectors, to about one-tenth to one-third of its 1988 extent, depending on the company. Also

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NOTE: This article was prepared from written material provided to the Solid State Sciences Committee by the speaker.

companies are attempting to measure and monitor more closely the output of both research and development, linking both to new product development. I define "blue sky" research as research that is not linked in any way to a possible product or is at least 15 years away from becoming a product. An emerging trend in the last several years that offsets this bleak picture for the future of industrial research is the recently renewed support for long-term research in the information technology (IT) sector. I define long-term research as that which could be at least 5 to15 years out but can be linked to possible future potential products of interest to the company.

R&D spending in the United States varies dramatically by economic sector: About 20 percent of corporate revenues are spent for R&D in the pharmaceutical sector, from 15 percent to 18 percent in the IT software sector, from 10 percent to 15 percent in the IT hardware sector, about 5 percent in the chemical/materials sector, at most 5 percent in the automotive/transportation sector, and only 1 to 2 percent in the energy/power sector of the economy. In this article, I will focus on the fast-growing IT sector, whose revenues constitute about 10 percent of the current gross domestic product. This includes U.S.-based companies such as AT&T, IBM, Motorola, Lucent, General Electric, Intel, Lotus Development, Microsoft, Silicon Graphics, Bay Networks, Adobe Systems, Tandem Computers, and so on. In this sector in 1967, hardware products accounted for 89 percent of the revenues; software, 2.6 percent; and services, 8 percent. Over the years, those percentages have dramatically changed, with the current balance more strongly favoring faster-growing software and services over hardware: In 1996, 50 percent of the revenues were related to hardware, 20 percent to software, and 30 percent to services. IT corporations have reacted by rebalancing their hardware (physical sciences) versus software and services (mathematics and computer science) research mix. For example, at Bell Laboratories, the central corporate research has evolved from a traditional hardware:software 70:30 split in the 1970s to closer to 50:50 today.

Some of the trends in corporate research in the IT sector can be summarized as follows:

The years of the 1970s and 1980s were the era of the Cold War, the last of Vannevar Bush's "New Frontier," and the age of the hardware near-monopolies (the Bell System, IBM, GE, and so on). The justification of corporate research could be characterized as "just in case." Blue sky research in the physical sciences flourished in industry. During the mid-1980s to the1990s, the Cold War ended; monopolies such as AT&T, IBM, and GE broke apart; software grew in importance; many corporations retrenched; and major U.S. consortia such as Sematech, SRC, MONET, and NSIC were formed in an attempt to pool resources for precompetitive research and involve universities, as well as to train a technical work force necessary for development and manufacturing. The justification for corporate research can be characterized in this era as "just in time." Many corporate central research laboratories were broken up and distributed to the various business units and focused on shorter-term product development. In many accounts, this created fears of the existence of a "valley of death" for research on products that are 5 to 10 years in the future: Companies were focusing most of their efforts on the period 0 to 5 years out, and universities and government laboratories were focusing on the period beyond 10 years out. In the silicon integrated circuit industry, this has been the justification for the formation of industry-university-federal laboratory consortia such as MARCO (the Microelectronics Advanced Research Consortium) to fill this gap.

In the late 1990s into 2000, because of the technological advances of this sector of the economy, we have entered the "Information Age": Corporations are global, there is exponential growth in both technology and profits for the IT sector, there is strong competition in hardware while new monopolies emerge in software and speed-to-market is essential, and the gap is closing between research and products while hardware information technologies are approaching their fundamental limits. Now, because of the exponential trends in all information technology, devices are becoming smaller and faster and, acquiring more functionality, all at lower cost, and are rapidly approaching real fundamental limits. The justification for corporate physical sciences research for much of the hardware IT sector is that it is "just indispensable." If the corporation wants to be a technology leader, being first to market is viewed as critical. This speed-to-market requires a much tighter coupling of research to products combined with a longer-term in-house research effort—allowing the fastest innovation to occur while avoiding being blindsided by competitors.

We will be approaching some fundamental limits in the next 20 years (around the year 2010). For example, silicon device scaling will produce metal-oxide semiconductor field-effect transistors with gate oxide thickness of less than 5 atoms, magnetic data storage spot sizes will approach the paramagnetic limit, and transmission of optical pulses through optical fibers will be approaching the Shannon information theory limit. Many companies in the hardware IT sector are actually increasing their support of internal long-term research as a result.

Why do companies spend money on internal R&D? If they are in the leading-edge technology market for the long haul and have evolved past the startup phase, they must maintain critical competencies in house, maintain an infusion of new technology, stimulate innovation, fuel growth and business development, extend their product horizons, and recruit top people. It is difficult to accomplish these objectives by funding external research at a university or within a consortium or by buying small companies. Companies spend money on external or cooperative R&D to leverage their internal R&D efforts, develop new applications for existing technology, make use of facilities and equipment that are too costly to develop internally, and acquire access to a skilled work force in the technologies relevant to their products. The major problems encountered by corporations in carrying out external or cooperative R&D at universities or government laboratories are the complications in intellectual property ownership and licensing, the relatively slow cycle times, and the focus on process rather than product that is natural for universities and government laboratories. A 1999 Battelle R&D magazine survey of all industries found that a large majority of respondents, 37 percent, used joint development agreements with other companies for external R&D and 23 percent purchased services from commercial laboratories. Only about 26 percent of respondents used academia for external R&D and about 3.5 percent used federal laboratories.

Why do companies spend money on internal long-term research? There are many reasons, depending on the competitive environment and growth of the economic sector. First, internal research stimulates invention leading to innovation. It provides insurance—it allows a company to maintain a breadth of technological expertise to make use of when it is suddenly needed. When integrated into the R&D community, long-term research can broaden horizons and provides a future beyond several product cycles. Often an internal research organization can be useful in recruiting top people into the business, enthralling customers, and challenging competitors. Internal research also allows companies to keep trade secrets and create a strong intellectual property portfolio, which is essential to become and stay a technology leader.

Two examples where physical science and materials research paid off, causing a factor of two increase in logarithmic slope in the technology "Moore" plots for magnetic data storage and optical networking, respectively, are the invention and development of giant magnetoresistance materials in magnetic read-heads by IBM research and the development of the Er-doped optical amplifier by Bell Laboratories research. There are also many other examples where long-term industrial research has resulted in a paradigm shift in technology and business opportunity for the parent company because it was the first to get products out on the market.

In the 1980s, the chain from physical sciences research to products in industry was either nonexistent (blue sky research) or linear—from applied research in the corporate research organization handing off to a development organization handing off to a manufacturing organization who would eventually create a product and be in contact with the customers. At every handoff along the way, there were roadblocks and bottlenecks—the entire process could take as long as 5 to 10 years, with a relatively low success rate of getting through the whole process and little communication along the way.

That approach no longer is a viable way of innovation. In a typical corporate research group, there are at least four types of research:

1. Long-term research in areas related to future technology needs, often in consultations with customers and marketing;
2. Cooperative long-term research with federal laboratories and/or universities not directly related to near-term future products;
3. Cooperative short- and long-term R&D with other companies in joint development agreements; and
4. A "massively parallel" approach to marketing, research, development, and manufacturing that brings a closely knit team of people from all organizations together to produce a product from a research concept in as little time as months to a few years, maintaining close customer contact and competitor awareness at all times.

In summary, industrial R&D is what has created the "Information Age." IT corporate research has evolved over the decades, but physical sciences research is as essential as ever for leading-edge high-technology companies.

Changing Roles for Research Universities

J. David Litster
Massachusetts Institute of Technology

MIT: A University in Transition

David Litster discussed the changing environment for research at the Massachusetts Institute of Technology (MIT). He pointed out that MIT is in some ways unique among the top 20 research universities in the United States. Of this group, it receives the largest amount of industrial research support and was among the lowest in self-support of research. For these reasons, he warned that one must be careful not to generalize the observations that he made.

The overall federal funding picture, excluding the National Institutes of Health (NIH), is that of flat or decreasing budgets. The Department of Defense (DOD), which supported some 65 percent of materials engineering research between 1993 and 1995, has experienced an overall decrease in funding throughout the 1990s. Its funding for research has not been spared and has fallen from about $16 billion in 1989 to about $9 billion in 1999. DOD-sponsored research at MIT has fared somewhat better, remaining relatively level at about $35 million (in 1993 dollars).

The flat or declining budgets of the federal agencies has put enormous pressure on overhead recovery rates at MIT. Between 1980 and 1990, the amount of indirect costs at MIT covered by the federal government hovered around 50 to 56 percent, whereas the amount covered by internal MIT sources was between 32 and 38 percent (the remainder was picked up by state sources). Since then, the proportion of the indirect costs borne by MIT has climbed steadily while the federal share has plummeted. The change was so rapid that by 1996 MIT was covering about 52 percent of the costs and the funding agencies were covering only about 36 percent—a complete reversal of roles.

Furthermore, during the 1980s, the federal government cut its financial aid for students. This trend is true for all schools that continue a need-blind admission policy. In 1980, MIT supplied about 50 percent of the financial aid to students. By 1990, MIT's share had grown to about 80 percent and has remained there since.

One thing MIT has done to counter these trends is to engage in partnerships with industry. Industrial partners who support research at MIT include Amgen, Ford Motor Company, Merck, and Merrill Lynch.

MIT Research Support Industrial Partnerships are long term (5 to 10 years). The support provided by these partners amounts to about $3 million per year. A joint committee of MIT and industry representatives allocates $2.5 million of this. The remaining $0.5 million is a "discretionary" fund.

The normal MIT policies on research support are followed in these partnerships. This means that the research should be of intellectual interest to the principal investigator on the project. The principal investigator is responsible for directing the project, which should provide some mix of thesis opportunities for students, the advancement of knowledge, or advancement of the state of the art. Any visiting scholars on the project are chosen by the faculty and are expected to make significant contributions to the research project. Ideally, these industrially sponsored research projects should balance MIT's educational purposes and the search for knowledge to meet the needs of industry.

The results of these partnership projects must be freely published—this is a requirement for MIT to maintain its tax-exempt status. Thus the results are available to anyone, regardless of the source of the research support. There is no delay in giving students academic credit for the work; however, to protect patent rights, publication of the results may be delayed by as much as 30 days (60 days in extreme circumstances).

The industrial sponsor approves any thesis proposal and agrees in advance that anything falling within the proposal can be freely published. The sponsor has 30 days to review the thesis and publications to ensure that they contain no proprietary information.

MIT retains title to all intellectual property developed by employees of MIT using significant funds or facilities administered by the university. All research sponsorship agreements at MIT are negotiated by the university and, regardless of the sponsor, transfer the rights to intellectual property to MIT. The university, in turn, licenses the intellectual property to encourage technology transfer for development by industry in the public interest. Intellectual property that is developed by visiting scholars also belongs to MIT.

If products produced under license from MIT are to be sold in the United States, then MIT requires a substantial amount of the manufacturing of that product to

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NOTE: This article was prepared from notes taken by a staff member of the Board on Physics and Astronomy.

be carried out in the United States. The royalty split is one-third to the inventor before expenses; the remaining after-expense income is divided equally between the inventor's department or laboratory and the central administration of MIT.

The sponsor may have a nonexclusive royalty-free license to these inventions for internal use. The sponsor may also obtain exclusive commercial rights and pay royalties to MIT, or the sponsor may obtain a nonexclusive commercial license in exchange for paying the patent maintenance costs, or the sponsor may waive all rights and receive 25 percent of the after-expense income from the patent. If MIT chooses not to file a patent, then the sponsor has the right to do so in MIT's name. The sponsor must then choose from the four options listed above.

Changing Roles for Government Laboratories

John P. McTague
Vice President (retired), Ford Motor Company

John McTague, in introducing his subject, declared that he would focus primarily on trends within the Department of Energy (DOE) laboratories, a focus sharpened by the perspectives that he has gained as co-chair of the Secretary of Energy's Laboratory Operations Board. He noted that the DOE laboratory complex has received considerable criticism over recent years, primarily in two areas: (1) for alleged, or perceived, duplication of effort within the laboratories; and (2) for the laboratories' tendency (in view of ever-tightening budgets and decreasing programmatic support in some of their traditional areas) toward "mission creep." Laboratories invent new missions—in particular, the formerly popular and politically correct mission of "industrial competitiveness," which many of the DOE laboratories embraced as the Cold War came to an end and as the defense-driven support for R&D began to wane.

These criticisms and the associated perception of DOE's inefficient management of its laboratories were highlighted in the Galvin Commission Report of 1994. McTague noted that the aforementioned critics are at least somewhat off the mark in the sense that the laboratories do not have missions from Congress—it is the Department of Energy that has the missions. The laboratories are premiere among the DOE's resources to execute its missions. Therefore, it is the Department of Energy's job to bring the laboratories, universities, and other R&D providers to bear, both collectively and individually, to accomplish its missions.

A challenge that has been gaining increasing acceptance and discussion in recent years is how to get the laboratories to operate as a true system and, more generally, how laboratories and other partners can work more effectively together to attack problems of national importance. In attempting to address this question, McTague described four examples of more-or-less successful orchestration of the suites of instruments represented by these laboratories and their partners.

The first example is the Center of Excellence for the Synthesis and Processing of Advanced Materials. It is a virtual center, directed by George Samara of Sandia National Laboratories, and involves 12 DOE laboratories, as well as several industries and some industrial partners. The idea is, with a modest incremental investment of only about $2.5 million a year, to provide value-added, enhanced coupling among projects of related natures that are already taking place within these many laboratories. Selective projects from within their suite of capabilities are coordinated and joined together, so that the whole exceeds the sum of the parts. This has been a very successful enterprise, and McTague identified some key elements of that success through the example of aluminum alloy formability.

In the auto industry, which worldwide produces something like two vehicles per second, a small advance can have a huge integrated impact. The center has achieved such an advance in this highly leveraged application. Similar opportunities arise in the areas of joining and welding, and McTague described some examples of using a transparent welding analog where the effect of weld freeze rates on joint shapes can be directly observed.

One important attribute of this center's approach is that it is multidimensional in the sense that the number of component projects is large enough that statistically a reasonable number of them will succeed, and the success of the whole project does not depend on every single element being successful on its own. This fairly loose coupling among the projects minimizes, therefore, the chances of overall failure and gives high leverage to the added value of the investment in affect-ing the coupling.

McTague's second example is "The Partnership for a New Generation of Vehicles," an extremely large project costing approximately $600 million a year. It involves USCAR (a consortium of the Big Three automakers in the United States) and a Department-of-Commerce-led government consortium of the Departments of Commerce, Defense, Energy, Transportation, and Interior, as well as the Environmental Protection Agency, the National Aeronautics and Space Administration, and the National Science Foundation (NSF). Industry has a very large influence on how the government participants allocate their resources in this case. The good news of this project is the high parallelism of interest among all the partners in reaching the stated goal of achieving a 300 percent increase in fuel efficiency in the next generation of vehicles.

The specific goals are stated as outcomes, but the paths to those outcomes are not specified. So, for example, the flywheel approach has been tried and abandoned. Fuel cells, on the other hand, look considerably more promising. The bad news is that there is an extremely high overhead as a result of working together because there are so many players. Indeed, it took 18 months to get the detailed agreements and working relationships in place for this collaboration. Nevertheless, it represents a collaboration at an interagency level, involving many of the Department of Energy laboratories and funding from several of the agencies. It is a good example of the kind of orchestration that is required for large advances in technology.

The third example is the Spallation Neutron Source project. This $1.3 billion facility, to be built at Oak Ridge National Laboratories, involves a collaboration among five DOE laboratories. The major risk and disadvantage of this project, aside from its considerable expense and complexity, is that it is "one-dimensional." Every single element, from the source through the accelerator, to the accumulator ring to the target station to the laboratory instruments is in series. The overall project can succeed if, and only if, every one of the elements, namely every one of the laboratories, does its job 100 percent correctly.

It is questionable whether proper orchestration of such an effort is really possible given the current structure of the laboratories and the Department of Energy. This project lacks what McTague would call the "statistical safety" of his first two examples. It is very much an open and important question as to whether the five DOE laboratories in this case can operate as a system. The answer is that they simply have to. The question remains, can they?

The fourth example is a major new initiative in information technology. "Information Technology for the 21st Century," or IT², adds approximately $150 million to the research portfolio—primarily in the NSF, but with additional funding for several of the other agencies as well. The idea is to push forward the development of distributed and highly interconnected computing capabilities. It is very important because it might lead to a revolution in engineering and product development, including safety, through the use of more realistic simulations.

McTague mentioned, as an aside, that at the Ford Motor Company, simulation has become an integral part of design and also product worthiness. Indeed the company is now at point where the simulation of an automobile crash can be "more accurate than the experiment" in the sense that in the simulation you can keep track, reproducibly and quantitatively, of every element of the vehicle and the event, whereas an experiment must typically be repeated many times without assurance that the exact initial conditions are reproduced or that measurements are done in sufficient detail. The IT² initiative resembles the DOE's major simulation advances in the Accelerated Strategic Computing Initiative Program and the Strategic Science Initiative. Even within the DOE, those two projects are really not being coordinated.

The involvement of the DOE with the NSF and other agencies in this major IT² initiative is still incompletely formed. Indeed the ownership and leadership of the whole IT² enterprise are still unsettled. Even with these caveats, though, McTague felt that the prospects for success are reasonable because the project is multidimensional. In other words, the success of the whole enterprise does not depend on the success of every single element working to perfection. The elements in this case are not catastrophically interdependent.

McTague concluded by noting that he felt cautiously optimistic that the agencies and the laboratories would develop more coherent and fully orchestrated ways of working together and that they might in fact evolve from a collection to a system in the foreseeable future.

During the questions following his talk, David Litster of MIT noted that the DOE's problems include having a number of "associate conductors" in their orchestra in the form of program managers within the headquarters and also at the field offices. McTague's comment was that the DOE often lacks the necessary in-house technical expertise among its managers, and therefore it is not managing the laboratories as a system. The Laboratory Operations Board has been examining the question of laboratory governance for a couple of years now, and a report on this is being prepared with a set of recommendations. At present, the preliminary grade is no better than a C+ in improving the systems approach to laboratory management by the DOE, and the rate of progress has been slow.

Murray Gibson of the University of Illinois asked about the notion of "corporatization" of the laboratories, as suggested by the Galvin Report. McTague's response was that the Galvin Report really indicated that it was the management dynamics of the laboratories that is poor, which stems from the government's tendency to focus on inputs as metrics rather than on outcomes. The Galvin Report suggested strongly that this emphasis is backward. Industry measures outputs and outcomes in order to determine its success. The most easily measured is the bottom line in the profit and loss statement. But McTague also noted that the idea of industrial or good business practices in management was the original basis for the concept of the government-owned, contractor-operated approach to the national laboratories. The question with respect to the DOE laboratories then becomes, "Is the path from the present input and compliance-driven focus to output and performance-driven focus adiabatically reversible?" The Galvin Report suggests that the answer is "no," and the Laboratory Operations Board is trying to figure out ways to approach the answer in the affirmative.

Jack Rush raised concerns about the DOE rules that impute increasing liability to the maintenance and operation contractors for the laboratories, implying that these rules inhibit the performance of existing contractors or the participation of new contractors who would do a good job at running the laboratories. McTague's answer was that the DOE "mega rule" allows the nonprofit maintenance and operation contractors to get relief from these increased liability concerns, but because for-profit contractors generally get large fees to run the laboratories, they are expected to address the liabilities. It remains unclear whether the shift of liability burden to the contractor is actually improving performance and lowering costs. He suggested that we need to have more data to examine the cost/benefit analysis of this "mega-rule" approach. Although it is clear that the costs to manage the laboratories have gone up, particularly for environmental safety and health concerns, it is not clear whether the health and safety of the environment in the laboratories have increased correspondingly.

Panel Discussion of the Future of Materials R&D

Moderator: Tom Russell, Chair, Solid State Sciences Committee

Panel: Cherry A. Murray, Committee on Condensed-Matter and Materials Physics; Venkatesh Narayanamurti, Chair, Committee on Condensed-Matter and Materials Physics; Skip Stiles, House Science Committee Minority Staff; William Oosterhuis, Department of Energy; Harlan Watson, House Science Committee Majority Staff; Thomas Weber, National Science Foundation

A panel discussion was held at the end of the first day. The panelists were asked to comment on the future of condensed-matter and materials physics research. There was a general discussion about changes in research funding during the previous decade and how the community can cope with them, the need for improved education at all levels, and the future directions of the field.

Skip Stiles pointed out that Congress will be living under spending caps for the next 2 fiscal years and that there will be no additional money until then unless Congress lifts the caps. Harlan Watson concurred with Stiles and said that he sees little likelihood that the caps will be lifted—at least in the near term.

According to Watson, the Administration's outyear projections for Department of Energy (DOE) research funding will remain flat for the next few years. To meet the flat budgets, the major DOE research facilities may need to cut costs by reducing their operating hours.

Thomas Weber pointed out that funding in his division has also been flat. He postulated that if the NSF were a mission agency it would: (1) strengthen

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NOTE: This article was prepared from notes taken by a staff member of the Board on Physics and Astronomy.

the physical infrastructure, (2) integrate research and education, and (3) promote partnerships.

Weber said that, despite some resistance among program managers at first, he sees funding of education as a win-win situation for his division. Venkatesh Narayanamurti pointed out that the NSF is one of the major stakeholders in the field and that although we have come a long way in preparing students to work in interdisciplinary teams, there is still much room for improvement.

Cherry Murray pointed out industry's need for highly skilled people and that university training is a key to the success of domestic and global industries. She said that industry often presents a "problem-rich" environment, with exciting science, and pointed out that condensed-matter and materials physics (CMMP) has applications that can be important for the Department of Defense (DOD), the National Science Foundation (NSF), DOE, or industry.

Stiles said that the CMMP community can make a compelling argument for increased funding but that the money will go to other needs unless the university and industrial communities present a unified case to Congress on a continuing basis. He pointed to *The Physics of Materials* as a document with the right tone and shape for Congress and said that much more along that line needs to be done.

Narayanamurti expressed a note of caution regarding changes at the DOE. He was concerned that the balance in the number of laboratories is very delicate. He said that if the DOE tries to fund too many laboratories, then rivalry between laboratories working in the same area will drag down the system and that, on the other hand, if the DOE funds too few laboratories, then there will not be enough interaction between them to stimulate progress. In his view, a key component in maintaining this balance is strong technical leadership.

Weber was concerned about the need he sees to promote international collaboration without giving away our advantages in research. He sees the main challenges of the future as making links to biologically inspired materials, inventing and improving microscopes and other instruments, making sense of complex phenomena, and producing students interested in science.

William Oosterhuis reminded the audience that scientists are involved in CMMP because of the stimulating questions that can be attacked using modern instruments and techniques. He would like to see a strengthening of the neutron infrastructure and new experimental techniques using them. He is concerned with how we can best study the growing array of self-organizing materials. He claimed that one technique is to combine the Scientific Simulation Initiative with combinatorial chemistry to fine-tune the computations. He believes that this combination will allow DOE-funded researchers to do things never before possible in modeling complex materials.

Following the panel discussion, the panelists received several questions from the audience.

Question: We are in danger of losing a cadre of excellent young researchers. How can this be addressed in an era of flat or declining budgets?

Narayanamurti replied that more Young Investigator awards need to be funded. NSF and the Office of Naval Research are funding some, but more needs to be done. Oosterhuis said that the DOE is interested in funding young people but there needs to be a formal program set up at the agency for funding them. Weber said that the NSF has established the Faculty Early Career Development (CAREER) program and that although his division has no formal program, he has set aside a small pool of money to fund a competitive program geared toward a diverse pool of applicants doing risky research.

Question: We all heard a lot about DOD's downsizing. Agencies used to look around and say, "If someone else is funding research in topic X, then we don't need to." Now there are areas that are not being investigated at all. Should agencies get money to pick up the areas that are not being adequately funded?

Stiles responded that under the current conditions, science has virtually no voice in Congress. He said that the science community needs to step up and help Congress set its priorities for funding and that it must be an ongoing process. Watson countered that Congress is not the right body to make these decisions. He said that the President's budget submission is where these priorities are set and the Office of Science and Technology Policy (OSTP) is probably the place to start.

Question: The scientific community is fairly effective at pointing out the benefits of doing research in particular fields. Is it less effective at pointing out the consequences of not funding certain research?

Stiles replied that if the community were prepared, it could help get more money for research, but the groundwork must be done. Furthermore, he said that the funding does not need to be tied to a particular crisis.

Question: Does the scientific community need a lobby to put pressure on Congress and OSTP?

According to Stiles, members of Congress do not need to have a deep understanding of the field. He said that what matters to them is how it touches the lives of people in their districts. Weber reiterated that the community should not focus all of its attention on Congress but should talk to the executive branch because it makes the initial budget proposal.

Question: We have heard many times that CMMP contributes to prosperity. How can we get the message across that if our government invests in CMMP, our society will get the largest return on the investment?

Stiles asked, "How is Congress getting this message?" He said that someone has to tell people in Congress on an individual level and inform public policy structure—and that information needs to be consistent. Judy Franz, Executive Officer of the American Physical Society, pointed out that the American Physical Society has worked hard to get the message out and that grassroots lobbying is the best way to do this. She added, however, that to be effective it has to be done continuously and making this happen is difficult because the community does not see this activity as an essential part of the life of a scientist.

Weber warned that the community needs to be careful in making economic arguments. He said that it is not possible to say how today's funding of research will impact the economy of the future.

Stiles advised the community to stay close to Congress because Congress can do things by accident that can harm the community, for example, the recent provision that makes data available to the public. He observed that research is becoming a commodity—we are going from a system of grants to one of contracts. Watson added that there is no free lunch in research and that most researchers get their money from the federal government.

Question: What are the statistics on collaborations? Is this a way to get federal funding?

Oosterhuis replied that research on significant problems needs to done by teams. He believes that the problems we currently face are more difficult and require input from diverse sources. He is trying to encourage collaboration at DOE laboratories in areas where it makes sense to do so. He pointed out that the DOE has the PAIR program to encourage these interactions. Weber called attention to the GOALI program at the NSF as an example of a program that encourages collaborations.

Question: How can we convert S. 1305 from an authorization bill to an appropriations bill?

Stiles replied that S. 1305 is a good organizing tool but will not produce more money for science. He said that in the short term, only having Congress declare an emergency or lift the budget caps will accomplish that. He urged the community to ensure that the subcommittees that fund the community's work get all the funding they need. Watson responded that the requests need to get into the Administration's budget request; otherwise, it will be difficult to get the requests into the final budget. He said that Congress can only "tweak" the numbers around the edges. Furthermore, he said that the community should bear in mind that there are huge numbers of claimants for any pot of money. Because one Congress cannot bind future Congresses, he thinks a large effort at passing "feel-good" legislation is a waste of time and effort.

III. Materials Education and Infrastructure

Materials Education for the 21st Century

Robert P.H. Chang
Northwestern University

The current state of affairs in U.S. education, although not altogether negative, should certainly give us pause. Over 90 percent of students now graduate from high school; 67 percent of them enroll in college. Approximately 14 million students were enrolled in colleges and universities in 1996. The number of students who enter college is not, however, commensurate with the number of degreed graduates. Indeed, the graduation rate of students attending NCAA Division I institutions in 1996 was a mere 56 percent. At the cost of approximately $10,000 per student per year in a public university, the college dropout rate means that taxpayers are suffering significant losses in both human and financial resources. Particularly in the areas of science and mathematics, students in the United States are lagging behind their international counterparts. The reasons for poor performance in mathematics and science include a dearth of teachers trained in the subject that they teach (only an estimated 30 percent of science and mathematics teachers actually majored in the subject that they are certified to teach) and students' failure to see the connections between scientific and mathematical principles and the world around them. Given students' lagging interest in science and the fact that there are states, Illinois, for instance, that require high school students to take no more than 2 years of science, it is hardly surprising that science and engineering programs are now facing declining enrollments.

In assessing the current state of education, we should also consider the changing population in the United States. Within the next 50 years, groups that are currently in the minority will become the majority. If members of minority groups are not able to receive a top-quality education, then our entire economy will suffer.

As we enter the next century, we find ourselves faced with the challenge of improving our educational system overall. Those of us invested in materials education also face some formidable obstacles. Most importantly, the general public is not aware of the existence of materials science and engineering (MSE). This lack of awareness may be largely attributed to the almost total absence of MSE at the precollege level. Even at the college level, MSE programs number only slightly more than 100, out of the 4,000 colleges and universities in the United States. Only 45—fewer than one-half—of those 100 programs have materials science and engineering departments.

Despite its low profile, materials science and engineering is an extremely important field for at least two reasons. First, MSE involves interdisciplinary teaching, drawing on concepts from engineering, biology, chemistry, physics, and mathematics. Second, these basic disciplines, through materials science and engineering, have countless industrial applications that benefit society. From seat belts and computers to items as basic and mundane as coffee filters, materials science and engineering contributes to the creation of products that allow us to perform daily tasks more safely and efficiently.

Its connection to real-world applications makes MSE a desirable field for many students, who realize that a degree in MSE can secure them a good job. In fact, about 90 percent of students in MSE programs will ultimately work in industry. Only about 10 percent of graduate students in MSE, on the other hand, will pursue careers as serious researchers. Within the past several years, more and more students have been transferring from science departments into MSE or have been doing materials-related research.

The graduate curriculum in MSE has also changed with the times. Specifically, the focus of study has shifted from areas like metallurgy to the study of electronic, polymeric, and biomolecular materials. Given these trends, the hiring of new faculty has been geared toward the recruitment of those with expertise in the study of new materials and in the study of materials at the atomic/molecular level, rather than at the macroscopic level.

One of the most significant sources of support for materials science and engineering is the National Science Foundation (NSF). The NSF funds 28 Materials Research Science and Engineering Centers, all of which promote MSE's multidisciplinary approach to research

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NOTE: This article was prepared from written material provided to the Solid State Sciences Committee by the speaker.

and education. In addition, 4 of the 24 Science and Technology Centers that are sponsored by the NSF are administered through the Division of Materials Research. Finally, a number of NSF-sponsored Engineering Research Centers also do materials-related research.

It is clear, when one looks at the state of education generally, as well as materials education specifically, from the earliest grades up through college and graduate school, that the precollege level requires the most attention. Elementary, middle, and high schools constitute the foundation of our educational system. Statistics show that as students progress through these grades, their proficiency scores on science tests drop dramatically. Fourth graders in the United States, for instance, scored an average of 565 out of 600 points on a science proficiency test, whereas 12th graders earned only 461 points. Additionally, U.S. students perform less competitively as they progress in school. Although the 4th graders placed second only to Japanese 4th graders, the 12th graders trailed students from all other countries in the study.

In light of such findings, we can see that high school in particular is a crucial time for science education. Many high school students lose interest and then find themselves ill-prepared to face the rigors of college-level science courses. Why does this happen? Is there a big difference in the approaches to education, and in particular science education, between high school and college? Can we hold students' insufficient preparation in high school responsible for the high dropout rate among college students? Most importantly, how can materials science education help to bridge this gap between high school and college, particularly in science and engineering?

All materials education initiatives must undertake to:

- Foster greater awareness of the importance of MSE in society and among the general public;
- Introduce materials science and technology at the precollege level to enhance mathematics and science education; and
- Get teachers involved in materials science education and research.

Many universities and centers have embarked on worthy initiatives to reach these goals. Northwestern University has programs for precollege materials science and technology education, for undergraduates (especially minority students) who are interested in materials science and engineering, and for professional development/teacher training.

The desire to provide teachers with the tools to spark their students' interest in science, mathematics, and technology, along with the wish to link university research to precollege education, led to the creation of the Materials World Modules (MWM). Developed with the support of a grant from the National Science Foundation, the Materials World Modules are hands-on, inquiry-based modules that focus on various topics in materials science. The modules have been designed to supplement middle and high school science, mathematics, and technology courses. Each module begins with a teacher demonstration that piques the students' interest. Next, students complete a series of inquiry-based activities, simulating the work that scientists do. Finally, each module culminates in two design challenges, where students simulate the work of engineers.

Materials World Modules is a total materials educational program that also offers services such as workshops for teachers, an interactive CD-ROM, and a Web site where teachers can access help and resources on line. To date, MWM has been introduced in 450 schools nationwide and used by approximately 9,000 students and 450 teachers. At 16 hub sites in 14 states, teachers have been trained in MWM workshops. The next step for the Materials World Modules program will be MWM-2002, a delivery system via the Internet that will enable teachers to order and purchase customized modules on line and to receive teaching development and support services via an interactive Web site.

In addition to the Materials World Modules program, Northwestern University has recently embarked on a collaborative effort with the Intel corporation to promote student participation in science fairs at seven sites in six states. This "Winning with Inquiry" initiative will involve the use of Materials World Modules, introducing students to materials science and technology.

At the college level, Northwestern offers the Research Experience for Undergraduates and Minority Students Programs. Begun in 1986, these programs provide the opportunity for undergraduates from schools across the country to participate in research at Northwestern. These programs encourage promising undergraduates to pursue graduate studies in MSE by enabling them to experience interdisciplinary materials research under the direction of faculty advisors.

Northwestern's Research Experience for Science Teachers allows high school teachers, and some college professors as well, to work with university professors during the summer on research projects related to their subject area.

At the college and graduate level, we must expand materials programs to more colleges and universities, involve college and university professors in materials-related research and teaching, and work toward the collective development of materials courses among science and engineering departments. Industry should also have a significant input in course design for MSE. Finally, at the college and graduate level, we can aim to set up interactive video linkage to other universities—especially minority institutions—whose students can then take advantage of existing courses, seminars, and research collaborations from MSE programs. Northwestern, for instance, is currently in the process of developing interactive video linkage to minority institutions.

Northwestern is also piloting a master's degree in Materials Technology and Education. This degree prepares students to teach technicians in community colleges. The requirements include at least three courses in the School of Education, as well as real classroom and research experience.

At the global level, the United States has the opportunity to set itself up as a role model for other countries wishing to improve and expand materials education at all levels of education and among the general public. International collaboration will also help to ensure greater success for all countries striving to attain these goals. To foster greater collaboration and communication, a series of workshops has been held and will continue to be held in preparation for building a Materials World Network for Education, Research, and Technology. Four NSF-sponsored workshops have already taken place, and a fifth is planned in Africa for the year 2000.

Meeting the Challenge in Neutron Science

Thom Mason
Scientific Director, Spallation Neutron Source
Oak Ridge National Laboratory

Thom Mason discussed the development of neutron-scattering research and the opportunities for new science presented by the Spallation Neutron Source (SNS). The development of neutron scattering has always depended on the availability of new, more powerful sources and techniques. Although the neutron was discovered in 1932, it was not until the late 1940s—after the first reactors were constructed—that sufficient neutron fluxes were available for diffraction experiments. These first experiments, performed by Ernest Wollan and Clifford Shull at the Oak Ridge Graphite Reactor, demonstrated the importance of neutron scattering for determining the atomic-scale structure and magnetic behavior of materials.

In 1957, the National Research Universal reactor became operational in Canada. This reactor design was specifically optimized for neutron production. The increased flux and lower background enabled the development of neutron spectroscopy—the use of inelastic neutron scattering to determine the dynamical properties of atoms in materials. Bertram Brockhouse led the development of neutron spectroscopy and, together with Shull, shared the 1994 Nobel Prize in Physics for the development of neutron-scattering techniques for studies of condensed matter.

The development of cold neutron sources and neutron guides in the 1970s stimulated applications of neutron scattering to studies of large-scale structures including polymers, macromolecular systems, and biological structures. Cold sources shift the spectrum of reactor neutrons from a peak temperature of approximately 300 K (corresponding to a wavelength of 1.7 Å) to 25 K or lower. This greatly increases the numbers of longer wavelength neutrons in the range from 2 to 20 Å, corresponding to important length scales in polymer chains, large molecules, and membranes. Neutron guides efficiently transport neutrons away from the reactor to experimental halls where background levels are greatly reduced. These developments, implemented first on a large scale at the Institut Laue Langevin in France, opened new areas of science and sensitivity to neutron scattering.

Today, we sit at another threshold in the development of neutron scattering. Pulsed spallation neutron sources, based on neutrons produced by bombarding heavy metal atoms with high-energy protons, are demonstrating exceptional promise in neutron scattering from studies of superconductivity to nondestructive measurements of internal stresses in turbine engines. These neutron sources produce intense pulses of neutrons at repetition rates of 10 to 60 pulses per second. The neutrons are moderated and transmitted through beam guides to experiments surrounded by hundreds of detectors. The pulsed time structure and large number of detectors result in enormous data rates for many important scattering experiments, resulting in increased sensitivity and sample throughput.

The neutron is a weakly interacting, nonperturbing probe of matter with simple, well-understood coupling to atoms and spins. The high penetrating power of neutrons means that extreme sample environments can be easily accommodated by passing the neutron beam through the walls of cryostats, furnaces, or pressure vessels. It also means that the interior of bulk samples and manufactured components can easily be probed with neutrons. Unlike x-rays, neutron-scattering cross sections are similar across the periodic table, making light and heavy elements equally visible. In addition, neutron-scattering cross sections are isotope specific, making it possible to distinguish hydrogen from deuterium, for example, in specially prepared samples. This sensitivity to light elements and isotopes makes neutrons particularly useful in determining the location and behavior of hydrogen and other low-Z elements in materials. The energies and wavelengths of neutrons are well matched to atomic and molecular length scales and excitation energies in materials, making the neutron an outstanding probe of structure and dynamics in superconductivity, magnetism, phase transitions, electronic properties, nonequilibrium phenomena, and macromolecular systems.

The Spallation Neutron Source, presently under development at Oak Ridge National Laboratory, will be the world's most powerful pulsed neutron source. The SNS is being constructed by a collaboration of Argonne, Brookhaven, Lawrence Berkeley, Los Alamos, and Oak Ridge national laboratories. Scheduled for completion at the end of 2005, the SNS will provide the nation with unprecedented capabilities in neutron scattering, satisfying a long-recognized scientific need. The SNS will be a 1 MW source, easily upgraded to 4 MW, supporting over 40 instruments. An initial complement of 10 instruments surrounding a target station operating at 60 pulses per second is currently being developed, and a second target station and additional instruments are in the planning stage. More than 2,000 scientists from universities, industry, and government laboratories are expected to perform neutron-scattering research at the SNS each year.

The SNS will enable new science in engineering materials, surfaces and interfaces, magnetic and superconducting systems, macromolecular science and biological structures, real space imaging of living systems, and many other areas of condensed-matter science where increased peak fluxes, signal-to-noise ratios, and data rates contribute to improved sensitivity. In studies of engineering materials, the SNS will provide submillimeter resolution for nondestructive measurements of strain, composition, texture, and plastic deformation history inside bulk materials and components. Neutron reflectrometry will provide monolayer sensitivity for investigations of thin magnetic films and molecular transport studies across biological membranes. Complex, interacting systems such as low-dimensional magnets and charge and spin ordering in superconductors will become increasingly accessible to fundamental study at the SNS. In biological systems, the SNS will help establish the link between structure and function by enabling studies in solution, by locating functional subunits within larger assemblies, and by exploiting hydrogen-deuterium contrast to locate hydrogen in biological molecules. New developments in imaging science are expected based on using the tunability of neutron energies to enhance sensitivity for selected nuclei in living systems. With these and other unique capabilities, the SNS represents the future of neutron scattering—a field that is providing much of our current understanding of condensed matter including magnetism, superconductivity, complex fluids and polymers, and the structure and dynamics of materials.

Toward a Fourth-Generation Light Source

David E. Moncton
Associate Laboratory Director, Advanced Photon Source
Argonne National Laboratory

Historically, x-ray research has been propelled by the existence of urgent and compelling scientific questions and by the push of powerful and exquisite source technology. These two factors have gone hand-in-hand since Roentgen discovered x-rays. Here we review the progress being made with existing third-generation synchrotron-radiation light sources and the prospects for a fourth-generation light source with dramatically improved laser-like beam characteristics.

The central technology for high-brilliance x-ray

NOTE: This article was prepared from written material provided to the Solid State Sciences Committee by the speaker.

beams is the x-ray undulator, a series of alternating-pole magnets situated above and below the particle beam. When the particle beam is oscillated by the alternating magnetic fields, a set of interacting and interfering wave fronts is produced, which leads to an x-ray beam with extraordinary properties. Third-generation sources of light in the hard x-ray range have been constructed at three principal facilities: the European Synchrotron Radiation Facility (ESRF) in France; the Super Photon Ring 8-GeV (or Spring-8) in Japan; and the Advanced Photon Source (APS) in the United States. Undulator technology is also used on a number of low-energy machines for radiation in the ultraviolet and soft x-ray regimes.

At the APS, these devices exceed our original expectations for beam brilliance, tunability, spectral range, and operational flexibility. Figure 1 presents the tuning curves of the first few harmonics, showing x-ray production from a few kiloelectronvolts to better than 40 keV. High-brilliance radiation extends to over 100 keV.

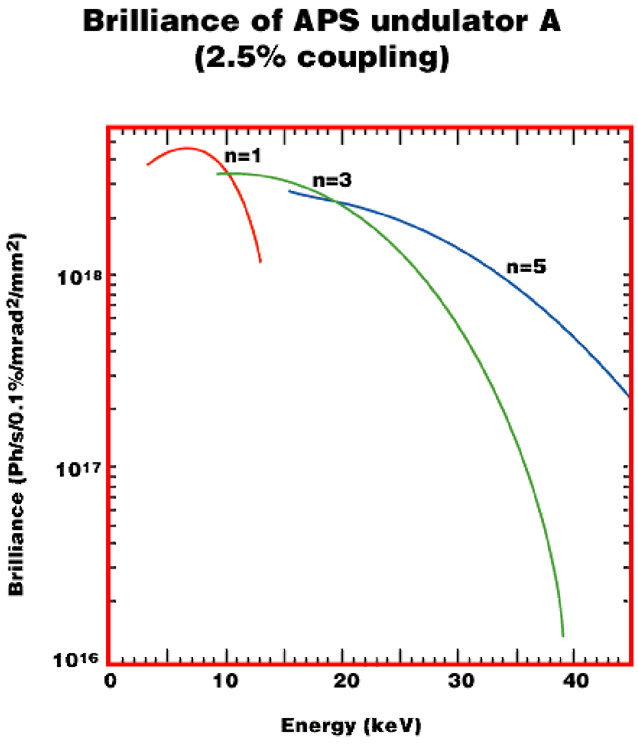


Figure 1. Tuning curves for the on-axis brilliance, first three odd harmonics of APS undulators.

The new science coming from the APS depends on its unique beam characteristics. A very high degree of collimation makes it possible to monochromate 20 keV x-ray beams to ~1 meV. These beams can be used for triple-axis inelastic scattering studies of lattice dynamics that had previously been the sole province of neutron scattering. But the most important aspect of x-ray inelastic scattering will be in charge excitations rather than in lattice dynamical excitations. Beautiful work in that respect is ongoing at the ESRF and beginning at the APS.

Although the x-ray beams from undulators are not substantially coherent, their extreme brilliance allows one to extract a small coherent fraction, which contains a significant number of photons. Recently, x-ray photon correlation spectroscopy methods have been developed to exploit this coherence for measuring the dynamics of fluid systems.

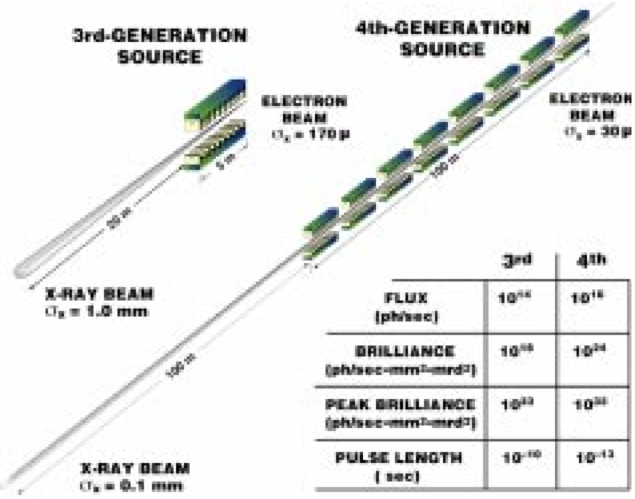
The unique characteristics of undulator radiation have recently been applied to macromolecular crystallography. The results have been spectacular. It is now possible, with a good crystal, to get a data set for a structure determination in well under 1 hour. In some cases, 15 or 20 minutes are adequate to collect all of the data necessary for structure determination. The x-ray step in a structure determination is no longer the rate-limiting step. The current ability to do structures at synchrotron x-ray sources would seem to be an ideal solution to determining the better than 100,000 structures whose codes are contained in the human genome. Such a “structural genomics” enterprise has generated considerable excitement.

But structural biologists will be able to go beyond static structures. X-ray beams from the APS undulators are so intense, one can acquire a high-quality diffraction pattern in a single pulse. These pulses are on the order of 100 ps long, and each of them contains enough photons to get a reasonable diffraction pattern from a good biological crystal. That capability opens the possibility of studying the time evolution of a molecular structure, for example, by using a laser to initiate a chemical reaction.

Very simple developments in instrumentation can have a profound scientific impact. Because the beam from APS undulators exhibits a high degree of brilliance and collimation, Fresnel zone plate lenses work extremely well to provide very-high-quality focal characteristics. With our most successful Fresnel lenses, we are able to achieve focal spots down to 100 nm and to preserve very high optical efficiency (in the 10 percent to 30 percent range). That small focal spot can be used for studying how the properties of materials vary on the submicrometer length scale. In another application, we propose to mount a number of Fresnel lenses on a chip. We would use these lenses to simultaneously probe a number of microsamples deposited on a second chip that have gradients in their chemical composition or in their preparation parameters and thus obtain data in a highly parallel fashion.

The sample chips could be used for x-ray diffraction experiments or x-ray microscopy experiments. Those same samples could be put into other instruments that would measure their physical properties, such as specific heat or conductivity. Thus, one can develop methodologies for accumulating very large databases, which will be very useful for studying complex materials problems, such as high-critical-temperature superconductors.

Concurrent with developing new applications for third-generation light sources, the community is thinking about the fourth generation of light sources (Figure 2) based on x-ray free-electron lasers (FELs). The most compelling parameter associated with this technology will be peak brilliance. It now appears possible to obtain a beam with peak brilliance 10 orders of magnitude higher than we have in APS today. That beam will also have a time-average brilliance higher by six orders of magnitude and a time-average flux higher by two orders of magnitude. Any new facility must serve a broad clientele, so R&D is under way to develop superconducting linacs, which should be capable of serving multiple (~100) beamlines simultaneously. It also appears possible to design a source that could serve the entire spectral range, from the infrared to the hard x-ray regime, in order to eliminate the need for different energy machines for different regions of the electromagnetic spectrum.



	3rd	4th
FLUX (ph/sec)	10^{14}	10^{16}
BRILLIANCE (ph/sec-mm²-mrd²)	10^{18}	10^{24}
PEAK BRILLIANCE (ph/sec-mm²-mrd²)	10^{23}	10^{33}
PULSE LENGTH (sec)	10^{-10}	10^{-13}

Figure 2. Comparison of technical parameters for third- and fourth-generation x-ray sources.

The technology for this next-generation light source is based on undulators just like those at the APS, but with significant interaction between the high-density particle beam generated in the linac and the electromagnetic field it generates. It is this interaction that produces the lasing action. There are different ways to achieve that lasing action in an FEL; but in the x-ray range, we will rely on self-amplified spontaneous emission. If the electron density is high enough, then the field that it produces causes an interaction that creates a lasing action. The undulator has to be long in order for that interaction to build up. At the APS, our undulators are typically a few meters long and produce beams which, 20 m away from the source, are on the order of ~1 mm in size. The new facility will have undulators that are ~100 m long and its beam will be on the order of 1/10 mm in size at 100 m.

Of the many scientific opportunities associated with this new facility, a few are extremely compelling. One is the large quantitative improvement in coherence. We expect significant advances in imaging structures using x-ray holographic methods, which could revolutionize structural chemistry and biology. And since this fully coherent beam will be only 100 fs long rather than the 100 ps at the APS, there will be opportunity for significant improvement in time-resolved measurements in what is clearly a very important time regime. But the advance that can potentially change the paradigm for x-ray research in the next century will be a 10^{10} to 10^{12} increase in photon degeneracy. It will enable the multiphoton methods that are not possible with third-generation sources, permit the study of x-ray nonlinear processes in matter, and perhaps open some new regimes of fundamental high-field physics, a very recent idea.

To have this major fourth-generation user facility ready by the year 2010, an aggressive R&D program must begin now. Fourth-generation light-source technology development represents a bigger step than did third-generation light-source technology. But existing linear accelerators, including those at Argonne National Laboratory, Brookhaven National Laboratory, and the Stanford Synchrotron Radiation Laboratory, offer a cost-effective way to reduce technical risk and begin to explore the extraordinary scientific possibilities that lie ahead.

Smaller Facilities—Opportunities and Needs

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Smaller-scale facilities often fall through the large crack that lies between the laboratory of an individual principal investigator and the large-scale facilities such as synchrotrons or neutron sources. Although the capital equipment investment in an individual researcher's laboratory is typically less than $100,000, the equipment in a smaller facility is typically worth between $100,000 and $10 million. A large facility costs more than $100 million. Such facilities provide capabilities that are far beyond what is available in the laboratory of an individual researcher. Activities usually involve visualization, atomic manipulation, materials synthesis and processing, and/or materials testing. Smaller facilities are found at 4 Department of Energy (DOE) national centers, 26 National Science Foundation (NSF) Materials Research Science and Engineering Centers (MRSECs), and about 100 smaller centers throughout the United States.

An example of a smaller facility is the DOE-supported Materials Research Laboratory at the University of Illinois, Urbana-Champaign. Characterization capabilities include Auger electron spectroscopy, Rutherford backscattering, x-ray photoelectron spectroscopy, transmission electron microscopy, scanning electron microscopy, atomic force microscopy, secondary ion mass spectrometry, and x-ray diffraction. The capital equipment in the center is worth about $50 million. Operating costs are approximately $1.5 million per year. Replacement costs for the capital equipment average about $2.5 million per year.

Many of the techniques found in smaller-scale facilities have improved dramatically over the last decade. As an example, the resolution of scanning electron microscopy has improved at the rate paralleling Moore's law. New characterization techniques have steadily entered the materials analysis arsenal, resulting from fundamental advances made in a variety of fields.

The accomplishments of characterization techniques found in smaller facilities have been very impressive in the 1990s. For example, scanning probe microscopies have developed and proliferated. These techniques are widely used in furthering understanding of thin film growth. It is now possible to watch atoms migrate across surfaces and to image electronic states from dopants and imperfections in semiconductors. Surface atoms can now be manipulated, one atom at a time, to make quantum corrals or whimsical atomic-size figures. New magnetic probes have emerged, including magnetic force microscopy and scanning electron microscopy with polarization analysis. Transmission electron microscopy holography has been used to image vortices in superconductors. Low-energy electron microscopy was invented decades ago, but recent improvements have made it considerably more usable and more widely available. Transmission electron microscopy was used to discover carbon nanotubes and probe the physical and electronic structure of interfaces. Interface and surface science studies have elucidated the Si surface structure at the Si/SiO_2 interface, they have provided fundamental information on bonding and adhesion, and they have given insight into catalysis via particle characterization and activity and zeolite structure determinations.

Various techniques have probed the relationship between defects and critical currents in high-temperature superconductivity.

Looking to the future, it seems clear that the techniques resident in smaller-scale facilities will continue to improve as we seek an ever more detailed view of the atomic-scale world. Some of the directions that appear particularly promising include "smart" tips on scanning probe microscopes that will have the ability to recognize and locate specific molecular species. The semiconductor industry will demand increasingly higher sensitivity analysis, particularly of surfaces, as design rules continue to shrink. Recent developments in microelectromechanical devices and systems raise the possibility of designing and performing portable microexperiments on very small samples, areas, or volumes. Increases in computational power and the advent of the Internet offer opportunities for remote control of apparatus and automated data analysis. Thirty years of work on electron optics has paid off with the development of aberration corrections that promise to have tremendous impact on the resolution obtainable in various electron microscopies, especially on the scanning electron microscopy of large samples (e.g., semiconductor wafers). Work on this problem required decades of patient investment in research—investment that was not made in the United States but instead occurred in Europe, particularly in Germany, and in Asia. A direct ramification of this is that the United States is now behind the rest of the world in being able to access newly available technology.

Smaller-scale facilities lack the visibility of large-scale facilities or the broad recognition of importance that principal investigator research enjoys. This leads to concerns that such facilities will increasingly be caught in a budget squeeze between the two ends of the funding spectrum. It is critical to realize the important role that smaller-scale facilities play—reports of microcharacterization appear in 30 percent of recently published materials physics articles and in 45 percent of materials chemistry articles. Facilities offer the ability to maintain and operate such capabilities efficiently. They also offer access to expert advice on the techniques, educational opportunities, and centers for technique development. The face of materials research would be unimaginably different without adequately supported facilities of this kind.

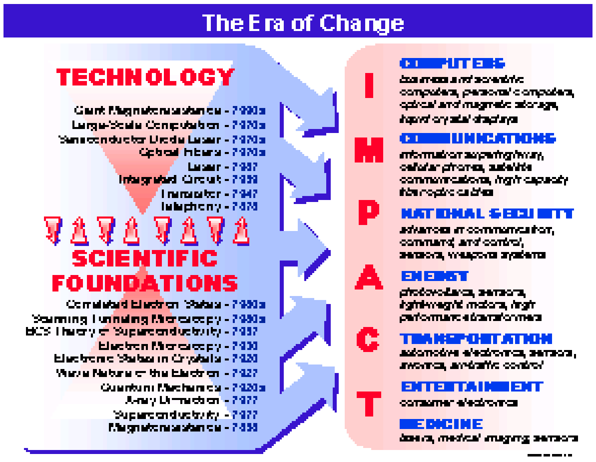

Figure 1. Examples of how major scientific and technological advances have an impact on new products.

IV. Materials R&D—A Vision of the Scientific Frontier

The Science of Modern Technology

Paul Peercy
SEMI/SEMATECH

Electronic, Optical, and Magnetic Materials and Phenomena

We have seen numerous important unexpected discoveries in all areas of condensed-matter and materials physics in the decade since *Physics Through the Nineties* was published. Although these scientific discoveries are extremely impressive, perhaps equally impressive are the technological advances based on our ever-increasing understanding of the basic physics of materials along with our increasing ability to tailor the composition and structure of materials in a cost-effective manner. Today's technological revolution would not be possible without the continuing increase in our scientific understanding of materials and phenomena, along with the processing and synthesis required for high-volume, low-cost manufacturing. This article examines selected examples of the scientific and technological impact of electronic, optical, and magnetic materials and phenomena.

Technology based on electronic, optical, and magnetic materials is driving the information age through revolutions in computing and communications. With the miniaturization made possible by the invention of the transistor and the integrated circuit (IC), enormous computing and communication capabilities are becoming readily available worldwide. These technological capabilities enabled the Information Age and are fundamentally changing how we live, interact, and transact business. These technologies provide an excellent demonstration of the strong interdependence and interplay of science and technology. They have greatly expanded the tools and capabilities available to scientists and engineers in all areas of research and development, ranging from basic physics and materials research to other areas of physics and to such diverse fields as medicine and biotechnology.

Incorporation of major scientific and technological advances into new products can take decades and often follows unpredictable paths. Selected technologies supported by the foundations of electronic, photonic, and magnetic phenomena and materials are illustrated in Figure 1 (shown on previous page). These technologies have enabled breakthrough technologies in virtually every sector of the national economy. The two-way interplay between foundations and technology is a major driving force in this field. The most recent fundamental advances and technological discoveries have yet to realize their potential.

The Science of Information Age Technology

The predominant semiconductor technology today is the silicon-based integrated circuit. The silicon integrated circuit is the engine that drives the information revolution. For the past 30 years, the technology has been dominated by Moore's law—the statement that the density of transistors on a silicon integrated circuit doubles about every 18 months. The relentless reduction in transistor size and increase in circuit density have provided the increased functionality per unit cost that underlies the information revolution. Today's computing and communications capability would not be possible without the phenomenal 25 to 30 percent per year exponential growth in capability per unit cost since the introduction of the integrated circuit in about 1960. That sustained rate of progress has resulted in low-cost volume manufacturing of high-density memories with 64 million bits of memory on a chip and complex, high-performance logic chips with ~10 million transistors on a chip. This trend is projected to continue for the next several years.

If the silicon integrated circuit is the engine that powers the computing and communications revolution, optical fibers are the highways for the Information Age. Although fiber optics is a relatively recent entrant in the high technology arena, the impact of this technology is enormous and growing. It is now the preferred technology for transmission of information over long distances. There are already approximately 30 million km of fiber installed in the United States and an estimated 100 million km installed worldwide. Due in part to the faster than exponential growth of connections to the Internet, the installation of optical fiber worldwide is occurring at an accelerated rate of over 20 million

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NOTE: This article was prepared from written material provided to the Solid State Sciences Committee by the speaker.

km per year—more than 2,000 km/h, or around Mach 2. In addition, the rate of information transmission down a single fiber is increasing exponentially at a rate of a factor of 100 every decade. Transmission in excess of 1 terabit per second has been demonstrated in the research laboratory, and the time lag between laboratory demonstration and commercial system deployment is about 5 years.

Compound semiconductor diode lasers provide the laser photons that are the vehicles that transport information along the optical information highways. Semiconductor diode lasers are also at the heart of optical storage and compact disk technology. In addition to their use in very-high-performance microelectronics applications, compound semiconductors have proven to be an extremely fertile field for advancing our understanding of fundamental physical phenomena. Exploiting decades of basic research, we are now beginning to be able to understand and control all aspects of compound semiconductor structures, from mechanical through electronic to optical, and to grow devices and structures with atomic layer control, in a few specific materials systems. This capability allows the manufacture of high-performance, high-reliability, compound semiconductor diode lasers that can be modulated at gigahertz frequencies to send information over the fiber-optical networks. High-speed semiconductor-based detectors receive and decode this information. These same materials provide the billions of light-emitting diodes sold annually for displays, free-space or short-range high-speed communication, and other applications. In addition, very-high-speed, low-power compound semiconductor electronics play a major role in wireless communication, especially for portable units and satellite systems.

Another key enabler of the information revolution is low-cost, low-power, high-density information storage that keeps pace with the exponential growth of computing and communication capability. Both magnetic and optical storage are in wide use. Very recently, the highest-performance magnetic storage/readout devices have begun to rely on giant magnetoresistance (GMR), a phenomenon that was discovered by building on more than a century of research in magnetic materials. Although Lord Kelvin discovered magnetoresistance in 1856, it was not until the early 1990s that commercial products using this technology were introduced. In the last decade, the condensed-matter and materials understanding converged with advances in our ability to deposit materials with atomic-level control to produce the GMR heads that were introduced in workstations in late 1997. It is hoped that, with additional research and development, spin valve and colossal magnetoresistance technology may be understood and applied to workstations of the future. This increased understanding, provided in part by our increased computational ability arising from the increasing power of silicon ICs, coupled with atomic-level control of materials, led to exponential growth in the storage density of magnetic materials analogous to Moore's law for transistor density in silicon ICs.

Future Directions and Research Priorities

Numerous outstanding scientific and technological research needs have been identified in electronic, photonic, and magnetic materials and phenomena. If those needs are met, it is anticipated that these technology areas will continue to follow their historical exponential growth in capability per unit cost for the next few years. Silicon integrated circuits are expected to follow Moore's law at least until the limits of optical lithography are reached, transmission bandwidth of optical fibers is expected to grow exponentially with advances in optical technology and the development of soliton propagation, and storage density in magnetic media is expected to grow exponentially with the maturation of GMR and development of colossal magnetoresistance in the not too distant future. Although these changes will have a major impact on computing and communications over the next few years, it is clear that extensive research will be required to produce new concepts and that new approaches must be developed to reduce research concepts to practice if these industries are to maintain their historical growth rate over the long term.

Continued research is needed to advance the fundamental understanding of materials and phenomena in all areas. More than a century of research in magnetic materials and phenomena has given us an understanding of many aspects of magnetism, but we still lack a comprehensive first-principles understanding of magnetism. By comparison, the technology underlying optical communication is very young. The past few years have seen enormous scientific and technological advances in optical structures, devices, and systems. New concepts such as photonic lattices, which are expected to have significant technological impact, are emerging. We have every reason to believe that this field will continue to advance rapidly with commensurate impact on communications and computing.

As device and feature sizes continue to shrink in integrated circuits, scaling will encounter fundamental physical limits. The feature sizes at which these limits will be encountered and their implications are not understood. Extensive research is needed to develop interconnect technologies that go beyond normal metal and dielectrics in the relatively near term. Longer term, technologies are needed to replace today's Si field-effect transistors. One approach that bears investigation is quantum state switching and logic as devices and structures move further into the quantum mechanical regime.

A major future direction is nanostructures and artificially structured materials, which was a general theme in all three areas. In all cases, artificially structured materials with properties not available in nature revealed unexpected new scientific phenomena and led to important technological applications. As sizes continue to decrease, new synthesis and processing technologies will be required. A particularly promising area is self-assembled materials. We need to expand research in self-assembled materials to address such questions as how to controllably create the desired one-, two-, and three-dimensional structures.

As our scientific understanding increases and synthesis and processing of organic materials systems mature, these materials are expected to increase in importance for optoelectronic, and perhaps electronic, applications. Many of the recent technological advances are the result of strong interdisciplinary efforts as research results from complementary fields are harvested at the interface between the fields. This is expected to be the case for organic materials; increased interdisciplinary efforts, for example between CMMP, chemistry, and biology, offer the promise of equally impressive advances in biotechnology.

Conclusion

In conclusion, we identify a few major scientific and technological questions that are still outstanding and call attention to research and development priorities.

Selected Major Unresolved Scientific and Technology Questions

- What technology will replace normal metals and dielectrics for interconnect in silicon ICs as speed continues to increase?
- What is beyond today's field-effect transistor-based Si technology?
- Can we create an all-optical communications/computing network
- Can we understand magnetism on the mesoscales and nanoscales needed to continue to advance technology?
- Can we fabricate devices with 100 percent spin-polarized current injection?

Priorities

- Advance synthesis and processing techniques, including nanostructures and self-assembled one-, two-, and three-dimensional structures;
- Pursue quantum state logic;
- Exploit physics and materials science for low-cost manufacturing;
- Pursue the physics and chemistry of organic and other complex materials for optical, electrical, and magnetic applications;
- Develop techniques to magnetically detect individual electron and nuclear spins with atomic-scale resolution; and
- Increase partnerships and cross-education/communications among industry, university, and government laboratories.

Novel Quantum Phenomena in Condensed-Matter Systems

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Indiana University

The various quantum Hall effects (QHEs) are arguably some of the most remarkable many-body phenomena discovered in the second half of the 20th century, comparable in intellectual importance to superconductivity and superfluidity. They are an extremely rich set of phenomena with deep and truly fundamental theoretical implications. The fractional effect, for which the 1998 Nobel Prize in Physics was awarded, has yielded fractional charge, spin, and statistics, as well as unprecedented order parameters. There are beautiful connections with a variety of different topological and conformal field theories studied as formal models in particle theory, each here made manifest by the twist of an experimental knob. Where else but in condensed-matter physics can an experimentalist change the number of flavors of relativistic chiral Fermions or set by hand the Chern-Simons coupling that controls the mixing angle for charge and flux in 2+1D electrodynamics?

Because of recent technological advances in molecular beam epitaxy and the fabrication of artificial structures, the field continues to advance with new discoveries even well into the second decade of its existence. Experiments in the field were limited for many years to simple transport measurements that indirectly determine charge gaps. However recent advances have led to many successful new optical, acoustic, microwave, specific heat, and nuclear magnetic resonance (NMR) probes, which continue to advance our knowledge as well as raise intriguing new puzzles.

The QHE takes place in a two-dimensional electron gas subjected to a high magnetic field. In essence, it is a result of commensuration between the number of electrons, N, and the number of flux quanta, N_Φ, in the applied magnetic field. The electrons undergo a series of condensations into new states with highly nontrivial properties whenever the filling factor $\nu = N/N_\Phi$ takes on simple rational values. The original experimental manifestation of the effect was the observation of an energy gap yielding dissipationless transport (at zero temperature) much like in a superconductor. The Hall conductivity in this dissipationless state is universal, given by $\sigma_{xy} = \nu e^2/h$ independent of microscopic details. As a result of this, it is possible to make a high-precision determination of the fine structure constant and to realize a highly reproducible quantum mechanical unit of electrical resistance, now used by standards laboratories around the world to maintain the ohm.

The integer quantum Hall effect owes its origin to an excitation gap associated with the discrete kinetic energy levels (Landau levels) in a magnetic field. The fractional quantum Hall effect has its origins in very different physics of strong Coulomb correlations, which produce a Mott-insulator-like excitation gap. In some ways, however, this gap is more like that in a superconductor, because it is not tied to a periodic lattice potential. This permits uniform charge flow of the incompressible electron liquid and hence a quantized Hall conductivity.

The microscopic correlations leading to the excitation gap are captured in a revolutionary wave function developed by R.B. Laughlin that describes an incompressible quantum liquid. The charged quasi particle excitations in this system are “anyons” carrying fractional statistics intermediate between bosons and Fermions and carrying fractional charge. This sharp fractional charge, which despite its bizarre nature has always been on solid theoretical ground, has recently been directly observed two different ways. The first is an equilibrium thermodynamic measurement using an ultrasensitive electrometer built from quantum dots. The second is a dynamical measurement using exquisitely sensitive detection of the shot noise for quasi particles tunneling across a quantum Hall device.

Quantum mechanics allows for the possibility of fractional average charge in both a trivial way and a highly nontrivial way. As an example of the former, consider a system of three protons forming an equilateral triangle and one electron tunneling among the 1S atomic bound states on the different protons. The electronic ground state is a symmetric linear superposition of quantum amplitudes to be in each of the three different 1S orbitals. In this trivial case, the mean electron number for a given orbital is 1/3. This, however, is a result of statistical fluctuations because a measurement will yield electron number 0 two-thirds of the time and electron number 1 one-third of the time. These fluctuations occur on a very slow time scale and are associated with the fact that the electronic spectrum

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consists of three very nearly degenerate states corresponding to the different orthogonal combinations of the three atomic orbitals.

The $\nu = 1/3$ QHE has charge 1/3 quasi particles but is profoundly different from the trivial scenario just described. An electron added to a $\nu = 1/3$ system breaks up into three charge 1/3 quasi particles. If the locations of the quasi particles are pinned by (say) an impurity potential, the excitation gap still remains robust and the resulting ground state is nondegenerate. This means that a quasi particle is not a place (like the proton above) where an extra electron spends one-third of its time. The lack of degeneracy implies that the location of the quasi particle completely specifies the state of the system, that is, implies that these are fundamental elementary particles with charge 1/3. Because there is a finite gap, this charge is a sharp quantum observable that does not fluctuate (for frequencies below the gap scale).

The message here is that the charge of the quasi particles is sharp to the observers as long as the gap energy scale is considered large. If the gap were 10 GeV instead of 10 K, we (living at room temperature) would have no trouble accepting the concept of fractional charge.

Magnetic Order of Spins and Pseudospins

At certain filling factors ($\nu = 1$, in particular) quantum Hall systems exhibit spontaneous magnetic order. For reasons peculiar to the band structure of the GaAs host semiconductor, the external magnetic field couples exceptionally strongly to the orbital motion (giving a large Landau level splitting) and exceptionally weakly to the spin degrees of freedom (giving a very small Zeeman gap). The resulting low-energy spin degrees of freedom of this ferromagnet have some rather novel properties that have recently begun to be probed by NMR, specific heat, and other measurements.

Because the lowest spin state of the lowest Landau is completely filled at $\nu = 1$, the only way to add charge is with reversed spin. However, because the exchange energy is large and prefers locally parallel spins (and because the Zeeman energy is small), it is cheaper to partially turn over several spins forming a smooth topological spin “texture.” Because this is an itinerant magnet with a quantized Hall conductivity, it turns out that this texture (called a skyrmion by analogy with the corresponding object in the Skyrme model of nuclear physics) accommodates precisely one extra unit of charge. NMR Knight shift measurements have confirmed the prediction that each charge added (or removed) from the $\nu = 1$ state flips over several (~ 4 to 30 depending on the pressure) spins. In the presence of skyrmions, the ferromagnetic order is no longer collinear, leading to the possibility of additional low-energy spin wave modes, which remain gapless even in the presence of the Zeeman field (somewhat analogous to an antiferromagnet). These low-frequency spin fluctuations have been indirectly observed through a dramatic enhancement of the nuclear spin relaxation rate $1/T_1$. In fact, under some conditions T_1 becomes so short that the nuclei come into thermal equilibrium with the lattice via interactions with the inversion layer electrons. This has recently been observed experimentally through an enormous enhancement of the specific heat by more than five orders of magnitude.

Spin is not the only internal degree of freedom that can spontaneously order. There has been considerable recent progress experimentally in overcoming technical difficulties in the MBE fabrication of high-quality multiple-well systems. It is now possible for example to make a pair of identical electron gases in quantum wells separated by a distance (~ 100 Å) comparable to the electron spacing within a single quantum well. Under these conditions, strong interlayer correlations can be expected. One of the peculiarities of quantum mechanics is that, even in the absence of tunneling between the layers, it is possible for the electrons to be in a coherent state in which their layer index is uncertain. To understand the implications of this, we can define a pseudospin that is up if the electron is in the first layer and down if it is in the second. Spontaneous interlayer coherence corresponds to spontaneous pseudospin magnetization lying in the XY plane (corresponding to a coherent mixture of pseudospin up and down). If the total filling factor for the two layers is $\nu = 1$, then the Coulomb exchange energy will strongly favor this magnetic order just as it does for real spins as discussed above. This long-range transverse order has been observed experimentally through the strong response of the system to a weak magnetic field applied in the plane of the electron gases in the presence of weak tunneling between the layers.

Another interesting aspect of two-layer systems is that, despite their extreme proximity, it is possible to make separate electrical contact to each layer and perform drag experiments in which current in one layer induces a voltage in the other due to Coulomb or phonon-mediated interactions.

Stacking together many quantum wells gives an artificial three-dimensional structure analogous to certain organic Bechgaard salts in which the QHE has been observed. There is recent growing interest in the bulk and edge ("surface") states of such three-dimensional systems and with the nature of possible Anderson localization transitions.

These phenomena and numerous others, which cannot be mentioned because of space limitations, have provided a wonderful testing ground for our understanding of strongly correlated quantum ground states that do not fit into the old framework of Landau's Fermi liquid picture. As such, they are providing valuable hints on how to think about other strongly correlated systems such as heavy Fermion materials and high-temperature superconductors.

Nonequilibrium Physics

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University of California, Santa Barbara

Nonequilibrium physics is concerned with systems that are not in mechanical or thermal equilibrium with their surroundings. Examples include flowing fluids under pressure gradients, solids deforming or fracturing under external stresses, and quantum systems driven by magnetic fields. These systems often lead to very familiar patterns such as snowflakes, dendritic microstructures in alloys, or chaotic motions in turbulent fluids. Many of these are familiar phenomena governed by well-understood equations of motion (e.g., the Navier Stokes equation), but in some of the most interesting cases, the implications of these equations are not understood.

The Brinkman report (*Physics Through the 1990s*, National Academy Press, Washington, D.C., 1986) recognized the significance of the emerging field of nonequilibrium physics but missed some of the most important topics of current research such as friction, fracture, and granular materials. Notable progress has been made in the last decade regarding patterns in convecting and vibrating fluids, reaction-diffusion systems, aggregation, and membrane morphology.

The patterns observed in nonequilibrium systems are especially sensitive to small perturbations. Weather phenomena are a prime example. Long-range weather forecasting requires precise characterization of current and past weather conditions. As such characterization becomes more detailed, it is possible to predict future patterns with increasing accuracy. One task of nonequilibrium physics is quantifying the relationship between precision and predictability.

In spite of decades of study, the origin of ductility in materials remains a key unsolved problem of nonequilibrium physics. Traditional explanations based on dislocations do not explain observations such as ductility in glassy materials. We lack a good theory of ductile yielding in situations where stresses and strains vary rapidly in space and time.

One of the most important recent observations is that fast brittle cracks undergo materials-specific instabilities leading to roughness on the fracture surface. Stick-slip friction is also observed on large scales, for example, in earthquake dynamics. The nature of these processes, including the issue of lubricated friction, is a key problem of nonequilibrium physics.

Granular materials are an example of a familiar class of materials of considerable industrial importance that have escaped scrutiny by physicists until recently. These materials are highly inelastic in their interactions. When granular materials cohere slightly, they can behave like viscous fluids as in saturated soil. If the coherence is strong, then we have sandstone or concrete, which behaves more like ordinary solids. If complex dynamics are added, we have foams or dense colloidal suspensions. The nature of lubrication is also relevant to these problems.

These and many other open problems show that the frontiers of physics include many very familiar phenomena. In many cases, these problems are of great importance to materials properties and industrial processes.

Soft Condensed Matter

V. Adrian Parsegian
National Institutes of Health

Adrian Parsegian opened his remarks on soft condensed matter research with the question, "When was American poetry born?" He quoted William Saroyan's response, "When people not trained in poetry began writing it." No one can imagine Walt Whitman's poetry being written in England or anywhere except America. It was "an instantaneous flop" because people did not think it was even "poetry." The clear implication for the field of condensed-matter and materials physics is that soft materials physics will flourish only after much initial skepticism and even resistance are overcome.

Advancing our understanding of soft materials requires an unprecedented combination of traditionally distinct, and noninteracting, fields. One of the greatest challenges is the simple recognition and appreciation of the disparate skills required for attacking problems with relentlessly increasing levels of complexity. For example, as the genome project unfolds, uncovering seemingly endless genetic information, synthetic chemists and physicists face the daunting task of producing and understanding the complex interactions that govern biological function occurring at length scales ranging from atomic to supramolecular dimensions. Such problems may not succumb to the conventional reductive methods familiar to most physicists. Modern instrumentation such as third- and even fourth-generation synchrotrons, high-flux neutron sources, and high-resolution nuclear magnetic resonance spectrometers provide powerful means for exploring these issues. However, are these potent tools the key to uncovering the secrets of biology? "What constitutes understanding in this business?" asks Parsegian, adding, "An explanation that satisfies the physicist may be thoroughly irrelevant to the gene therapist." Established approaches toward education and funding and even attitudes about industrial interactions must change if the physics community is to have a demonstrable and meaningful impact on this burgeoning field.

Many of the macroscopic properties of soft materials are foreign to the condensed-matter physicist. Softness is substituted for hardness as a desirable property; malleability, extensibility, and compliance replace stiffness and shape retention; and fragility is often more valuable than durability. These themes are stimulating a new type of physics that relies on the same bedrock principles enumerated in elementary physics education but must be augmented by the targeted interdisciplinary studies of medicine, food, polymers, and many others.

The field of polymers provides a bridge between conventional physics and the biologically oriented sciences and engineering. Both natural and synthetic macromolecules offer numerous research and development opportunities. Polysaccharides and milk proteins are identified by Parsegian as examples of ubiquitous and naturally occurring macromolecules that may be formulated into novel items of commerce for use in foods and environmentally benign—even biodegradable—plastics. Advances in synthetic chemistry during the past decade have greatly expanded our ability to tailor molecular architecture, even in the simplest of polymers known as polyolefins, prepared from just carbon and hydrogen. This class of synthetic polymers makes up roughly 60 percent of the entire synthetic polymer market. Yet the commercial consequences of varying the number and length of side branches, grafts, and block sequencing on the melt flow properties, crystallization kinetics, and ultimate mechanical properties are just now being realized. Dendrimers, precisely and highly branched giant molecules that can assume a nearly perfect spherical topology, offer fresh strategies for manipulating polymer rheology and may provide ideal substrates for delivering drugs to the human body.

Parsegian noted that polyelectrolytes are an especially important class of materials, since almost all forms of biologically relevant matter contain macromolecules with some degree of ionic charging. Yet polyelectrolytes present some of the toughest challenges to condensed matter physics, convoluting electrostatic interactions, self-avoiding chain statistics, and traditional solution thermodynamics with self-assembly into higher-order structures that rely on tertiary and quaternary interactions.

Application of physics to biological problems is not a new phenomenon. Physicists have made significant contributions to the field of protein folding for nearly 35 years. In fact, physicists have defined the "language" of the field and created exquisite tools for simulating and even "watching" individual molecules. For example, optical tweezers techniques permit quantification of the force versus extension relationship of individual biomolecules such as DNA. These studies are not yet the clinical analysis of protein-folding and prion-related illnesses such as Alzheimer's and "Mad Cow" disease.

"Why are physicists frequently off the biological radar screen? " asks Parsegian.

"In large part they are seen as insular and parochial," is the response he has received to this question. He points out key differences in how physicists approach problemsolving through a simple example—understanding the force required to separate two interacting biomolecules, as might be encountered in cell adhesion. This delicate problem depends on the time scale of the experiment as much as the force applied and the displacement measured. Given enough time, the molecules will disengage without any applied force. Physicists must resist the temptation to connect or reconfigure anything biological into a conventional, solved, physics problem, in this case treating the biomolecular interactions with traditional static intermolecular potentials.

Rectifying these shortcomings, that is, making physics visible and relevant to the biological sciences, will require education on the part of biologists as well as physicists. Biologists and medical researchers must understand the utility and importance of physics to their work. For example, the sophisticated instrumentation that is often the source of so many scientific revelations (e.g., three-dimensional NMR and x-ray imaging) often comes from fundamental advances in physics. Medical doctors and researchers should understand the origins of their equipment and appreciate the underlying principles of operation. Parsegian offered an assortment of recommendations for improving the current situation. Basic research, which fuels practical developments in industry and medicine, would benefit from the following innovations: (1) grant mechanisms that encourage interdisciplinary work; (2) special grants that circumvent the double jeopardy of being judged both as a biologist and a physicist; (3) fellowships for physicists, including theorists, to work in biological laboratories; and (4) maximized contact between university researchers and industrial scientists, especially those from the chemical, medical, and pharmaceutical industries.

Changes in education were also prescribed. New physics courses must be developed that are targeted at biologists; and physicists should be trained in chemistry, biochemistry, and molecular biology. Introductory physics courses must begin to emphasize soft systems in addition to the traditional curriculum. There should be "bilingual" textbooks, aimed at both physicists and biologists. Summer schools with laboratories for scientists at all stages of their careers and interdisciplinary workshops can be established. In short, the field of physics should spread itself out from the confines of physics departments, while broadening its horizons to encompass the emerging exciting world of soft matter.

Fractional Charges and Other Tales from Flatland

Horst Störmer
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Flatland is two-dimensional space. In nature it is found at surfaces or at interfaces. The quantum Hall effect (QHE) and fractional quantum Hall effect (FQHE) are properties of electrons confined to the interface region of semiconductor quantum wells. The electrons can move along the two-dimensional surface of the interface but are confined in the third direction. A Nobel prize was awarded to Klaus von Klitzing in 1985 for the discovery of the QHE, and Störmer, D.C. Tsui, and Robert Laughlin shared the 1998 Nobel Prize in Physics for their discovery of the FQHE. This research area continues to be interesting, with many new ideas and discoveries.

E.H. Hall discovered in 1878 a transverse voltage V_{xy} when a magnetic field B is imposed perpendicular (z-direction) to the direction of electrical current. The voltage is proportional to the current I_x in the layer. The ratio $V_{xy}/I_x = R_{xy}$ defines the transverse resistance. The QHE is the observation of plateaus in the transverse resistance when measured as a function of magnetic field. These plateaus occur when Landau levels are completely filled with electrons. During these plateaus, the longitudinal resistance ($R_{XX} = V_{XX}/I_x$) appears to vanish: It actually declines to a very small value. The plateaus have a value of resistance that are multiples of the fundamental value $h/e^2 = 258120$, where h is Planck's constant and e is the unit of charge. The plateaus have the same value in each sample. They have become the new international standard of resistance.

Störmer, Tsui, and Gossard continued the measurements of the Hall effect to very high values of magnetic field. They discovered additional plateaus in the transverse resistance. These plateaus occur at values that imply that the Landau levels are fractionally occupied: 1/3, 2/5, and so on. The experiments continue, with samples of increasing purity, at lower temperature, and with higher magnetic field. Low-temperature values of the mobility in GaAs/AlGaAs wells are now $\mu = 2 \times 10^7$ cm^2/(V_s). The mean-free-path of the electrons is on the order of 100×10^{-6} m. In these recent measurements, the list of fractions is quite large, with unlikely numbers such as 5/23 appearing.

Why are there fractions? The two-dimensional gas of electrons becomes highly correlated. It is difficult to imagine a many-body system that is as simple and as profound. At these high values of magnetic field, the electrons have circular orbits, due to the field, which have a small radius. The separation between electrons is much longer then the diameter of the orbits. The electrons are becoming localized into a kind of Wigner crystal. However, they have unusual motion, because they have no kinetics. Their correlation is entirely due to their mutual Coulomb interaction. The fractions indicate the existence of highly correlated states that occur at these fractional fillings. The topic is fascinating to theoretical physicists, who try to explain the origin of all of these states.

The most important fraction is 1/3. It was discovered first and has a large plateau in the Hall resistance. Each quantum of flux can be considered to be a vortex in the plane. For the 1/3 state, there are three vortices for each electron. The three vortices get attached to the electron and form a quasi particle called a “composite.” For the 1/3 state, it is a “composite Boson,” and the collective state is due to a Bose-Einstein condensation of these quasi particles. Noise measurements in the resistivity confirm that the charge on the current carriers is actually e/3. The excitation energy to excite an electron out of the correlated state is $\Delta E = 10$ K in temperature units. This energy is large, because the experiments are performed at a small fraction of a degree.

At the fraction 1/2, the quasi particles are “composite Fermions,” which cannot form a condensate. There are no plateaus at this fraction, although it is speculated that the Fermions form a superfluid state akin to the Bardeen-Cooper-Schrieffer state in a superconductor. This pairing of Fermions is thought to explain the features of the 5/2 state in particular. For fractions written as the ratio of two integers q/p, even values of p are composite Fermions and odd values of p denote composite Bosons.

New fractions continue to be discovered. The graph of the transverse resistance appears to be a “devil’s staircase” of an infinite number of steps of irregular width. Physicists have always been fascinated by the highly correlated electron gas. There is no more highly correlated system of electrons than is found in the FQHE.

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