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Driving Innovation Through Materials Research

Proceedings of the 1996 Solid State Sciences Committee Forum

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

National Research Council

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Driving Innovation Through Materials Research

Proceedings of the 1996 Solid State Sciences Committee Forum

Abstract

The 1996 Solid State Sciences Committee Forum, "Driving Innovation Through Materials Research," was convened at the National Academy of Sciences on February 12–13, 1996. The atmosphere was a mix of apprehension and excitement, confusion and exhilaration.

Apprehension that "the times they are a-changing" was brought into sharper focus by several speakers. Dramatic forces of change—political, economic, military, and social—are driving a need for a new social contract to underpin U.S. support for R&D. Participants in the forum represented many different stakeholders in the R&D enterprise, including universities, federal laboratories, industry, federal funding agencies, and the U.S. Congress. They differed in their perspectives on these changes, and they differed in their proposed responses, but a few remarkably consistent themes emerged:

- Federal support for R&D has been declining since 1987 and will continue to decline.
- National defense, the premier driver for R&D support for decades, has not yet been replaced by a similarly compelling mission now that the Cold War is over.
- Changing congressional priorities and reduced congressional familiarity with science and technology (S&T) issues pose serious problems.
- Industry is changing, driven by such forces as globalization, mobility of capital, competition, and R&D mobility.
- The nature and longevity of a science/engineering education must change to meet the demands of customers, i.e., students and employers.
- Accountability and impact are replacing "the needs of the discipline" as reasons for support.
- The Department of Energy laboratories must evolve into a "system."
- Partnerships across disciplines and among universities, industry, and government laboratories are the key to more effective R&D in the future.
- The S&T community needs to communicate the value of science to the Congress and the public.

Despite all these concerns and challenges, materials R&D today has unprecedentedly high vitality and impact. Specific case histories presented at the forum demonstrated that entire industries—among them optical and wireless communications, computing and semiconductors, transportation, and defense—have flourished because of materials R&D. The field's accomplishments have been prodigious, and the opportunities that remain, just those that we can already identify, promise even greater benefits. The new research facilities and techniques described at the forum give confidence that today's investment in materials R&D will pay off more handsomely than ever in tomorrow's innovations.

Executive Summary

Paul Fleury
Chair, Solid State Sciences Committee

The 1996 Solid State Sciences Committee Forum, entitled "Driving Innovation Through Materials Research," was held at the National Academy of Sciences in Washington, D.C., on February 12–13, 1996. The meeting examined policy issues surrounding materials R&D, looked at the field's recent accomplishments, and addressed the opportunities and challenges that face the materials community.

The first day of the meeting focused on the political and institutional environment in which materials-related R&D is conducted and supported.

Thomas Weimer, staff director of the Basic Research Subcommittee of the House Science Committee, set the stage from a national perspective in his keynote address. He identified several themes emerging from the current Congress, driven by geopolitical, social, and economic factors. These themes included the end of the Cold War, concern over the U.S. budget deficit, the public's dissatisfaction with government bureaucracy and institutions in general, and an increasing belief that government and technology have failed to solve the societal problems that face us. Weimer noted the recent sea change in the makeup and viewpoints of the Congress. For example, 31 of the 50 members of the House Science Committee have less than four years seniority. A record number of retirements have already been announced in the Senate, indicating a further loss of senior members familiar with technology-related issues. The debate on the restructuring of federal support for science and technology (S&T) continues, as does experimentation with various relationships among industry, government, and universities as providers of R&D. All these factors call into question long-held assumptions about society's underlying support for R&D. Weimer challenged the science community to become involved at all levels in educating the Congress and the public at large about the critical role that science and technology play as investments in the long-term future of the country. He cautioned against taking a discipline-by-discipline approach, citing the need to emphasize instead the broad nature of investment in R&D.

Erich Bloch presented a view from the Council on Competitiveness. He detailed a number of the council's recommendations to all the major sectors of the R&D community. Though aimed broadly at the entire U.S. R&D enterprise, the Council's recent study *Endless Frontier, Limited Resources* (1996) contains several lessons and recommendations that are specifically applicable to the materials community. In particular, the central finding was that "R&D partnerships hold the key to meeting the challenge of transition that our nation now faces." If the policy recommendations from the study are followed, the climate for such partnerships will improve, industry will increase its participation in R&D, and there will be more sharing of costs, resources, and experiences among sectors.

Arden Bement of Purdue spoke about changes needed in the research universities: the changing demand for and character of graduate and undergraduate degrees, particularly in science and engineering; the evolving demands of industry, which are shifting away from the narrowly focused research Ph.D. and toward personnel who are adept at problem solving, communications, and leadership and are able to work in an adaptable and interdisciplinary manner; and the growing importance of the master's degree in science and engineering. Collaborations in both education and research, both within the United States and globally, will increase. There will be more minors and dual-degree programs and a greater emphasis on industry-friendly positions in matters such as intellectual property. As technology continues to shift rapidly, there will be increased use of distance learning and an increased need to serve and retrain the mature technical work force.

Charles Shanley of Motorola described the industrial perspective on research. He used three case studies to illustrate the importance of materials research to his industry: engineered ceramics, gallium arsenide circuits, and optical fibers for data transmission. He also described some successful modes of operation for researchers and innovators and emphasized particular approaches that have worked in his company.

The national laboratories were represented by Al Narath of Lockheed Martin, who detailed the complexity and diversity of the capabilities and missions of the Department of Energy (DOE) under its new "System of Laboratories" approach. These capabilities range from the science enabled by large facilities to the defense responsibilities borne by the complex, multiprogram weapons laboratories. The DOE laboratories are undergoing an unprecedented reexamination of their missions, their cost-effectiveness, and their future role in addressing national needs. Shrinking support has led to some tension between research universities and the laboratories, which sometimes see each other as potential competitors. The promising interactions with industry that are growing out of cooperative research and development agreement (CRADA)-like partnerships appear threatened. Nevertheless, Narath's message was upbeat, for he believes that progress is being made toward a true system of laboratories, with complementary and cooperative strengths that will better address a broad variety of national needs. This system will incorporate an improved set of partnerships with the industrial and academic sectors and among government organizations.

Neal Lane of the National Science Foundation (NSF) echoed the point made earlier that R&D support from the federal government peaked in real terms in 1987. It has been declining steadily every since, and another 30% decline is projected over the next six years. Although the NSF commitment to materials research is firm, the field will not be exempt from this retrenchment. Lane called for "civic scientists" to articulate the value that R&D delivers to the country and to lead an increasing involvement of scientists in defining the future, not only of our scientific research but also of our technology. The importance of educating members of Congress and other political leaders about the need for continued R&D investment for the good of the country cannot be overemphasized. Lane urged engagement in a new and active dialogue at all levels.

Arati Prabhakar of the National Institute of Standards and Technology (NIST), Martha Krebs of DOE, and Anita Jones of the Department of Defense (DOD) all gave examples from their agencies of the impact that materials research has had on their missions. They were uniform in their support for the value of materials R&D. Nevertheless, they all emphasized the need for more accountability and better tools for measuring the impact of research. Programs that prove to have a significant impact on each agency's mission will be the ones that survive there. The struggle between long-term and short-term views, which industry and the laboratories are already facing, is evident as well in these three mission agencies, which are responsible for so much of the funding of materials R&D.

The above presentations were followed by a lively panel discussion involving the agency leaders and three congressional staff members. Many of the day's issues were explored in terms of partnership experiments, such as technology transfer from government laboratories to industry, partnerships between the laboratories and universities, and direct government funding of research in industrial settings. A particularly lively discussion centered on the recent change in political climate and its effect on the national laboratories' technology transfer programs, the Technology Reinvestment Program, and other similar efforts. The panel was divided as to the merits of these programs, but there was general agreement that each program must come with a set of criteria against which its success can be measured, to use in determining whether to continue making investments. Some panelists felt that government participation in such programs smacked of "corporate welfare." If a project is really in a company's best interest, they said, the company itself should fund it. "Any company that fails to invest properly in R&D deserves to go out of business," said one panelist. When asked whether he would say the same about a country (in light of the 30% cuts mentioned above), he gave no response. It was emphasized by all that success criteria should be tailored to each individual program, because the programs all have different objectives. There was also general agreement that there is a need for a new social contract for research, that R&D funding will continue to shrink, and that a national debate on the structure, strategy, and substance of federally supported R&D must be pushed to a conclusion soon.

On the second day, the forum turned to the accomplishments of materials R&D in driving industrial innovation.

Bill Brinkman of Lucent Technologies dramatically detailed the amazing explosion in information-carrying capacity of high-speed networks based on optical communications. Glass fibers of unimaginable transparency, with exquisitely tailored waveguide properties, permit transmission of billions of bits per second over thousand-mile distances without the need for intervening electronics. Semiconductor laser sources and detectors allow simultaneous sending of many colors over the same fiber.

Mike Polcari of IBM vividly demonstrated the equally prodigious advances in semiconductors and magnetic materials, which form the basis for computing and information storage. Materials for gate insulators, metallic interconnects, and ever-smaller circuit elements are enabling the continuing exponential increase in computer processing power and semiconductor memory capacity. Equally exciting new magnetoresistive materials are permitting a 100-fold increase in magnetic disk memory capacity.

Norm Gjostein of the Ford Motor Company, tracing the influence of materials research in the automobile industry, emphasized the societal and competitive drivers for cheaper, more efficient, and more environmentally benign motor vehicles. The materials challenges in this field range from developing cheaper, stronger, lighter materials, to understanding the materials science of the combustion process and engine design, to designing recyclable materials for components and even entire vehicles. Gjostein emphasized cost synergy with other industries, such as the aircraft industry, and detailed the clear value of materials technology in U.S. automotive competitiveness.

In his talk on technology development in Japan, Jeffrey Frey of the University of Maryland emphasized the special culture of that island nation, which drives its approach to education, work, research, development, and manufacturing. He emphasized differences between Japan and the United States in formal education, job training, work methods, the structure of industrial laboratories, and the training and mobility of the technical work force.

The final session of the forum was devoted to future research opportunities. Dave Moncton of Argonne National Laboratory described the major photon facilities that use synchrotron radiation for materials research. New sources like the Advanced Photon Source put researchers on the threshold of qualitatively different abilities in materials characterization and modification, using light at wavelengths from the subangstrom to the submillimeter. Structural biologists, polymer chemists, and others are joining physicists, chemists, and materials scientists as the user communities expand into the many thousands. There is hot international competition with respect to photon sources, but U.S. investment and the current U.S. position are both competitive.

Regarding neutron sources, on the other hand, the United States is not at the forefront in either metric. Mike Rowe of NIST reviewed the situation for neutron sources and neutron science in the United States. He began by describing the properties of neutrons that make them unique probes of molecular and condensed matter. His review of reactor and spallation sources and their use by thousands of scientists in the United States was followed by a striking contrast with the European scene. Although neutron scattering was pioneered in the United States (as recognized by the 1994 Nobel Prize for physics), U.S. investment in the field has fallen behind Europe's investment for the last two decades, with the result that the leading sources of both reactor and spallation neutrons are now European. Superior science will surely follow.

A fitting climax to the discussions of research opportunities was provided by George Whitesides of Harvard University, who spoke on molecular self-assembly and nanostructured systems. By letting nature take its course toward thermodynamic stability, materials can be designed to assemble themselves into desired aggregates, structures, or replicas. Microcontact printing and micromolding are two examples of the new vistas opened by this bottom-up approach to the fabrication of complex and useful structures.

The wrap-up session that ended the forum was energizing. It was unusual in two ways. First, it was focused on actions and next steps, rather than on a mere review of the material presented in previous sessions. Second, it was attended by a substantial majority of the forum participants. The factors influencing this high attendance included the strong degree of engagement and discussion throughout the forum by all attendees, as well as the unusual candor with which speakers raised issues of concern. The community appears to have moved beyond the "denial phase." It now recognizes the profound changes that have occurred in the nation's attitude toward R&D and accepts that austerity and accountability will henceforth be a way of life. It is stepping up to the responsibility to articulate the value of the nation's R&D investment.

Participants in the forum were unusually open in discussing their current and contemplated plans and programs, considering the ordinarily competing elements within the materials community. Everyone invited all concerned to contribute their ideas, join in studies, submit proposals for joint projects, and so on. Since all sectors were represented (including universities, industry, government laboratories, federal agencies, and the Congress), the participants came away with the hope—and perhaps even the impression—that we as a nation will address the issues of priority, accountability, and partnership more effectively than ever. If so, the 1996 Solid State Sciences Committee Forum was indeed a great success.

I. National Perspectives on R&D

Keynote Address: A Congressional Perspective on Federally Supported R&D

Thomas Weimer
Staff Director, Subcommittee on Basic Research,
Committee on Science, U.S. House of Representatives

Thomas Weimer stated that his purpose was to identify themes emerging from the 104th Congress that have long-term implications for science and technology. He began by pointing to some of the changes that have already occurred that are being reflected both in the Congress and in the broader debate on science, technology, and public policy. Noting that these views are rather widely held in Washington, he cited a recent article by Radford Byerly, his former colleague on the staff of the House Science Committee.[1] Some key points:

- The end of the Cold War has weakened the engine of the freight train that has pulled federal science and technology support since World War II. No replacement engine has emerged with political support like that of the national security engine.
- The American public is dissatisfied with its government and inherently suspicious of bureaucracy.
- This makes it ready to reduce government's size and reach.
- The public is calling for substantial deficit reduction.

The public is increasingly dissatisfied that government and science have not solved societal problems. "Yes, science and technology helped win the Cold War, but what have they done to reduce crime, improve health care, combat racism, and prevent drug abuse?"

Byerly's conclusion? The Vannevar Bush social contract, which has defined the interaction between science and the rest of society for the past 50 years, may no longer be valid. Bush argued that (1) scientific progress is essential to the national welfare, (2) science provides a reservoir of knowledge that can be applied to national needs, and (3) scientific progress results from the free intellectual pursuit of subjects of the scientists' choice. These assumptions, though perhaps still necessary to sustain societal support in the post-Cold War era, are no longer sufficient. A national debate is needed to identify a new and sustainable paradigm that will define how science and technology contribute to the national welfare and how the troika of government and its laboratories, industry, and research universities can best work together to address societal goals.

The Political and Policy Environment of the 104th Congress

How does this thesis regarding the need for a new paradigm relate to the political and policy environment we have seen during the first session of the 104th Congress? The House of Representatives has been widely acknowledged as a leader in the debate on these issues, especially their nonmilitary science and technology aspects on which the House Science Committee has specifically focused. The ideological and party leadership changes, as well as the broadly heard calls to balance the budget and downsize government, have been widely reported. However, other factors that have received less attention may have equally important ramifications. In particular, a major change is the turnover in the membership of the Congress. New members now constitute more than 50% of the House. On the House Science Committee, which has 50 members, 22 are freshmen and 9 are sophomores, so that 62% of the members of the committee have served for less than four years.

In general, new members of the House Science Committee have little relevant education or experience that positions them at the outset to engage fully in the science policy debate. This is not new. What is new is that the large number of new members now constitutes a majority voting block. Weimer noted his personal observation that new members generally take two to six years to become sufficiently familiar with the is-

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[1] R. Byerly, Jr., and R.A. Pielke, Jr., "The Changing Ecology of United States Science," *Science* 269:5230 (September 15, 1995), 1531.

sues that they can engage independently in science policy debates; obviously it takes time to educate oneself on complex issues.

The Senate is lagging in this generational transition, in part because of its longer election cycle, but by the time of the forum in February 1996, the Senate had already seen 13 announced retirements, the highest number in more than 100 years. Clearly the generational transition is occurring in both houses.

What conclusion do we reach from this observation? The science community needs a continuing program of education for new members of Congress and their staffs on federal investment in science. Everyone involved must take part in crafting and delivering the relevant messages as "civic scientists." [Compare Neal Lane's talk later in the forum.] Information delivered by constituents is often the most effective, but all messages must reinforce each other and resonate if they are to have the desired impact. Site visits within a member's district and visits with young researchers are very effective methods of delivery.

Sixty-two percent of the members of the House Science Committee have served for less than four years. The science community needs a continuing program of education for new members of Congress and their staffs.

Federal Budget Trends

Many people are unaware of the trends in aggregate federal R&D spending (both defense and civilian) since World War II. In inflation-adjusted dollars, federal support rose annually through 1966 and then declined in the aftermath of the Apollo program and the Vietnam War. The trough occurred in 1975, 28% below the 1966 peak. After 1975, federal support once more rose steadily to a new peak in 1987. It has been declining since that time. In other words, after adjusting for inflation, there have now been eight successive years of declining federal support, extending through three Presidents and five Congresses, and amounting to a cumulative decrease to date of approximately 10%. Under the current budget scenarios of the Administration and the Congress, this declining trend will continue for six more years. Projections by the American Association for the Advancement of Science, based on the FY1996 budget resolution, predicted a decline of approximately one-third. Of course, the actual percentage will depend on the performance of the economy and many other factors.

Thus the debate in Washington is not over the overall direction of federal R&D support, which is continuing downward, but rather over the pace of the reduction and the ratio of research versus development and military R&D versus civilian R&D. The message is that science is being treated no differently, at this time at least, than any other discretionary programs. But this should be a warning: as the discretionary appropriations pie gets smaller and smaller, science is competing directly with all the other discretionary programs, many of which have strong advocacy groups skilled in congressional lobbying.

Restructuring the Federal S&T Support Infrastructure

Driven in part by these budget trends, there has been renewed discussion of restructuring the federal science and technology support infrastructure within government. Proposals to form a Department of Science reemerged in the 104th Congress as one possible approach to addressing efficiency of administration and budgeting issues, albeit with the loss of pluralistic funding sources. This debate was not fully engaged this past year, in part because of ongoing strategic realignments at the National Aeronautics and Space Administration (NASA) and DOE, but it does not appear to be over. Discussions over the restructuring of the infrastructure, such as those concerning the future of the Commerce and Energy departments, will continue into the second session of the 104th Congress. With continuing diminished federal resources as a given, the fundamental question is, Do we have the best and most efficient government infrastructure in place for delivering scarcer dollars to those who actually perform research?

Restructuring Government-Industry-University Relationships

Finally, Weimer addressed the issue of government-industry-university relationships and their contribution to the federal R&D enterprise. Achieving better relationships is clearly going to be critical to the performance of science and technology. "I've been struck in visiting national laboratories over the last year at the signs of changes I see and by the way they are doing business," he said. This includes both technology transfer and laboratory-university partnerships. Weimer noted that Congress remains pro-CRADA as long as the agreements are mission-oriented and the money comes from programs and not from set-asides. Industrial research has declined in the last three years, and for basic research this has been a rather precipitous decline, which increases the importance of interactions between industry and the other sectors. Within government, indirect avenues of enhancement, such as tax and regulatory changes, must continue to be examined for improvements.

For universities, there is a need to confront cultural barriers to industrial partnerships, where they exist, and to further encourage interactions outside the university. Another change is the growing importance of state-federal partnerships that identify and invest in strategic science and technology areas and define economic development goals.

Weimer sounded a clarion call to the science community to get involved in educating Congress and the public at large about the critical importance of science and technology investments to the long-term future of the country.

Summary

In summary, Weimer clearly identified the generational change in Congress as a new and significant development with long-term effects on S&T policy. He sounded a clarion call to the science community to get involved in educating Congress and the public at large about the critical importance of science and technology investments to the long-term future of this country.

In responding to questions, Weimer noted that as regards the education of Congress, members often learn first from other members, then from the Washington establishment, and third from their constituent base. The latter may have the greatest long-term impact. He cautioned against a discipline-by-discipline approach to arguments in support of S&T, citing the need to emphasize the broad nature of investments in science and technology. He pointed out that although most people believe that federal spending in S&T is indeed an investment, the difficult argument comes when one tries to decide how much is enough or how much can be cut. Such issues do not have simple white-paper answers, and it is primarily through the experience gained from years of involvement that members of Congress arrive at the conclusion that investment in S&T is critical and become strong supporters of it.

II. Institutional Perspectives on the R&D Landscape

Reinventing R&D

Erich Bloch
Distinguished Fellow, Council on Competitiveness

The landscape for research is undergoing profound changes. With the end of the Cold War, the civilian sector, not defense, will be the dominant force for research. This shift, however, is only one of the factors that are affecting and necessitating change. In addition there is an unprecedented mobility of technical resources worldwide, together with continuing developments in computer and communications technologies and the imperative to balance the federal budget. Combined, these factors are forcing industrial, academic, and government institutions to rethink how research should be done in the most efficient manner to best utilize limited resources. The United States now faces this challenge, and all sectors of the U.S. research effort, private and public, must respond rapidly in order to remain competitive.

> ***The simplistic differentiation between basic and applied research will not work. The spectrum of research has changed, and it is necessary to redefine the points of reference.***

With the reduction in the funding provided for research by the federal government and the redirection of industrial funds away from the more basic side of research, it is crucial that partnerships between industry, academia, and government laboratories be used to meet this challenge. It must be realized that competition and cooperation are not mutually exclusive. Research in such partnerships would draw on the different strengths of the different institutions. To be effective, partnerships require the commitment of the participants to share costs, resources, and experiences for the common good of the research. Such partnerships require significant changes in the manner in which research is approached, intellectual property is handled, and students are trained.

It is urgent that the polarized debate over the proper federal funding role be resolved. The simplistic differentiation between basic and applied research will not work. The spectrum of research has changed, and it is necessary to redefine the points of reference. Perhaps time could be used as a differentiator, with there being short-, intermediate-, and long-term research that bears respectively, low, medium, and high risks. Industry, academia, or government laboratories would assume responsibility, either individually or as a team, for research in each of these categories.

It is necessary that the government stimulate research in the institutional and private sectors as much as possible. With the reduction in the funding levels for research, this goal requires a refocusing and serious prioritization of the federal research mission.

To meet the challenge posed by this new environment, industry must increase its contribution to research and development; overcome the barriers to establishing effective partnerships with academia, national laboratories, and other industrial partners; focus its research priorities; and take advantage of leading-edge results from universities and national laboratories. The government, in turn, must stimulate civilian research related to technologies; foster partnerships; create a regulatory and tax credit environment that is more conducive to research; and prioritize the research that it supports. Academia must reinforce its vital teaching role; strike a proper balance between formal education and research; alter its curriculum to better prepare the student for a career; and revise intellectual property policies to promote the development of partnerships with the private sector.

It is imperative that bureaucratic barriers to research be removed. The question of what type of research the government should support must be rephrased. We must cut through the political rhetoric. We must ask what research is necessary to retain the technological competitiveness of the United States. It is this research that the nation must address. We must ask what endeavors will not be accomplished without government investment. Only by a unified effort from government, industry, and academia will the United States be able to meet the challenge of the global economy and emerge competitive, able to make and exploit discoveries and innovations in critical technology areas while maintaining world-class educational institutions.

The Research University in 2000

Arden Bement
Purdue University

Arden Bement focused on the stresses on the graduate education system in the 600-odd U.S. research universities, which, he recognized, span a wide spectrum of emphasis and quality. The context in which research is done has shifted from one focused on defense and space, in which there was a consensus that basic research made important contributions, to one involving economic competition, environmental concerns, natural resources and energy, crime, violence, poverty, and the stabilization of emergent democracies. In this new context, the role of basic research is not so obvious to policy makers. The change has led to debates over how to allocate resources in a time of shrinking funding, how to measure the value of research and the standing of the United States in global competition, whether and how to promote government-industry partnerships, and what role the government should play in supporting the behavioral and social sciences.

> ***The challenge to universitites is to broaden the horizons of students without increasing the time needed to complete a Ph.D. Universities must continue to provide an intense research experience in which students obtain a comprehensive knowledge of the current state of their chosen fields, but at the same time they must promote career preparation and exposure to other related fields.***

At present, university research is carried out mainly by graduate research assistants tied to faculty research projects. Both students and faculty have career building as an objective, but the rate of production of Ph.D.s is governed more by the availability of research funds than by the marketplace for employment of graduates. After being essentially constant for about 25 years, the number of Ph.D.s being awarded in science and engineering has been rising over the past decade, largely because of an increased inflow of foreign students into U.S. Ph.D. programs. The majority of science and engineering (S&E) Ph.D. recipients are now employed in business and industry, even though they have been prepared mainly for careers in academia. In 1991, only 31% of all U.S. S&E Ph.D. recipients were in tenure-track positions in universities. Contrary to many reports, unemployment is lower for those with S&E Ph.D.s than for other professions, but it is rising. Graduates are experiencing double-digit unemployment for extended periods, as well as the pain of unmet expectations, an increase in the average time to degree, and longer times spent in postdoctoral and other temporary positions. This situation is not aided by the pressure exerted on faculty by their institutions to educate as many graduate students as they can support.

While industry wants Ph.D.s with a research background, it also wants them to be adept in problem solving, communication, and leadership, to be able to work adaptively in interdisciplinary teams, and to have an entrepreneurial spirit.

There are many stresses that promote changes in the education of Ph.D. students who are headed for industry. The drivers for investment in industry are quarterly performance and the cost of capital. Neither of these favors R&D investment. The shortening of new-product cycles in industry contrasts with the lengthening time to the Ph.D. degree in universities. Public support for government-funded R&D now favors health research over science and engineering, and federal priorities in funding tend to follow public opinion. Congress is continuing to attack overhead recovery and student and faculty support. There is adverse public opinion about misconduct and conflicts of interest in federally funded research. The cost of education is widely viewed as being out of control. Merit review is favored, but political geography is increasingly strong; 80% of federal research dollars go to the top 50 research universities. Finally, the potential impacts of computer and communications technologies on higher education are not yet fully understood or appreciated by universities. These new technologies will affect not only enrolled students, but also continuing education, as industry searches for more cost-effective technology-based alternatives.

The challenge to universities is to broaden the horizons of students without increasing the time needed to complete a Ph.D. Universities must continue to provide an intense research experience in which students obtain a comprehensive knowledge of the current state of their chosen fields, but at the same time they must promote career preparation and exposure to other related fields. As examples of interdisciplinary programs that allow this, Bement mentioned computational science and engineering, bioscience and engineering, and materials science and engineering. He noted that all three are closely related to economic development. He also noted that integrated multidisciplinary programs bring benefits to universities, including improved attractiveness to top students and faculty, better leveraging of expensive facilities, greater availability of minor and dual-degree programs, easier marketing to both internal and external constituents, and a more realistic preparation for industrial research.

Bement foresees a number of changes in the research universities in the coming few years:

- Growth of the M.S. degree in professional education in both science and engineering;
- Deemphasis of the "basic research versus applied research" question in favor of asking more about "good research versus bad research";
- Increasing collaboration in the United States and globally in consortia for both education and research;
- More minor and dual-degree programs;
- Adoption of more industry-friendly positions in matters such as intellectual property;
- Greater efforts to shorten the time to the Ph.D. degree;
- Greater differentiation, rationalization, and focusing among research universities;
- Increasing use of distance learning for conveying factual knowledge, with universities continuing to provide mentoring, tutoring, and coaching on-site;
- More emphasis on rebalancing the education, research, and service roles of the research university; and
- Greater efforts to promote wider geographical distribution of federal research funding.

Semiconductor and Telecommunications Industries

Charles Shanley
Motorola

Charles Shanley presented three case studies that demonstrate the pervasive importance of materials in the semiconductor and telecommunications industries. He went on to describe current trends in research funding and to discuss new research methodologies that might better leverage investments by government and industry.

The first case involves a device not commonly known outside the telecommunications industry: the radio frequency (RF) duplexer. These devices are filtering elements that permit the simultaneous transmission and reception of radio signals. Their dimensions are largely determined by the wavelength of the RF signals and the dielectric constant of the filter material. Historically, the duplexer material has been barium titanate, which has acceptable temperature coefficients, electrical parameters, and cost. However, the trend to smaller cellular radios mandated the development of smaller duplexers, which in turn mandated the development of new materials. Neodymium titanate, a new material with a higher dielectric constant, was developed specifically to answer these requirements and has resulted in a significant size reduction for duplexers and cellular radios in general.

The second case is also related to the need to decrease the size of cellular radios. Because most of the circuitry of a radio is current controlled, one can decrease the power consumption of a radio by reducing its operating voltage—say, from 5 V to 3 V. However, conventional RF power amplifiers become inefficient at these low voltages, which increases the power consumption of the radio. To optimize operation at lower voltages, the band gaps of GaAs devices were modified by the addition of indium and other elements. The result is a power amplifier with an efficiency of over 76%, compared to the 40% efficiency of conventional silicon devices. This higher efficiency, in conjunction with the lower operating voltage, permits lower power consumption and allows the use of a smaller battery.

The final case involves progress in optical fiber efficiency. Ordinary window glass may seem transparent, but it has a transmission loss of 1000 dB/km when drawn into a fiber. The high-quality optical glass first used for optical fibers had a loss of 100 dB/km. By 1970, specialty glasses had been developed at Corning to bring this loss down to 20 dB/km. Finally, in 1982, techniques were developed to lower the loss to around

0.02 dB/km, near where it stands today. This reduction of transmission loss represents an increase in transmitted power of over 100 orders of magnitude. Seldom has the impact of materials research on telecommunications been so substantial.

Shanley noted that, in each of these three examples, the innovators were part of a large industrial concern. While not always so by any means, it is not uncommon for materials research to be capital intensive, requiring the resources of a large industry, the national laboratories, or a well-equipped university. Given the highly competitive industrial environment and the declining funding for government-sponsored research, it is important to ask where future research will be performed.

Shanley believes that the picture is not altogether bleak. Support for basic research, properly the province of universities and to some extent the national laboratories, is being held essentially flat. He argued that basic research is the most important investment in research that the country as a whole can make. Applied research will continue at companies, large and small, since it is a necessity for their survival. The increasing tendency of companies to be more aggressive in searching widely for new technology and applied research may augur well for universities, which have shown increasing interest in moving into applied research as well as basic research. Further progress on this front will depend on greater flexibility on the part of all participants with respect to the ownership of the results of this research.

The increasing tendency of companies to be more aggressive in searching widely for new technology and applied research may augur well for universities. Further progress on this front will depend on greater flexibility on the part of all participants.

On another front, some of the excellent interdisciplinary applied research at the national laboratories is being cut significantly more than is advisable. When the national laboratories focus on applied research within their missions, their productivity is often substantial.

As companies and the government seek to gain more effectiveness from their research investment, Shanley suggested, it may be useful to look at the types of researchers who have been the most successful innovators. Thomas Kuhn, in *The Structure of Scientific Revolutions* (University of Chicago Press, 1970), identifies two classes of scientific innovators. The first class consists of recent graduates, who, largely unaware of what is impossible, often obtain it. An exemplar of this class is Einstein. This class is well served by the U.S. university system and the basic research funding mechanisms of the National Science Foundation. Although funding is tight and should certainly be increased, significant work continues to be done. The second class of innovators identified by Kuhn consists of older researchers who change fields. The older researcher has the advantage of experience in his or her prior field, experience that often has unexpected applicability in the new field. Examples here are legion also, though less well known than the previous case.

One mechanism for increasing the effectiveness of research investments, which has proven successful at Motorola, is the minority report. Shanley described a minority report as an “ad hoc call to action,” by an individual or a group, concerning a matter of strategic importance to the company or an opportunity for the company to invest in a new technology platform. Minority reports have alerted Motorola to the strategic importance of issues such as the need for increased quality in its products, the strategic nature of high-efficiency GaAs power amplifiers, and the need for an internal surface acoustic wave (SAW) capability for wideband radios. Some new technology platforms that began as minority reports include the Iridium satellite communications system and Motorola’s recent forays into flat panel displays. By highlighting vulnerabilities and opportunities through minority reports, individuals can bypass middle management entirely and report ideas either to the sector management or directly to the chief executive officer. Well-argued minority reports are always seriously considered.

A View from the National Laboratories

Al Narath
Lockheed Martin Corporation

Al Narath described the changing R&D landscape from the perspective of the Department of Energy (DOE) national laboratories. This perspective depends a great deal on one's vantage point. First, no two laboratories are exactly alike. Two broad classes can be distinguished: program-dedicated laboratories (such as the Stanford Linear Accelerator Center, Fermilab, and the National Renewable Energy Laboratory) and multiprogram laboratories. The multiprogram laboratories include five Energy Research laboratories (Argonne, Brookhaven, Lawrence Berkeley, Oak Ridge, and Pacific Northwest), three Defense Programs laboratories (Lawrence Livermore, Los Alamos, and Sandia), and an Environmental Management laboratory (Idaho National Engineering Laboratory).

These laboratories are active and vibrant in many areas of research and development. For example, in materials research, the funding level summed over all sponsors is approximately $400 million. The DOE laboratories lead in research using neutron scattering and synchrotron light scattering. They make broad and often unique contributions in many areas of materials R&D, including materials processing, microelectronics, high-strength alloys and ceramics for energy applications, actinide chemistry and physics, aerogels, microcharacterization of materials, and combustion science. Each year, DOE's materials facilities are used by over 4500 researchers from universities, industry, and government laboratories. And we are beginning to see profound impacts on materials science and engineering brought about by DOE's high-performance computing initiatives.

At the same time, this broader view of the laboratories is shrouded by an unhealthy haze of uncertainty. Recently, a small group of DOE laboratory directors had the opportunity to exchange views with House Speaker Newt Gingrich, who remarked that "the problem the labs face is that they are caught between a world that no longer exists and a world that has not yet been created." During this period of increasingly constrained federal budgets, DOE and its laboratories are experiencing considerable pressure. Important issues are being discussed:

- With the end of the Cold War, mission relevance tops the list of concerns.
- Critics perceive unnecessary redundancy and duplication of technical competencies among the laboratories.
- The laboratories' cost-effectiveness is questioned in comparison with that of other performers of research.
- The legitimacy of federal support for some of the more recent laboratory initiatives is questioned.
- Worst of all, tensions have grown between research universities and the laboratories, as the academic community confronts its own financial problems.

> ***Although currently contracting, the DOE laboratories constitute the single largest federally funded R&D complex in the United States. They are unmatched in scientific and engineering facilities, both in collective terms and in the uniqueness of the major scientific user facilities.***

Despite these concerns, it is difficult to dismiss the national importance of the broad capabilities that exist in the DOE national laboratories, capabilities that have evolved steadily over the past half century. Although currently contracting, the DOE laboratories constitute the single largest federally funded R&D complex in the United States, with 50,000 employees and an annual budget of $5 billion to $6 billion. The laboratories are unmatched in scientific and engineering facilities, both in collective terms and in the uniqueness of the major scientific user facilities that have been developed in recent years.

Among the issues being debated, none is more critical to the future of the laboratories than their mission and the extent to which they should (or should not) move outside their historic domain. This issue is critically important because functions are best derived from missions—the reverse is difficult to justify. It is also important because mission priorities are not entirely clear today.

This was not always the case. First, there was the Manhattan Project. Then came the Atomic Energy Commission with a transition to civilian control, Atoms for Peace, and the Cold War and nuclear arms race. During this period, the focus was on the utilization of nuclear energy and the enabling science and technology. The program was well integrated and enjoyed unquestioned congressional support. The "energy crisis" in the 1970s led to a diversification into nonnuclear energy R&D and the establishment of the Department of Energy. This was accompanied by a proliferation of congressional committees overseeing activities of the new department.

Twenty years have passed, and DOE has accomplished a great deal in science and technology. Nevertheless, the R&D portfolio suffers from a number of weaknesses. There is an attenuation in support for energy R&D, despite repeated admonitions that a stable, affordable, environmentally benign energy supply is fundamental to national security.[2] Nuclear weapons "stockpile stewardship" does little to guarantee long-term support for the necessary R&D infrastructure. Near-term (and often unrealistic) commitments to clean up DOE's waste accumulations impede support for innovative approaches to environmental management. And much of DOE's science has become decoupled from its applied missions and viewed by some as being in competition with the universities.

DOE recognized these problems and crafted a strategic plan in 1994 under the direction of Secretary Hazel O'Leary. The plan placed science and technology at the center of an R&D enterprise whose purpose was to support DOE's energy, national security, environmental, and basic science missions. The plan also identified a strategic role in contributing to national economic competitiveness through technology transfer. This broadened the DOE mission, consistent with the prevailing mood of the country and the Congress.

But this mood turned out to be short-lived. First came the Galvin report, *Alternative Futures for the Department of Energy National Laboratories,*[3] which was issued in February 1995. The Galvin report acknowledged that the laboratories are an important part of the nation's R&D infrastructure, with essential historic missions in national security, energy, the environment, and basic science. On the other hand, it stressed that the laboratories should work as a system, were oversized for their current mission, needed management reform, and should incorporate national economic competitiveness only as a derivative mission.

Meanwhile, the congressional leadership changed, and a new phrase crept into the vocabulary: "corporate welfare." This term reflected the belief by many that federal science and technology programs should be limited to basic science unless they directly support a specific government mission.

The DOE response to the Galvin report and the shifting political winds has been swift and decisive. It includes a strategic realignment of the department, initiatives to reduce bureaucracy and costs, and the implementation of a "System of Laboratories" approach to operating the DOE complex.

Regrettably, the national science and technology debate seems to be focused on the wrong questions, namely the impact of funding shortages and ways of changing the distribution algorithm. While budgetary problems are important, obsessive preoccupation with the financial term is driving our institutions toward predatory behavior—at a time when greater cooperation among R&D performers is more likely to yield positive results. For the national laboratories, sizing is not the most critical issue. Any realistic extrapolation into the future would suggest that the laboratories will constitute a formidable resource long after the current turmoil has subsided. The issue is how best to continue the laboratories' distinguished record of service in the national interest.

The key to this puzzle (as already noted by Galvin) lies in strengthening the interactions among the laboratories and in enhancing the efficiency of their internal operations. The laboratories are making rapid progress in both areas. The System of Laboratories is beginning to take root on a scale not previously practiced. For example, in materials science and engineering, a growing number of coordinated, multilaboratory projects have been initiated by the DOE Office of Basic Energy Sciences. These cooperative efforts illustrate what is truly unique about the national laboratories—the ability to organize and execute multidisciplinary programs of significant scale, to integrate basic research and practical applications, to develop and operate major user facilities, and to create partnerships with universities and industry.

Industry, universities, and national laboratories are all essential cornerstones of an interactive national R&D enterprise. Each has distinguishing characteristics. Each gains value in proportion to the strength of its linkages to the others. In time, our nation will arrive at a solution to the imperative of politically sustainable private-public R&D partnerships.

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[2] U.S. Department of Energy, *Energy R&D: Shaping Our Nation's Future in a Competitive World, Final Report of the Task Force on Strategic Energy Research and Development* (the Yergin report), Washington, D.C., June 1995.

[3] U.S. Department of Energy, *Alternative Futures for the Department of Energy National Laboratories* (the Galvin report), Washington, D.C., February 1995.

III. Outlook from the Federal Agencies

National Science Foundation: Why Federal Support for Basic Science? Will the Civic Scientist Step Forward and Answer?

Neal Lane
Director, National Science Foundation

The post-war public gratitude for science, and the political translation of this gratitude into tangible support, seem finally to have waned, perhaps irreversibly. Neal Lane reiterated the projection by the American Association for the Advancement of Science, which was mentioned frequently at the forum, that except for the health- and defense-related sciences, we are facing a general decrease in funding of about one-third over a period of six to seven years. This seems to be independent of political ideology, and it raises a crucial question: Can we, in the face of such cuts, remain competitive with our industrial neighbors? And can we remain, as we are now in many fields of science, a nation of leadership? In terms of diversity, materials research is one of the richest of fields. (Everything is made from something!) Materials are of critical importance to modern technology, and although the reduction in funding for basic materials research appears to run counter to the aim of cutting the federal budget deficit, the public still seems to question the need for federal support, even for research on components, which so obviously enhances the prospects of growth. Can it really profit this nation to engage in a process that balances its budget but leaves it in a state where its capacity to generate new wealth is seriously weakened?

Against this background, Lane laid out the impending challenges to be faced by the National Science Foundation (NSF) in this period of entrenchment. He made it clear that NSF's commitment to materials research is firm. But while the public still admires science in a general way, it appears not to appreciate the importance of materials in what is loosely described as "the good life." The key challenge devolves squarely on communication, both with the public and with our representatives in government. Ingenuity, creativity, and productivity on the part of the materials physics community are clearly no longer enough. In addition, said Lane, "we need a stronger dialogue with the American public." 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. Without it we will increasingly face difficulty in getting the attention of our congressional representatives, who are already beset by mounting concerns that are increasingly of a social nature.

> ***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.***

Ideally, we would arrange matters so that, as is common in our competitor nations, science and technology become embedded in a long-term political framework that offers protection. Lane reminded us that science is in that small part of the federal budget known as "discretionary." This term, he said, means exactly what it says. Our funding is at the discretion of the President and the Congress, and we have potent competition, for the civilian discretionary budget is now down to just 17% of the entire federal funding pie. The civic scientist must engage in a new and active dialogue with the American electorate to inform it (and remind it) of the manifold benefits of science to society at large. And this exchange of views must begin soon.

National Institute of Standards and Technology

Arati Prabhakar
Director, National Institute of Standards and Technology

The U.S. economy and its R&D enterprise are being strongly influenced by the globalization of corporate and economic trends, the increasing pressures of international competition, and the accelerating pace of technological change. As we've all observed, many companies are taking a more narrowly focused research approach. This is often an understandable and sound decision for individual companies. But what about the national picture? Arati Prabhakar said that there is a role for government in facilitating (but not leading) timely progress on preproduct technologies that are often too risky to be adequately supported with private funds alone. She also said that a modest investment in such ventures will in many cases lead to new products and new jobs and a more competitive U.S. economy.

NIST's Advanced Technology Program (ATP) was initiated in 1980 to foster such industrial technology opportunities. It should be noted, however, that the core laboratories of the National Bureau of Standards still exist within the new National Institute of Standards and Technology (NIST) and still carry out the long-term missions in measurements, standards, and science that have served the U.S. industrial and research communities for almost 100 years. The broad NIST role in materials science and engineering is centered on measurement methods and standard reference data and materials, along with underlying research to serve the materials community.

There is no better example than materials science and engineering to explain the need for the Advanced Technology Program. There are, of course, stories over and over of new materials with exciting properties—magnetic, electronic, high-strength—the list goes on. But incorporating novel or improved materials properties into new products or improved manufacturing is a perennial chicken-and-egg problem. The goal of the ATP is to link our first-rate research base to the development of new products or processes, which in turn lead to better economic payoffs and jobs for our people.

Another part of the role of NIST in technology assistance is the Manufacturing Extension Program (MEP). This approximately $80 million per year program is aimed at providing timely, focused assistance to several hundred small firms, throughout the United States, that represent where much of U.S. manufacturing occurs. If interested firms are not abreast of the latest technology or computer methods, MEP can provide access and short-range support to help them become competitive. As in the ATP, the small technology centers created under this program require matching funds and are chosen by a competitive selection process.

The final important element of NIST's efforts in support of U.S. business and industry is the Malcolm Baldrige Award for excellence in quality and efficiency. This past year, two materials-based companies received the award, including Armstrong World Industries Building Products Operations, many of whose products, including building tiles and insulation, are not high-technology but are economically very important.

In the last few years, NIST has tried with these programs to better link public investment to private investment in R&D. In the last couple of years there have been vigorous attacks and disputes about such efforts, but there has been some recent progress in the nature of the discussion. The public invests in research, said Prabhakar, not only for new knowledge but also to improve their lives: by improving the economy, health, jobs, and so on. A recent survey indicated that the public does recognize R&D as a vital investment. Citizens do not believe, however, that this investment should be made in a disconnected way, and they are appalled when they hear about the apparent waste of such "disconnected" research.

So the question that the Administration and the Congress are dealing with is how to balance the science and technology portfolio to meet the real needs of the country. NIST is trying to provide part of the answer with its small fraction of the government's R&D investment. It clearly recognizes the need to provide measures of effectiveness and payoff. This payoff has been broad, clear, and widely accepted for almost 100 years for the continuing basic measurement and standards mission of the NIST laboratories. A serious effort is being made to measure the ATP's effectiveness, in spite of the fact that the program has been in existence only for a short period. The results look good so far, but NIST must continue to evaluate and improve. The MEP is somewhat easier to gauge in the near term, and early studies indicate an $8 benefit per federal dollar expended. Prabhakar said that she and others at NIST recognize that they must pay a great deal of attention to measures of success, as they continue to use their resources to enhance the nation's competitiveness and economy.

Materials Science and the Department of Energy: Surviving Success

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

Martha Krebs described the historic changes that are occurring in the political landscape and the impact they are having on science and technology programs at the Department of Energy. There are many new faces in the Congress, most of them not educated about science, and some senior members who do strongly support science are retiring next year. Furthermore, the new Congress has confused applied science with "corporate welfare" and has even questioned the DOE's very mission. Secretary O'Leary has initiated broad reforms to address these concerns, including significant cost savings and reductions, but in the 104th Congress applied science at DOE was devastated nevertheless. There are concerns about the future of basic science, and all research institutions are at risk.

The Office of Energy Research (ER) is in the interesting position of having to "survive success." ER-supported researchers won the 1994 Nobel Prize in physics and the 1995 Nobel Prize in chemistry, received seven R&D 100 Awards for developing promising new technologies, discovered the top quark, achieved world records in plasma performance at the Tokamak Fusion Test Reactor, and made significant contributions to the Human Genome Project. But despite these and other successes, ER's research funding declined 5% in FY 1996.

ER's priorities for FY 1997 are to sustain the high-energy physics program, restructure the fusion program, maintain the Scientific Facilities Initiative, maintain balance between facilities and research, and integrate basic research with applied programs. The Scientific Facilities Initiative is allowing major national research facilities (including neutron and light sources) to run longer, improve beam lines, and enhance research support. Also of interest to the materials research community is ER's congressionally requested evaluation of upgrade opportunities at existing neutron sources while the next-generation source is developed. There are even some new opportunities for ER-supported materials research in certain targeted areas, such as the Partnership for a New Generation of Vehicles and the environmental science and management initiatives.

DOE and the Office of Energy Research are meeting the challenge of change. The Galvin report[4] on alternative futures for the DOE national laboratories has had a significant positive impact, and mechanisms have been put in place to ensure better regulation and management and provide substantial cost savings. A Laboratory Operations Board has been chartered to monitor this process and provide strategic direction. Increased cooperation among the laboratories and with universities and industry is essential to the future of science in the United States.

The missions of the Office of Energy Research—knowledge generation, knowledge transfer, knowledge applied to the public good—remain vital. But circumstances have changed, and the department's approach must change. The community must be more effective in educating the public and the Congress about the benefits of science. We must make better use of the available resources by improving cooperation across disciplines and among universities, laboratories, and industry. And we must avoid pitting basic research against applied research or universities against national laboratories. Funding lost in one area will not reappear in another. We must make the case for all of science.

Department of Defense Materials Research and Technology

Anita K. Jones
Director, Defense Research and Engineering, U.S. Department of Defense

Anita Jones summarized how sustained investment in defense technology, driven by the objective of national security, has allowed the United States to achieve technological superiority. The unmatched systems that provide this superiority include stealth aircraft, "own-the-night" sensors, cruise missiles, precision guided weapons, airborne ground surveillance radar, and the global positioning system. The presentation emphasized the role of materials in the Department of Defense's R&D investment strategy. Stealth technology and the F119 engine were cited as illustrations.

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[4] See footnote 3.

The Department of Defense (DOD) is the dominant federal investor in numerous critical fields, even though it administers only 18% of the total federal research budget. For example, DOD provides 73% of all federal research funding for metallurgy and materials, administered by the Defense Advanced Research Projects Agency (33%), the Air Force (15%), the Navy (14%), and the Army (6%). DOD also supports 69% of the materials research performed in universities. The DOD investment portfolio in materials research includes contributions to combatant and sensor survivability and life extension of military systems (60%), structural and propulsion materials (21%), and weapons systems structures.

The end of the Cold War has introduced a new era with markedly new demands. Today's competitor is not a country, but the global arms market. The U.S. military must maintain technological superiority despite reduced budgets. Military demands are actually broader than ever, with new emphases on peacekeeping and nonproliferation. Moreover, while the military mission has become more complex, the challenge of global economic competition is shifting national priorities toward the civilian economy.

These realities have made affordability the major criterion for military technology, replacing the formerly singular criterion of performance. As a result, the defense science and technology strategy now emphasizes reducing the cost of systems, dual use to strengthen the integrated commercial-military industrial base, rapid transition of technology to the warfighter, integrated technology planning, basic research, and assurance of the quality and superiority of technology.

The Department of Defense is the dominant federal investor in numerous critical fields.

Long-term defense materials research investments have benefited both national security and the economy. Jones illustrated this point with some examples of materials research areas that have provided key defense advantages while also leading to major new industries: carbon-carbon composites, advanced polymer composites, single-crystal superalloys, high-strength steels, and titanium matrix composites.

In spite of this record of success, though, there are serious concerns for the future. There is immense pressure for budget decreases, especially in basic research (DOD's 6.1 budget category). There is also pressure from some quarters to trade long-term goals for short-term goals. DOD-funded research must be supported by a vision of what opportunities it could lead to, but that does not and should not mean a short-term focus.

Materials research holds the promise of improved future defense capabilities, and it therefore remains a high priority at DOD.

Panel Discussion

Moderator: Paul Fleury, Chair, Solid State Sciences Committee
Panel: Thomas Weber, NSF; Arati Prabhakar, NIST; Martha Krebs, DOE; Anita K. Jones, DOD; Thomas Weimer, House Basic Research Subcommittee; Douglas Comer, House Technology Subcommittee; Patrick Windham, Senate Commerce Committee

A panel discussion followed the agency presentations summarized above. It focused on the changing environment in the United States for federal R&D funding, particularly basic research funding.

As mentioned by earlier speakers, the "congressional revolution" has resulted in a general lack of familiarity with both science and technology among the new members of Congress. Many of the members most familiar with long-standing science and technology issues have been replaced. The panel emphasized and agreed upon the need for the science and technology community to engage broadly and at all levels in a process of educating members of Congress, their staffs, and the public at large about the value delivered to society by R&D in science and engineering.

There was some debate on the proper place of the federal government in supporting the spectrum from research to development to application. In the talks summarized above, speakers from the agencies pointed to a number of programs at their agencies that aim to foster partnerships: cooperative research and development agreements (CRADAs), the Advanced Technology Program (ATP), the Technology Reinvestment Program (TRP), programs at the Defense Advanced Research Projects Agency (DARPA), and others. Asked which of these many programs have been successful and can serve as models, and which can be shown to have failed, the panel was divided. Arati

Prabhakar pointed out that the programs each have somewhat different objectives and said that it is important to evaluate them separately in terms of their own goals. Doug Comer emphasized that the Congress is working on ways to increase the laboratories' ability to do CRADA-like partnerships even while the set-aside funding for these programs is disappearing. Several panelists shared the view that if cooperation between industry and government laboratories is indeed in the best interest of both parties, it will be funded without the need for congressionally mandated set-asides. There was general agreement on the need for a clear set of metrics for each such program.

Peter Eisenberger (Princeton University) noted the large changes in industrial R&D operations, changes driven largely by cost and the need to involve R&D strategically in corporate operations and planning. How can the government approach the restructuring of R&D at the same fundamental level? This question evoked the observation that the Department of Energy, through the Laboratory Operations Board, is attempting to take a similarly broad look at its many laboratories.

The panel emphasized and agreed upon the need for the science and technology community to engage broadly and at all levels in a process of educating members of Congress, their staffs, and the public at large about the value delivered to society by R&D in science and engineering.

Anita Jones pointed out the need for increased emphasis on targeted programs within the DOD, that focus on affordability and dual use. Both these themes have been emphasized at DOE as well.

Marc Kastner (Massachusetts Institute of Technology) asked what advice the panel would give to members of the community in order to best preserve support for basic research. The answers involved prioritization and the identification by the community of the most important research areas. The MS&E report was cited.[5]

The panel was in general agreement that there will be less money from the federal treasury for R&D and that some operations will simply have to disappear. A means will have to be developed of striking a balance between facilities, universities, individual investigators, and large-project-type research.

Doug Comer pointed out the great tension between the fiercely competitive environment in which industry operates and the onerous regulatory environment imposed on it by the federal government. This affects the conduct of both R&D and manufacturing. This issue will have to be resolved.

Tom Weber emphasized again that funding for new research areas will not come out of new money. Priority setting is essential, even if painful, and if the scientific community does not do it, it will be done for them.

Lyle Schwartz (NIST) asked about specific means of educating congressional staff. Tom Weimer pointed out that while it is generally a good idea to inform the Congress and its staff of the value of research, Congress does not usually get involved in priority setting for basic research, with the exception of large facilities. Supporters of research must be able to make the connection between science and the national good. All agreed that both individuals and the professional societies should quickly increase their emphasis on such education.

What could conceivably replace the Cold War as a driver for basic R&D? Economic competitiveness was considered, as well as health, transportation, and other possibilities, but it was generally agreed that no single overriding issue is as compelling as the Cold War. So we must all work harder, articulating the value that R&D has delivered at a more specific level.

Paul Fleury raised the question of other countries' investment in basic research, specifically in nondefense R&D. He questioned whether this country can remain a first-class nation if it continues on a path toward reducing such R&D in real terms by another 30%. The importance of the debate about the value received by the nation from investment in R&D was generally agreed to by all.

Bob Laudise (Bell Laboratories) suggested that the community take the high road and avoid being drawn into a short-term political debate. Instead, it should focus on giving advice on what is generally good for the country from an investment standpoint. All agreed that an honest and open debate is needed and that it had better get started.

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[5] National Research Council, *Materials Science and Engineering for the 1990s: Maintaining Competitiveness in the Age of Materials*, National Academy Press, Washington, D.C., 1989.

IV. Materials R&D: Wealth Creation Through Technology

Photonics Accomplishments and Challenges

William F. Brinkman
Vice President, Physical Sciences and Engineering,
AT&T Bell Laboratories (now Lucent Technologies)

Optical telecommunication was introduced into the marketplace in 1980 and has become a multi-billion dollar enterprise. Today, almost all long-distance telephony uses an optical network, without which the sheer volume of communication would not be possible. William Brinkman summarized some of the advances in materials that have enabled this revolution, but focused mostly on advances that are needed for anticipated accelerated growth.

Optical fibers are the backbone of optical communication networks. The initial advance in fibers that enabled optical communication was the reduction of transmission losses in the 1.3- to 1.5-mm window in silica from more than 500 dB/km in 1965 to as low as 0.15 dB/km today. This advance resulted from purification and processing improvements. Over the years, as system requirements have changed, there has been a continuing evolution of fibers from multimode, to single-mode, to dispersion-optimized.

> ***As fast as optical communications has grown, the future looks even brighter, in large part due to advances in optical materials.***

Fiber would be useless without a variety of other passive and active components. Lasers and detectors have largely been based on III–V semiconductors, which have direct gaps that can be tuned throughout the required range. The light source has evolved from the first-generation light-emitting diodes (LEDs), to broad (2-nm) lasers, to single-wavelength lasers. The most recent advance is an integrated electroabsorption modulated laser with distributed feedback. Other critical components include avalanche photodiode detectors and semiconductor pump lasers.

Recent advances in making active fiber components promise to dramatically change the architecture of future systems. Examples of these components include fiber lasers and optical amplifiers. Optical amplification (as opposed to conversion to an electronic signal and reconversion to light) has several advantages, including bit rate independence and the possibility of achieving higher transmission rates through wavelength division multiplexing (WDM). Optical amplification at 1.5 mm can be achieved with erbium-doped fiber amplifiers (EDFA). The need for high-power EDFAs may be met by co-doping with ytterbium to increase the absorption of 980-nm pump light or by pumping standard erbium fiber with high power at 1480 nm from a cascaded Raman fiber laser. The Raman lasers use a series of Bragg gratings in germanosilicate glass to resonate at wavelengths successively Stokes-shifted (450 cm^{-1} per grating). An overall 20% conversion efficiency can be attained in going from 1064 to 1480 nm.

The advances in optical components play a central role in the ongoing debate on how next-generation lightwave networks (NGLNs) will be configured, including possibilities such as WDM, time division multiplexing, point-to-point transport, multiwavelength/multipoint fixed networks, photonic cross-connect systems with a different wavelength for each service provider, and others. The consensus is that costs will come down, reliability will go up, and upgradability is essential. All this is projected to mean that fiber will come closer to the home, long-haul transmission will be all-optical (including amplification and perhaps switching), computers will be interconnected, and voice, data, and video will be integrated.

Submarine systems push the technological frontiers because they must have high capacity and reliability and because companies can afford to pay more for them than for terrestrial infrastructure. Today, undersea cables with capacities of 100,000 conversations per fiber (5 Gbit/sec) at $400 per channel (down from $20,000 in 1965 and $2,000 in 1983) are a reality. This capability enables previously unthinkable projects such as the planned Africa Optical Network, an undersea cable around Africa with individual links to each country.

As fast as optical communications has grown, the future looks even brighter, in large part due to advances in optical materials.

Materials Aspects of Computer and Storage Sciences

Michael R. Polcari
Director, Silicon Technology, IBM T.J. Watson Research Center

The information revolution has been made possible by the rapidly decreasing cost of computer hardware. In particular, the cost of computer memory continues to decrease exponentially with time. Semiconductor memory has decreased in cost by about a factor of 10 in the last decade, and magnetic disk memory has declined in cost even more rapidly, by about a factor of 100 in the same time period. Michael Polcari demonstrated how advances in the understanding and control of materials have propelled this tremendous increase in computing efficiency.

> ***Continuation of the information revolution depends on advances in materials science and engineering.***

Magnetic disk storage density has grown rapidly because of the wide variety of new materials used. The density increased by less than a factor of ten between 1985 and 1992, but it has increased by a full factor of ten in just the last four years, because new materials have been invented that allow the use of magnetoresistance (the change of electrical resistance with magnetic field), instead of pick-up coils, to detect the magnetization of domains in a disk. Pick-up coils are relatively large and limit the size of the magnetic domains that can be used to store information. In contrast, magnetoresistance devices can be made as small as semiconductor devices. Most materials have magnetoresistance that is too small for detecting the domains in a disk, but new materials systems have recently been discovered with such a large response that it is called giant magnetoresistance.

This was just one of many examples Polcari gave of the materials advances that have led to innovations in magnetic disk storage. Others included the special metallic components of the disk head and a unique layered structure of the disk itself that allows the head to ride at enormous speeds, very close to the disk surface, equivalent to a 747 jet flying a few feet off the ground.

The reduction of the size of semiconductor memory and processor devices is also often limited by materials properties. There are numerous examples of how the understanding of materials physics and chemistry have been critical in designing new materials that perform well under new circumstances.

Smaller devices require thinner insulators between the silicon and the metal gate that turns the transistor on and off. Research has shown that, over time, the resulting higher electric fields cause degradation of the oxide because hydrogen is released from the gate, causing defects. Incorporation of a nitrogen-rich layer prevents this.

Another example involves metal interconnects between devices. As devices get smaller, the metal layers connecting them get thinner. Using the National Synchrotron Light Source at Brookhaven National Laboratory, IBM researchers have learned how to control the chemistry of these metal layers so that they can be kept metallic even when very thin. The complex structure of semiconductor circuits, soon to consist of six layers created by successive photolithography, has posed great materials challenges. In addition, the resistance of interconnects will lead the industry to switch from aluminum to copper, but copper degrades silicon device performance, and so special layers must be incorporated to isolate the interconnects from the devices.

These examples demonstrate how materials physics and chemistry have led to new understanding that has been rapidly incorporated into the technology of the computer industry. The message is clear: continuation of the information revolution depends on advances in materials science and engineering.

Materials in the New Auto Age

Norman Gjostein
Director, Materials Research Laboratory, Ford Motor Company

Norman Gjostein's theme was that for the past two decades the dominant driving force for the auto industry's enormous materials needs has been competition for cost and reliability. The auto industry has been and will continue to be an enormous consumer of materials. It consumes 14% of U.S. steel, 16% of aluminum, 10% of copper, 23% of zinc, 68% of lead, 60% of cast iron, 34% of platinum, and 50% of rubber. Yet when a vehicle is finally assembled, Gjostein pointed out, its finished value is only about $5 per pound. Furthermore, the dominant material used, steel, costs only 30 to 35 cents per pound! This means that the materials components used in vehicles must be mass-produced reliably and cost-effectively with high throughput. The need for high labor productivity will constrain the use of advanced materials and processing technologies in the auto industry in the near term.

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Concerns about fuel efficiency and the environment also pose challenges to the auto industry. For instance, there is concern in the United States about our reliance on imported oil, which increased from 23% of consumption in 1970 to 45% in 1991. Roughly 65% of the total consumption of oil is related to highway transportation. At the same time, there is growing concern about rising CO_2 emissions, which are widely believed to have a major impact on the global climate. These concerns have translated into pressure for continuing reduction of fuel consumption by highway vehicles.

There is also concern about disposal of solid waste and toxic materials. Existing landfills are becoming filled to capacity, and most communities are reluctant to establish new landfills or incineration facilities. Although about 75% of the materials used by the auto industry are already recycled, with the net result that auto scraps make up less than 2% of landfill waste, the industry will likely encounter growing scrutiny.

It is abundantly clear that the next generation of vehicles will consume less energy, pollute less, and use materials that are more durable and more easily recyclable. The Clinton Administration has formed a partnership with the big three auto makers, called the Partnership for a New Generation of Vehicles, through which a new generation of automotive technology will be developed. The ultimate aim is to develop a prototype family-size car with a fuel consumption of approximately 80 miles per gallon. This will require the development of new materials to reduce vehicle weight. New materials will also be involved in the search for alternative fuels.

The main candidates for use in lightweight body components are glass fiber reinforced polymers (FRP) and aluminum. Graphite fiber reinforced polymers (GrFRP) may be an option, but only if their cost can be decreased significantly. Aluminum, magnesium, metal matrix composites, titanium, titanium aluminides, ceramics, and FRP are all potential lightweight materials for use in engine, transmission, chassis, suspension, and brake components.

Both FRP and aluminum will compete with steel as the primary vehicle body material, but recyclability will become increasingly important, and so aluminum is likely to be favored unless recycling technologies can be developed for composites. Better electronic materials systems are also needed for environmental and emission controls. In special situations, such as electric and alternative-fuel vehicles, lightweight structures may be developed.

Technology Development in Japan

Jeffrey Frey
University of Maryland

Jeffrey Frey's talk focused on the crisis that he sees in Japanese technology. The special characteristics of Japanese engineering arise from the special characteristics of Japanese culture. These characteristics have led to success in fields like the automobile industry and the manufacturing of memory chips because they facilitate cooperation in large enterprises that produce millions of similar products every year. However, they work against the development of products in which the value is added not by the hardware itself, but by the function that the hardware achieves. This has led to a "software crisis" in Japan, at a time when there is also a loss of high-production businesses to Korea and other countries with lower labor costs.

In Japan, neither graduates nor companies place much value on the educational efforts of the universities. Engineers' specialized knowledge and skills are developed and transmitted mainly through on-the-job training.

The special culture of Japan arises from its status as an island nation that has undergone hundreds of years of isolation and developed a survival mentality. Japanese society values harmony above all. This enforces cooperation and cultural uniformity among its citizens, who in turn value group loyalty and dislike being in the spotlight.

The Japanese engineering culture arises from the structure of the society as a whole, starting in the home and in preuniversity education, followed by the university experience and especially on-the-job training in companies, and finally by experience in the workplace. Preuniversity education involves 5 1/2 days per week, 40 weeks a year. It emphasizes group effort and the learning of facts, rather than analysis and critical thought, and it is supplemented by a system of after-school schools called *juku*. By grade nine, almost 50% of children attend *juku*, which are intended to prepare students for university examinations. There is a quality pyramid throughout the system, culminating at the university level. Periodic examinations sort students in this pyramid. The best students get into the best universities and are recruited by the best companies, which means the large, well-established companies, not the new or small ones.

This intense public education peters out after the twelfth grade, however. The roles of the university are to administer entrance exams, to teach fundamental principles, and to allow students to develop social skills. Although class and laboratory time are about the same as in the United States, there is little homework. Group projects are emphasized, final grades come from written exams, and graduation is almost assured. Neither graduates nor companies place much value on the educational efforts of the universities.

Graduate education is emphasized much less in Japan than in the United States. Fewer students continue past the bachelor's degree, and most of them stop at the M.S. level. Graduate degrees do not result in higher salaries in companies, and research Ph.D.s are useful only for professors. (Many company researchers get "paper" Ph.D.s, however, for which they submit papers based on their work at their companies and take an examination.) In general, graduate schools are isolated from industry.

Engineers' specialized knowledge and skills are developed and transmitted mainly through on-the-job training (OJT). Thus technology is developed and held in companies, and there is no inflow of ideas and information from universities as there is in the United States. The function of OJT is to teach the company culture and structure (which is layered by age) and the practical application of fundamentals. OJT also promotes communication across barriers and provides continuity of learning, since it goes on throughout the career of an engineer. It is carried out by formal in-house courses and conferences, by a mentor system, in artificial projects for new hires, and through job rotation. OJT is expensive in terms of unproductive years and other costs, but it is justified in terms of investment in long-term employment.

Job mobility in Japan is much lower than in the United States until the age of about 50, though it exceeds the U.S. rate by age 55, which is the normal retirement age. After age 55 or so, engineers who have not made it to high-level management positions move on to jobs in smaller companies or to colleges and universities. The OJT investment is facilitated by accounting procedures in which there is little direct association between costs and returns and a system in which acceptable profit margins are relatively low.

Industrial laboratories in Japan are of three types. Basic research is conducted in central research laboratories that are funded almost entirely at the corporate level. These laboratories have a number of functions, including setting the technology agenda for the company and building a technology foundation, providing a window on the world, enhancing the prestige of the company, and providing an interface with universities. The project time frame is typically five years or more. In the second tier are the engineering or divisional laboratories, which are funded at the divisional level and which have a time frame of one to three years. This is where new products and new processes are developed. The third tier is the factory development laboratory, funded at the factory level with a time frame of under one year and an emphasis on problem solving and prototype production lines. Here, major inputs come from subcontractors and equipment suppliers. Most company engineers work in third-tier laboratories, transferring new technology to production.

The Japanese strengths lie in the desire for harmony and the emphasis on long-term thinking, as well as the preuniversity education system that provides well-educated production workers, aided by the extensive OJT system, good internal communications, and a general will to succeed. These factors are aided by a relatively flat salary structure and acceptance of relatively low profits. The major weaknesses are the exhaustive planning process, which tends to lock programs in inflexibly for long times, and the tendency for linear thinking, which leaves little opportunity for new ideas.

V. Opportunities in Techniques and Technology

Photon Facilities for Materials Research

David Moncton
Director, Advanced Photon Source, Argonne National Laboratory

David Moncton described the changes that have occurred in the first century of x-ray research, from Wilhelm Roentgen's discovery of x-rays in 1895 to the development of third-generation synchrotron light sources in the 1990s. Over this period, 14 Nobel Prizes have been awarded for research using x-rays, and there has been a trillion-fold increase in the brilliance of x-ray sources. Synchrotron sources, large rings containing high-energy circulating currents of charged particles, have accounted for most of the gains in intensity.

Synchrotron radiation is as old as the universe. Created by charged particles spiraling through the cosmos, it is in the starlight that we see at night. Man-made synchrotron radiation was first observed in 1947 at General Electric, in a 70-magnet ring designed to test theories on accelerating electrons using synchronized pulses of radio-frequency voltage. This followed from theoretical research 40 years earlier, which had suggested that charged particles following a curved trajectory (in a magnetic field, for example) must radiate energy. Synchrotrons were first used for high-energy physics experiments, where synchrotron radiation is regarded as an annoyance since the energy given up by the orbiting particles has to be replaced.

Of particular importance is the ability of third-generation synchrotrons to probe materials with submicron spatial resolution and part-per-billion sensitivity for trace species

In the 1950s, researchers began to appreciate the opportunites presented by synchrotrons for photon research. In 1958, Lyman Parratt of Cornell University suggested that using synchrotron radiation to produce x-rays "would be a boon in many aspects of x-ray physics." This suggestion led to the development of synchrotron research facilities that used the "free" radiation from high-energy physics machines. By the mid-1970s, a new generation of synchrotrons was being designed and constructed, dedicated to the production of synchrotron light from bending magnets. These included facilities in Europe, Japan, and the United States, such as the National Synchrotron Light Source (NSLS) at Brookhaven National Laboratory. A third generation of synchrotron sources, optimized for the use of undulators (linear arrays of alternating magnetic fields), began to come on line in the 1990s. These include facilities in France (the European Synchrotron Radiation Facility), Japan (the Super Photon Ring 8 GeV), and the United States (the Advanced Light Source at Lawrence Berkeley National Laboratory and the Advanced Photon Source at Argonne National Laboratory). Compared with conventional x-ray tubes, third-generation synchrotrons represent an improvement in brilliance (photons per unit area per energy bandwidth per solid angle) of 12 orders of magnitude.

Synchrotron facilities have generated intense interest in the scientific community over the past two decades. The NSLS has over 2000 users each year, from 350 different institutions. Participating research teams from universities, industry, and other laboratories have invested $126 million in experimental equipment to utilize the NSLS. As the Advanced Photon Source comes on line, more than 700 investigators representing 150 institutions have raised $150 million for the initial complement of experimental beam lines.

The high brilliance of third-generation synchrotrons represents the frontier of research, using ultraviolet and x-ray radiation to study complex materials systems and processes from the atomic arrangement of superconductors and catalysts to the structure of DNA and viruses. This work includes research in structural biology, x-ray imaging, materials science, chemistry, environmental science, and microtechnology. Of particular importance is the ability to probe materials with submicron spatial resolution and part-per-billion sensitivity for trace species.

We have come a long way since Roentgen's original experiments in 1895, and further advances can be envisioned with improvements in accelerator and undulator technology. Already on the horizon are proposed fourth-generation x-ray sources, which might consist of a 20-GeV linear accelerator feeding an undulator farm. Such facilities would be 1000 times more brilliant than today's third-generation sources.

Neutron Facilities for Materials Research

J. Michael Rowe
Chief, Reactor Radiation Division, National Institute of Standards and Technology

Neutron sources are an essential element in the national science and technology infrastructure because they provide unique measurement capabilities. Thermalized neutrons have wavelengths of order 0.1 nm and energies of order 25 meV, so that scattering techniques can readily probe distances of 0.1 to 1000 nm ($q = 0.005$ to 100 nm^{-1}) and time scales of 10^{-6} to 10^{-14} seconds ($\nu = 1$ MHz to 100 THz). The neutron has spin 1/2 and therefore interacts directly with atomic moments in materials, providing a sensitive probe of magnetic structure and dynamics. As a result of the nature of the nuclear force, the neutron scattering length has a nonmonotonic dependence on atomic number and mass, providing the capability of measuring light atoms in the presence of heavy ones and of performing isotopic substitutions. The neutron interacts weakly with matter, providing high penetrating power and the ability to measure samples in a variety of environments. Finally, neutrons can be captured by nuclei, and the nature of the induced radioactivity can be used to probe chemical composition, in some cases with depth and position sensitivity. This set of properties makes the neutron a unique and valuable probe of virtually all classes of materials important to modern technology.

Neutrons are produced by nuclear reactions, with the fission and spallation reactions being the most important for modern neutron research facilities. Useful fluxes require reasonably powerful reactors or large accelerators, so that large facilities are required, located at the major national laboratories (currently including Argonne, Brookhaven, Los Alamos, NIST, and Oak Ridge). These facilities exist to serve large numbers of users, and they provide the opportunity for these users to conduct “small science” of forefront quality at a reasonable cost through shared use of the facilities. The facilities can be used very efficiently, operating 24 hours a day, 7 days a week, typically for 50 to 90% of real time. The facilities serve a diverse set of biology, chemistry, physics, and materials science researchers from industry, universities, and government.

Neutron scattering was pioneered in the United States and Canada, as recognized in the 1994 Nobel Prize for physics, and for many years the United States was the clear leader in the field. However, in the past two decades, the United States has made little investment in neutron facilities, the main exceptions being a new experimental hall at Los Alamos and the Cold Neutron Research Facility at NIST. The Europeans, in contrast, have completely refurbished the world’s premier facility at Grenoble, upgraded several smaller reactors, and created the world’s premier pulsed spallation source (supplanting the Intense Pulsed Neutron Source (IPNS) at Argonne National Laboratory) at ISIS in England. As a result, leadership in the field has passed from the United States to Europe.

However, in spite of this relative neglect and decline, the United States has remained strong in many areas of neutron research, and the number of users has doubled in the past decade. (Note that at NIST, where there was investment, the number of users has quadrupled.) Opportunities for further progress, through upgrades to existing facilities and construction of new, more powerful sources, are currently under active consideration by DOE. Developments in instrumentation and methods, along with the increased flux that will be provided by new sources, will provide many opportunities for new science. As the examples given here show, many opportunities for innovative and creative science and technology are already accessible, but the scarcity of adequate facilities severely limits their exploitation.

Neutron techniques contribute to the understanding of virtually all classes of materials in use today, including molecular and macromolecular materials, magnetic and superconducting materials, engineering materials, infrastructure materials, complex fluids, and nanostructured materials. In these materials, neutrons are used to probe structure at the nanometer to micrometer scale, in order to provide understanding of the structure-property relationships that are at the heart of materials innovation. Neutron methods are also being used to probe the dynamics-function relationship, which is becoming recognized as a critical need in many areas (e.g., in biological processes). Continued progress in the innovative use of new or improved materials requires continued efforts to understand the factors that determine materials properties. The nation’s neutron facilities now provide unique measurement capabilities for this task. With adequate future investment, they will continue to do so in the next century.

Molecular Self-Assembly and Nanostructured Systems

George M. Whitesides
Harvard University

Supramolecular chemistry is among the most active areas of chemical research. Supramolecular phenomena range from short-range interactions such as van der Waals interactions to macroscopic properties such as surface tension. Under appropriate conditions these interactions can lead to a self-assembled material. Self-assembly is crucial to the formation of many natural materials, from cell membranes to seashells. George Whitesides discussed several approaches to the fabrication of unusual device structures that have their basis in chemical self-assembly. The possibilities include nonplanar and three-dimensional structures that are virtually impossible to make by standard methods such as lithography. While the bulk of today's microfabrication is aimed at electronic systems, the methods envisioned here could prove to be useful for photonic or chemical systems for which conventional techniques are inappropriate.

Supramolecular chemistry is among the most active areas of chemical research. Under appropriate conditions, supramolecular interactions can lead to self-assembled nonplanar and three-dimensional structures that are impossible to make by standard methods.

The concept of self-assembly is that the shape adopted by the material follows directly from free energy minimization of forces. These forces may range from van der Waals interactions between molecules to interfacial surface tension. The energy minimization and the range of sizes and shapes are analogous to what we observe in soap bubbles. Since the shape of the material is driven toward thermodynamic stability, nature is a help rather than the hindrance that it often is in many conventional techniques.

Whitesides showed several examples to illustrate these concepts. One approach is microcontact printing, which is similar in concept to replication using an inked rubber stamp. The "stamp" is prepared by first making a mold with a relief structure, by lithography or any other means, and then making a cast with a rubbery substance such as polydimethoxysiloxane. The stamp is then "inked" with a thiol. The thiol is readily transferred to a gold surface by bringing it within van der Waals distance of the surface, where strong Au-SR bonds form on contact, creating a dense, self-assembled monomolecular layer (SAM). The stamp can be used many times, and the properties of the gold surface (conductivity, wettability, and so on) are modified by the properties of the thiol.

In one example, a tight helix of gold was formed around a capillary by "inking" the helix and then removing the "uninked" portion by chemical etchants. Such helically wound capillaries are of interest for micro-NMR experiments.

Another example illustrated in the talk was micromolding in capillaries (MIMIC). In this technique, a "stamp" is created as in microcontact printing and then used to replicate the original relief structure in a rigid plastic such as PMMA. Capillary channels can be created from the vias by adding a flat plate over the surface. Capitalizing on differences in the physical or chemical interactions between molecules and the surface of the capillary can lead to very effective chromatographic separation. The capillary space can also be used to induce regular packing of objects within the capillary. A "fly's eye" lens can be made from such an array of plastic spheres. Capillary-induced ordering may be a way to take advantage of the large third-order optical nonlinearities of nano-clusters.

Large-area surfaces with minimal free energy can be created by self-assembly at liquid-liquid interfaces using patterned Au-SR SAMs as constraining elements, thus avoiding the need for complementary, three-dimensional molds. Cylinders, cones, and catenoids are among the shapes produced. Lenses and optical waveguides are among the possible applications.

The ultimate minimum length scale for each of the techniques described is on the order of the molecular dimensions, i.e., nanometers. In current practice, the scale is determined by an initial lithography step that is carried through the whole process, but replication is extremely accurate and, in principle, one could capitalize on the most modern patterning techniques, such as direct writing with ion beams or atomic force microscopes. Part of the beauty of these techniques is that they are applicable to all size scales from nanometers up.

Wrap-Up Discussion: Next Steps and Action Items for the Community

Moderator: Paul Fleury, Chair, Solid State Sciences Committee

The final session of the forum was a general wrap-up intended to focus on next steps and action items for the materials research community. A large fraction of the forum participants remained for this last session, even though it was held at the end of the second day. To set the stage, Paul Fleury reviewed the elements of the changing landscape at the end of the Cold War: the U.S. budget deficit, public suspicion of institutions, corporate fixation with the bottom line, and the need to be competitive globally. He noted that real support for science and technology in the United States peaked in 1987 and has been declining ever since, and he reemphasized the congressional sea change discussed in Tom Weimer's opening keynote talk.

A principal theme of the speakers at the forum—from industry, government, national laboratories, and universities alike—was the need to educate the public, members of Congress, and the congressional staff about the value of R&D to society. The research community must use impact and outcome as the compelling arguments, not the health of individual fields. Fleury suggested that researchers "advocate globally and illustrate locally." That is, they should argue in general for the societal good brought about by R&D in any field: admit that different subfields of a discipline, or different disciplines, all deliver some value, but "illustrate locally" in the sense of showing real examples that a specific member of Congress or staffer can relate to and understand. It is particularly useful if such examples come from the member's own district. Finally, emphasis should be given to those methods of partnership among institutions and fields that have worked or that are showing signs of working.

> ***Advocate globally, illustrate locally. Argue in general for the societal good brought about by R&D, in the different subfields of a discipline and in other disciplines. But show real examples that a member of Congress or staffer can relate to and understand.***

Among the community actions to be considered are further studies and reports, several of which are under way, as discussed below. These reports should be viewed not as ends in themselves, but as tools around which to build briefings and educational forums, with the notion of illustrating the positive impacts of R&D on society. Case studies that exemplify the research roots of wealth created or industries started (computers or optical communications, for example) illustrate in real terms the societal value delivered by R&D. Studies should also point out opportunities for potential payoff in the future, both research opportunities and partnership opportunities. A through discussion of these opportunities relative to each other will, in the end, amount to setting priorities. In addition to such reports, there is a general need for marketing that value of R&D and its accomplishments. This can be done through National Research Council committees, through institutions such as universities and major laboratories, and through the professional societies and their respective divisions.

With that introduction, several audience members rose to provide their views. Bob Laudise, the president of the Federation of Materials Societies (FMS) and the incoming chair of the National Materials Advisory Board, gave three pieces of advice:

1. Don't swim upstream.
2. Realize that policy, like politics, is largely local.
3. Strive to avoid boring your audience. Presenting examples helps.

Laudise said that the R&D community should adopt policies and positions that are long lasting and transcend local political office holders. Examples should come from the heartland of the country, not just the two coasts. There should be coordinated marketing sessions at Washington-related meetings, materials policy forums, and so on. For example, the FMS is having its biennial policy forum in June 1996 in Washington. (Bob Eagan of Sandia is organizing it, and various societies are invited to participate.) The National Materials Advisory Board is considering a study on the status and needs of materials research with a focus on engineering and manufacturing aspects. Such a study should be complementary to the forthcoming study of condensed matter and materials physics that is being launched by the Solid State Sciences Committee.

Lyle Schwartz of NIST reminded the audience that in 1993 the SSSC Forum was focused on the Advanced Materials and Processing Program. This program, while well conceived and important to the country, died aborning with the change of administrations. With the change of science advisors, the cross-cutting initiatives that Allan Bromley had championed fell by the wayside. But there has been some movement, like the establishment by a group of young researchers at the University of California at San Diego of an institute designed to bridge the gap between materials and applied mechanics. Several other initiatives have been launched independently, but they need coordination or at least more communication.

Peter Eisenberger (Princeton University) described a series of workshops that he and Jim Langer (University of California at Santa Barbara) have held to expose researchers in materials to national needs and what their research can do to contribute. The first workshop was on transportation, the second on modeling and simulation in industry. A third is planned on the environment. The workshops' purpose is to bring together communities that usually have little contact and that tend to approach problems differently. There is funding for three more workshops in this series. Eisenberger is in the process of soliciting ideas for topics.

Dick Siegel (Rensselaer Polytechnic Institute) expressed the need for a forum on how materials discoveries move from research laboratories to the manufacturing arena. He is looking for specific action items to emerge from a workshop of 25 to 50 people that will be held later in 1996. Judy Franz of the American Physical Society offered the March APS meeting both in 1996 and 1997 as a forum to discuss and bring together these ideas and activities.

The SSSC Forum concluded with a summary call to action in terms of coordinating, preparing studies and reports, and educating both ourselves and our colleagues in the Congress and in the country as a whole about the past and future value of the country's investment in R&D.

List of Participants

Wade Adams	Air Force Wright Laboratory
Mufit Akinc	Iowa State University
S. James Allen	University of California, Santa Barbara
Neal G. Anderson	University of Massachusetts
Bill R. Appleton	Oak Ridge National Laboratory
Jose M. Arias	Rockwell International
Neil Ashcroft	Cornell University
Jeff Barber	Inside Energy
John Barnard	University of Alabama
Bertram Batlogg	Bell Laboratories
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