Materials Chemistry

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Materials Chemistry

An Emerging Discipline

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FOREWORD

The ADVANCES IN CHEMISTRY SERIES was founded in 1949 by the American Chemical Society as an outlet for symposia and collections of data in special areas of topical interest that could not be accommodated in the Society's journals. It provides a medium for symposia that would otherwise be fragmented because their papers would be distributed among several journals or not published at all.

Papers are reviewed critically according to ACS editorial standards and receive the careful attention and processing characteristic of ACS publications. Volumes in the ADVANCES IN CHEMISTRY SERIES maintain the integrity of the symposia on which they are based; however, verbatim reproductions of previously published papers are not accepted. Papers may include reports of research as well as reviews, because symposia may embrace both types of presentation.

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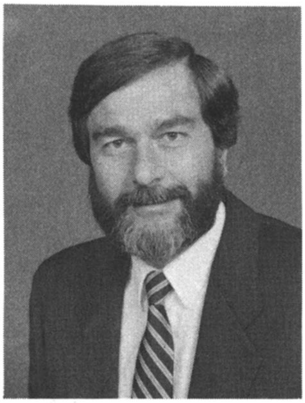
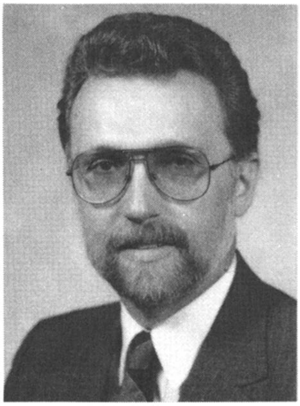


LEONARD V. INTERRANTE is Professor of Inorganic and Materials Chemistry at Rensselaer Polytechnic Institute. He received his Ph.D. degree in inorganic chemistry with J. C. Bailar, Jr., at the University of Illinois in 1964. He was a National Science Foundation Postdoctoral Fellow at University College, London, and an assistant professor in the Chemistry Department at the University of California at Berkeley from 1964 to 1968. Before coming to Rensselaer Polytechnic Institute in 1985, he spent 17 years as a staff scientist at the General Electric Research and Development Center in Schenectady. He has served as the chair of two Gordon Research Conferences (Inorganic and Chemistry of Electronic Materials) and as Program Chair, Secretary–Treasurer, and Chairman of the Inorganic Division of the ACS. He is currently Editor-in-Chief of the ACS journal, *Chemistry of Materials*. His research areas include molecular precursor routes to ceramic materials, inorganic polymer chemistry, chemical vapor deposition using organometallic precursors, and high-temperature structural composites. He has published more than 140 papers, holds seven patents, and has edited three other books in these various areas of materials-related chemistry.

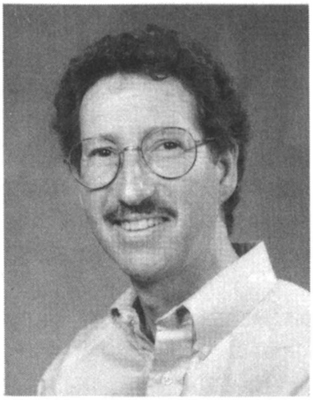


LAWRENCE A. CASPER received his B.S. degree in chemistry from Juniata College and his Ph.D. degree in Chemistry from Lehigh University, both in Pennsylvania. He also earned an M.S. degree in Environmental Science from the University of Alaska. From 1977 until 1982 he conducted research on advanced materials for energy systems at the Idaho National Engineering Laboratory of the U.S. Department of Energy, specializing in surface and thin-film chemistry problems.

From 1982 until 1990, Casper was an Engineering Fellow on the technical staff of the Honeywell Solid State

Electronics Center in Minneapolis, where he developed a materials and device characterization laboratory and worked on development of advanced integrated circuit devices.

In 1990, Casper moved to the University of Wisconsin—Madison, where he is Assistant Dean of Engineering for Industrial R&D and Associate Director of the University–Industry Research program.



ARTHUR B. ELLIS is Meloche–Bascom Professor of Chemistry at the University of Wisconsin—Madison. From 1990 to 1993, he chaired the UW—Madison's interdisciplinary graduate Materials Science Program. Ellis received his Ph.D. degree from Massachusetts Institute of Technology in inorganic chemistry and his B.S. degree in chemistry from Caltech. His research interests are in materials chemistry, specifically in the electro-optical properties of solids, and he has co-authored more than 100 research papers and holds eight patents. Ellis has been the recipient of Exxon, Sloan, and Guggenheim fellowships. He has helped develop a variety of instructional materials for integrating solids into the chemistry curriculum, including a superconductor levitation kit and an optical transform kit. Since 1990, Ellis has chaired an ad hoc committee that has produced a book to help chemistry teachers integrate materials chemistry into introductory chemistry courses. This volume, published by ACS Books, is entitled *Teaching General Chemistry: A Materials Science Companion.*

DEDICATION

THIS VOLUME IS DEDICATED TO THE MEMORY of Kenneth G. Hancock, an author in this volume and the former Director of the Chemistry Division of the National Science Foundation.

As Director of the Division of Chemistry at the National Science Foundation, Hancock pioneered many new initiatives, especially those that encouraged interdisciplinary and international collaborations. He had an expansive view of chemistry as a science and urged chemists to pursue imaginative research on the discipline's traditional boundaries that would expand chemistry's frontiers. In materials chemistry, he saw a vital and growing area to which chemists could make important contributions. Under his leadership, the Division's support for research in materials chemistry grew to over $20 million in 1993.

Hancock died in Budapest, Hungary, in September 1993 while on official travel. He had served as Division Director since 1990, and since 1987 had provided direction either as Acting Division Director or Deputy Division Director. He guided the development of joint programs with the Division of Chemical and Thermal Systems in Electrochemical Synthesis and in Environmentally Benign Synthesis and Processing. Hancock recognized very early the opportunities for U.S. scientists in Eastern Europe after the demise of the Soviet Union, and the Chemistry Division responded by sponsoring visits by groups of U.S. chemists to Eastern Europe, by granting supplements to promote collaborations, and by bringing an intern from the Soviet Academy of Sciences to the Division. At the time of his death, Hancock was attending a workshop on Environmental Chemistry under joint United States–Hungarian–French sponsorship, a workshop that had been his idea.

Hancock advocated collaboration among government agencies and between government and the private sector. For example, he negotiated pioneering agreements for NSF with the Environmental Protection Agency and the National Institute of Standards and Technology, and helped design a unique pilot program with a private entity, the Electric Power Research Institute. The environmental program he helped fashion included the Council on Chemical Research as a partner.

Hancock received his B.A. from Harvard and his Ph.D. from the University of Wisconsin in 1968. After a National Institutes of Health Postdoctoral Fellowship at Yale, he worked as assistant and associate professor in the chemistry department of the University of California—Davis from 1968 to 1979, where he taught graduate and undergraduate chemistry and did research in organic and organometallic photochemistry. His work opened a new field of study in organoboron photochemistry.

Hancock joined the NSF as a Visiting Scientist in 1977 and held a variety of positions within the Chemistry Division, including Program Director for Chemical Dynamics, for Organic and Macromolecular Chemistry, and for Chemical Instrumentation. He served for two years as Senior Manager of Cooperative Science Programs with Southern Europe in the Division of International Programs, during which time he negotiated, established, and administered a new joint science and technology research agreement with Spain. Several years later, he again worked with International Programs as Interim Office Head, NSF—Europe. To broaden his knowledge of the legislative process Hancock served for one year as a legislative assistant to Senator John C. Danforth, while on leave from NSF as a LEGIS Fellow. He served on numerous NSF-wide committees and task forces, including the Director's Long Range Planning Task Force for Disciplinary Research and Facilities. In 1992, he was awarded the Director's Award for Excellence in Management.

His broad public service included membership on the National Research Council's Committee on Chemical Industry, Chemical and Engineering News' Editorial Advisory Board, the American Chemical Society's Committee on Science, and numerous other posts.

Marge Cavanaugh
National Science Foundation
Washington, DC

PREFACE

MATERIALS CHEMISTRY is receiving increasing recognition worldwide as a key area of chemical research and technology. If we define materials chemistry as chemistry related to the preparation, processing, and analysis of materials[1], it is apparent that "materials chemistry" has always been an integral part of chemistry and that a substantial fraction (approximately one-third by one estimate[2]) of chemists are in fact "materials chemists".

On the other hand, this label is not always applied to the wide range of activities that constitute the component subjects of materials chemistry. Instead, terms such as "polymer chemistry", "solid-state chemistry", and "surface chemistry", are more usually employed by chemists when referring to their background, interest, or research and development (R&D) activity relating to materials. In this context, one might question the need for a relabeling of these various activities under the common heading of materials chemistry. The thesis of this volume, and of a growing number of scientists, engineers, and educators, is that there is indeed a real benefit to be gained by viewing these activities in the broader context of materials chemistry or the "chemistry of materials". In part, this benefit relates to the well-developed concepts of "strength in numbers" and "critical mass". The effectiveness of a group that includes one-third of the entire chemistry profession in promoting changes in policy, the distribution of funding, the education of chemists, etc., can hardly be compared with even that commanded by the largest subgroup of materials chemists.

Beyond this pragmatic line of reasoning, a materials chemistry subdiscipline combines the various components of the subject in a way that makes sense from both operational and educational viewpoints. Many concepts relating to structure, bonding, and properties are common to materials composed of organic molecules, inorganic networks, or polymer chains, and a more integrated perspective could aid both in fundamental understanding and practical applications of new materials.

Although many internal and external obstacles remain to be overcome, considerable evidence supports the idea that the chemistry profession worldwide is gradually accepting the view that there is a distinct chemistry of materials. In the past few years, the American Chemical Society, the Royal Society of Great Britain, and VCH Publishers have established journals in this area that feature titles such as *Chemistry of Materials, Journal of Materials Chemistry,* and *Advanced Materials*. All of these journals appear to be thriving; the number of papers being published, issues per year, and subscribers are increasing. In general, the number of publications in the materials-related areas of chemistry has grown at a significantly higher rate than the total in all areas of chemistry during the past 20 years or so, and this growth suggests a substantial increase in materials chemistry research over this period.[3]

This revolution in thinking about materials chemistry is beginning to have an impact on the education of chemists. In the United States, several universities have instituted courses at the graduate and undergraduate levels in materials chemistry, and a large number of faculty members in chemistry departments all over the country are engaged in research programs in this area, typically involving interdisciplinary efforts with faculty from other departments. These efforts are in addition to the long-standing programs in many universities in the various component areas of materials chemistry, such as polymer, solid-state, and surface chemistry. In some cases these efforts are being stimulated by funding agencies such as the National Science Foundation, which have established special research initiatives and have funded efforts to evaluate and change the way in which chemists view materials science, and materials scientists view chemistry.

The symposium from which this volume derives was sponsored by the Industrial and Engineering Division of the ACS and was designated, by the ACS Joint Board–Council Committee on Science, as one of the first in a series of pedagogical symposia relating to the 22 National Critical Technologies identified by the White House Office of Science and Technology Policy in 1991, based on previous critical technology studies by the Departments of Defense and Commerce. The symposium was also cosponsored by the Federation of Materials Societies and endorsed by the Materials Research Society. In addition to the ACS Committee on Science, it was supported financially by the Chemistry Division of the National Science Foundation and nine industrial organizations (*see* Acknowledgments). Its five sessions were attended by a large and diverse audience, including scientists, engineers, educators, and members of the press.

The symposium's location in the nation's capital, Washington, DC, was viewed as a unique opportunity to address the role of materials chemistry in national science and technology policy in general; consequently, the first session of this symposium was devoted to the discussion of broad issues relevant to the needs, opportunities, and problems confronting materials chemistry R&D today. This plenary session featured representatives from the U.S. Government, the National Academy of Sciences, industry, and academia. The second session was directed at educational issues and covered a range of topics relating to education of—and communication between—chemists, materials scientists, and the general public regarding materials chemistry. The last three sessions featured internationally recognized leaders in materials chemistry R&D from universities, government laboratories, and industries throughout the United States. These individuals were asked to highlight a few of the many specific topics that characterize current materials chemistry R&D and to indicate the problems, prospective solutions, and opportunities for new technology in these key areas.

The impetus for this volume came from the symposium, and many of the presentations from that symposium are represented here as chapters or parts of chapters. To broaden the scope of this volume, other individuals were invited to contribute chapters relating to their own topic of interest. Our chief objective is to provide, for chemists, materials scientists/technologists, and the science and engineering community in general, an overview of this emerging "new" subdiscipline of chemistry.

Acknowledgments

It remains only to thank the many individuals and organizations who have made the ACS symposium and volume possible. The ACS Committee on Science and the NSF Chemistry Division in particular provided both financial and moral support, without which we could not have managed a symposium, and a volume, of this type. This support was supplemented by individual grants from nine companies, representing a wide range of products and services in materials chemistry. The companies and the other organizations who provided financial support to the symposium are Allied Signal, Inc.; Air Products and Chemicals; AKZO America, Inc.; AT&T Bell Laboratories; Corning Inc.; General Electric Corporate Research and Development; Hoechst Celanese Corp.; Milliken Research Corp.; and Schumaker.

Next, the authors of the chapters that make up this volume deserve particular thanks for their excellent contributions. We also gratefully ack-

nowledge the help of the individuals who served as reviewers for the papers in this volume. Finally, we thank the ACS Books staff who so ably managed the many details involved in the preparation and publication of a volume of this size.

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[1] Interrante, L. V. "Materials Chemistry—A New Subdiscipline?" *MRS Bull.,* January 1992.

[2] "National Materials Policy", Proceedings of a Joint Meeting of the National Academy of Sciences and National Academy of Engineering; National Academy of Sciences Press: Washington, DC, 1975, p 125.

[3] Based on a comparison of *Chemical Abstracts* by section and publications type for the years 1970 and 1992.

Critical Technologies and U.S. Competitiveness: The Materials Connection

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MATERIALS SCIENCE IS A CRITICAL TECHNOLOGY for America. In 1987 and again in 1990, the U.S. Department of Commerce included advanced materials such as ceramics, polymers, advanced composites, and superconductors in a short list (*1*) of very important emerging technologies. The world market based on these advanced materials was estimated conservatively at $600 million by the year 2000.

The U.S. Department of Defense (DOD) has its own list (*2*) of critical technologies. Semiconductor materials rank high on this list, followed by composite materials and superconductors. In the private sector, the Council on Competitiveness released a report called *Gaining New Ground* (*3*), which listed technological priorities for America's future. Again, materials science and its associated process technologies were among their five major headings. Furthermore, a report (*4*) of the National Critical Technologies Panel highlighted an array of materials synthesis and processing technologies and singled out three advanced classes of materials: ceramics, composites, and high-performance metals. Japan (*5*) and Europe (*6*) have generated similar lists. The general consensus seems to be that materials science and its associated technologies constitute a growth industry.

Except for a few minor differences, these lists are really all the same. The relatively recent proliferation of these critical technologies reflects a growing realization that they play a critical role in our strategic and economic well-being. Technology is increasingly recognized as a resource that we have to learn to manage.

A Critical Technology

The general agreement on which technologies belong on the list suggests similar agreement on the attributes of a critical technology. One such attribute is the support of other technologies. Materials are the building blocks for electronics, aircraft, automobiles, etc. Supporting materials include semiconductors, optical materials, ceramics, polymer composites, and many others. But in some sense, this widespread use can also be a problem. The benefit from investment in materials, although highly leveraged for society, is diluted for any particular investing company. This situation often tends to discourage investment. On the other hand, it is the primary reason for U.S. Government support of an area such as this.

A critical technology also tends to be vertical, that is, its real application requires a series of advances at all stages of development. For example, high-temperature superconductors constitute an interesting class of materials. To use these materials, process technologies for making wires will need to be developed. The process technologies will have to be followed by manufacturing technology. And certainly the applications themselves will stimulate progress. The use of new classes of materials in a motor, for example, will require new concepts in power generation.

Effective utilization of a critical technology requires a much closer collaboration throughout the whole chain in which the material is used. Critical technologies evolve and develop over a long period, and so they can support a broad industrial base. This relationship creates a certain inertia with respect to revolutionary change, but it certainly indicates that it is very important to stimulate and maintain evolutionary change.

The importance of materials science to U.S. competitiveness can hardly be overstated. Key materials science areas underlie virtually every facet of modern life. Semiconductors underpin our electronics industry. Optical fibers are essential for communications. Superconducting materials will probably affect many areas; ceramics, composites, and thin films are having a big impact now in transportation, construction, manufacturing, and even in sports—tennis rackets are an example.

More than just intuition tells us how important materials are. In 1989 the National Research Council (NRC) prepared a report, *Materials Science and Engineering for the 1990s* (*7*) that examined in detail the impact of materials science on our national competitiveness. The NRC study surveyed eight major industries that together employed 7 million people in 1987 and had sales of more than $1.4 trillion. Additional millions of jobs in ancillary industries depend on the materials industry. Despite the very different needs for particular materials, the NRC survey also showed a remarkable consistency in generic and technological needs. Every industry surveyed expressed a clear need to produce new and traditional materials more economically and with a higher reproducibility and quality than is currently possible.

In particular, the industry survey revealed a serious weakness in U.S. research efforts involving the synthesis and processing of materials. Moreover, industry has the major responsibility for maintaining the competitiveness of its products and product operations. Collaboration with research efforts in universities and U.S. Government laboratories tends to enhance the effectiveness of those research and development (R&D) programs for the involved company.

These efforts will result in renewed emphasis on the effective long-range R&D capabilities of the industry. The materials science industry must take the lead in developing a strong competitive position for this country. However, the U.S. Government also has a clear role in supporting that effort.

Government's Role

Beyond the knowledge, technology management, and manufacturing skills, competitive commercial technologies depend heavily on a mix of complex issues and economic trade and regulatory policies. The Government can do many things to affect our global competitiveness in these areas. Examples of such activities are education, procurement, antitrust regulations, intellectual property rights, product liability, tariff barriers, nontariff barriers such as international standards, regulatory uncertainty, and the general financial climate.

The Department of Commerce has active programs in all of these policy areas. Among other areas, the Federal Government is playing an important role in the funding of research and the transfer of federal technology.

As an example, consider a test section of a prototype crush tube for the frame of a Ford Escort. The composite material consists of glass fibers in a thermoset resin. Complete frame members made of this component weigh less than one-third as much as the steel that would be used in the original component. The lighter weight of the composite material produces a corresponding savings in fuel. The Automotive Components Consortium (a joint venture of Ford, General Motors, and Chrysler) is working in a cooperative program with the National Institute of Standards and Technology (NIST, the Department of Commerce's R&D organization) to develop an improved process technology, structural reaction injection molding, to produce such parts. This part is not a particularly high-tech example of the materials revolution. It contains no carbon or ceramic fibers and no exotic polymer blends. But it is a practical technology resulting in a real product.

The Federal Government has made very significant progress in developing creative and cooperative relationships among the different departments and agencies. Federal agencies have realigned and enhanced their R&D programs. They have coordinated their activities with other agencies and share common resources. Nowhere has this been more successful than in the area of materials science. The forum for much of this coordination during the Bush administration was the Federal Coordinating Council for Science, Engineering, and Technology (FCCSET).

The FCCSET Committee on Industry and Technology, which I chaired, undertook to inventory what the Federal Government was doing in a variety of critical technology areas. Materials science is obviously one of these areas. In fiscal year 1991–1992 the Federal Government funded $1.66 billion in materials R&D. That figure has remained fairly constant since approximately 1976. Materials now account for about 2.3% of the federal R&D expenditures.

Our inventory also showed that funding levels for materials vary widely across differing materials classes. R&D on advanced metals received 13% (the largest fraction in 1992), composites were 11%, electronic materials were 10%, and biomaterials were also 10%. The FCCSET process proved enormously successful in focusing the federal program on materials research.

Presidential Initiative

The NRC report expressed concern about U.S. weakness in synthesis and processing. These areas were given high priority as the FCCSET inventory became the foundation for a presidential initiative that was referred to as the Advanced Materials and Processing Program (AMPP). This program was prepared by the FCCSET Committee and published in a January 1993 report (*8*). It represents the first effort to coordinate the approach to materials research across all the federal agencies. The goal of AMPP is to improve the manufacture and performance of materials and thus to enhance the nation's quality of life, security, industrial productivity, and economic growth. AMPP adopted four strategic objectives:

- to establish a leadership position in advanced materials and processing
- to bridge the gap between science and applications in materials
- to support the mission agencies
- to encourage university and private R&D activities, particularly in the area of applications

The AMPP identified four areas that required critical efforts. Not surprisingly, synthesis and processing was the first area. AMPP also decided to capitalize on U.S. leadership in computational techniques by emphasizing theory, modeling, and simulation (the second area). The third area is materials characterization, and the fourth is education.

A unified program that was submitted to the U.S. Congress requested $1.8 billion in the 1993 budget. That amount represented a 10% increase over 1992. The final Congressional appropriations only added up to a 2% increase. This budget reflected both direct research and the construction and operation of user facilities such as the cold neutron facility at NIST. The increases would have gone to specific AMPP program enhancements chosen by an interagency committee for their technical content and the extent to which they support the chosen goals. The enhancements generally follow the critical program areas of synthesis and processing, simulation, characterization, and education. The program had an enormous impact on coordination of efforts within the Federal Government. Fifty-five memoranda of understanding or agreements had been established between different agencies in the materials area at the time the budget was submitted. This number represented 55 collaborations that did not exist a few years previously. Obviously, if part of the goal of such a program is to increase industrial productivity and economic growth, there must be strong private sector involvement. There was a great deal of involvement at the technical level; 105 cooperative research and development agreements (CRADAs) between the private sector and federal agencies existed in the materials area.

Many academic and industrial scientists serve as advisors to various federal agency programs in materials science. For example, the evaluation board for the Materials Science and Engineering Laboratory (MSEL) at NIST contains representatives from Bell Laboratories, DuPont, General Electric, Allied Signal, and numerous universities. The private sector would like to improve the interactions at the strategic policy level, but some bureaucratic handicaps must be overcome.

Under the Clinton administration, the FCCSET Committee has become the National Science and Technology Committee (NSTC). The AMPP no longer exists as a stand-alone initiative, but its components have been folded into specific programs such as the Partnership for a New Generation of Vehicles (the "clean car" initiative).

Advanced Technology Program

Considering the crush tube example, you might ask why we should not improve the material itself, as well as the process technology. Thermoset plastics may not be the best practical choice for automobiles, because they are difficult to recycle. That, in fact, was the subject of a new research project announced in the spring of 1992 by the Department of Commerce's Advanced Technology Program (ATP). ATP is co-funding research at Ford Motors and General Electric to develop the basic technologies and materials data needed to use "cyclictherm" plastic composts in automobiles. Like most ATP projects, this one is somewhat risky. It requires advanced work in chemistry and materials, but the rewards can be great. The ATP is one of the Department of Commerce's key efforts in support of industrial R&D. Materials research has fared quite well in this program; in the first four rounds, materials received 13% of the funding.

Because these programs were not targeted at any particular industry or technology, advanced materials research was a natural for ATP. Like materials science, the characteristics of the critical technologies closely match the philosophy of ATP. The goal is to assist U.S. industry to carry out R&D technologies that are enabling and also have high values.

This Government program is unique on several accounts. Input originates from industry itself, from business leaders, venture capitalists, R&D directors, and also economists. The ATP program is also very highly leveraged, requiring cost sharing from industry or matching funds for grants that go to consortia. After four general competitions, ATP has committed $247 million to 89 projects; industry has committed an additional $258 million. The ATP awards completely match the lists of critical technologies. That type of comparison is the best way to determine what is a critical technology.

Under the Clinton administration, a portion of ATP funding will be "focused" in certain areas. One of these, manufacturing composite structures, relates directly to materials. Does ATP work? It is too early after just a few years to make a valid judgement about the success or failure of a program that, by its nature, is supposed to support long-term R&D. Still, some early indications are very encouraging. The program has spurred both increased investment and better leveraged investment in important technologies. Small companies with ATP awards report that they have an improved ability to raise private capital and to develop strategic partnerships with larger firms. ATP has also been quite successful in encouraging the formation of research collaborations and strategic alliances. During the first four competitions, joint ventures accounted for 26% of the awards with 134 participants, including 42 small businesses. Small businesses themselves accounted for 48% of the funding (43 companies).

Government and Industrial Cooperation

The challenge we still face is how to fund what I would call "megatechnologies". Just as we have megascience projects, we now have megatechnology projects. In some sense they are a subset of a critical technology, but they require something on the order of $100 million to fund. Flat panel display technology could be an example. The Clinton administration is using flat panel displays as a test for an entirely new way to encourage industry to engage in the manufacture of such high-risk technologies. The

Government, through ARPA, will provide R&D funds to match what a company invests in the manufacturing. This is a new concept of "matching".

I mentioned that the automotive composites consortium is working with NIST, under one of the CRADAs. CRADA, once an obscure acronym, has become very popular in Washington, DC. If federal research initiatives are to be fully successful, the results of this research must be transferred to industry, where they can form the basis for new and enhanced products and processes. Traditional mechanisms exist (such as contracts, patent licensing, and the like), but I don't think any of them are quite as powerful as the CRADA.

NIST has perhaps more experience than many Government agencies in working with private industry. Close to 90 years of collaboration in research programs with industries has taught NIST technologists one lesson in particular: There is no substitute for hands-on cooperative R&D programs if your goal is to transfer technology.

More and more companies are discovering the advantages of access to federal laboratories through CRADAs, including a wide range of technical facilities and world-class experts. CRADAs provide a way to leverage a company's resources with the research power of more than 700 federal laboratories. In 1988 there were probably only about 100 of these cooperative research and development agreements; today there are several thousand.

The increasing use of the CRADA as a tool for technology transfer was one of the key motivations behind the National Technology Initiative (NTI) at the end of the Bush administration. These were regional meetings held across the country to identify specific areas for collaboration between business, Government, and the university. These NTIs prompted dramatically increased contact and cooperation between private industry and Government laboratories. The NTI has also promoted increased collaboration between Government agencies, to make more effective use of our resources.

Much can be done by both Government and industry to enhance America's competitive position and to advance materials research, even in this time of fiscal restraint. But we should certainly make sure that we are using all of the existing resources to the best advantage, eliminating duplication of effort, and avoiding lost or wasted opportunities. Through mechanisms such as CRADAs and resource consortia, Government and industry can join forces to maximize our return on investment.

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Materials Science and Engineering for the 1990s: A National Academies Study

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THE MATERIALS SCIENCE AND ENGINEERING STUDY of the National Research Council was initiated by a letter from U.S. Representative Don Fuqua (who was at the time Chairman of the House Science and Technology Committee) to the presidents of two academies of science and engineering. Fuqua asked about the definition of materials science and about its priorities. After deliberations and several meetings, the academies approached Merton Flemings and me in 1988 to chair a study that would involve scientists from the universities, industry, and Government laboratories.

Description of the Study

The study, concluded in December 1988, was formally unveiled in the fall of 1989 with a report entitled *Materials Science and Engineering for the 1990s* (*1*). Funding was provided by a number of agencies. About 400 people contributed to this study, and about 100 of these were formally appointed by the two academies.

We soon decided that we would not follow the pattern of earlier studies, such as the physics and chemistry surveys. Instead we would focus on issues associated with materials science and engineering and its relationship to industry. We organized ourselves into five issues-related panels. The goal of the first panel was basically to examine opportunities and needs. They sought the opinions of our colleagues at universities, Government laboratories, and industrial laboratories about the intellectually exciting areas in this field. Our colleagues in industry, particularly the senior technical people, were asked what they thought was needed and what would give them a competitive advantage in their business. We asked the second panel to explore ways by which all of this knowledge could be utilized. The third panel considered what our colleagues abroad were doing, particularly our trading partners such as Germany and Japan.

The fourth panel examined research resources within the United States, and the fifth looked at education.

The study results were integrated into the report that was published. The project surveyed eight industries that collectively employ more than 7 million people and account for more than $1.4 trillion in business annually. The influence of this survey permeates our study.

We also found that in the field of materials science education, both education and work force needed considerable reorientation. For historical reasons (listed in the study) synthesis processing had been neglected at university and Government laboratories. We also looked at the debate about the role of a principal investigator versus large facilities, such as the synchrotron radiation laboratories. We concluded that materials science needs all of these different modes of research, and no particular approach is more decisively effective than another.

At the time of the study we tried to get the best possible information about the financial support available from the Federal Government. Over the past decade, funding had declined in terms of constant dollars. In contrast, materials science and engineering, information science, and biotechnology had been targeted as the three main growth areas by most of our trading partners. Government had played a proactive role in materials science and engineering in these countries. Rather than covering a broad range, as we tend to do here, these countries focused on specific areas that complemented their economies. We recommended a substantial increase of federal funding in selected areas, with a $160 million increase targeted for 1993 as the first step in a multiyear program.

Vitality of Materials Science

Materials science and engineering is a vital field of endeavor for industry and defense and also with regard to its sheer intellectual content. This field is no longer a disparate collection of disciplines. Its unity and coherence can be seen in a tetrahedron; this image captures the essence of the field. The four aspects to any materials-related activity are as follows:

1. performance—provides a yardstick for measuring whether a material is good or bad, and what is needed to make it better. This yardstick can be technical, financial, or both.
2. properties—in physics they would be called phenomena.
3. structure—where the atoms are and what kinds of atoms are present.
4. the making (synthesis and processing) of the material

All of these factors are interconnected parts of the tetrahedron.

We found no exception to this description in any materials class or materials problem. The perspective of the tetrahedron shows that the

United States is relatively weak in the area of synthesis and processing. Other themes common to all four corners are instrumentation and computers. Instruments are essential for making advances in science. The United States had a unique advantage in being at the forefront in computer use. We felt that this advantage should be exploited in materials science.

What measures do we have for our assertion that this field is vital? We tried to generate a diverse data set from varied areas.

The first measure concerns the structural strength of materials. The prevailing strength-to-density ratio has increased over time and has been accelerating throughout the past two decades. The quality of products used in permanent magnets has improved a great deal over the past decade. This measure of energy efficiency is important in designing motors or generators. Even in a more prosaic area, such as cutting tool materials, superior materials are making it possible to cut faster. In more complex areas such as aircraft engines, there are continuous advances in operating temperatures, which determine thermodynamic efficiency.

Materials science has often led to major changes in the way we live and the way we carry out our day-to-day transactions. A recent example is the impact of glass fibers for optical communication. The most dramatic improvement occurred in the mid-to-late 1970s. During this period transmission through glass fibers increased by several orders of magnitude. Now, 96–99% transmission is possible through a thick glass windowpane. These glass fibers, when they reach our homes, will change the way we live and entertain ourselves. The products of a number of industries are nothing more than a very sophisticated assemblage of materials. The car and aircraft industries are notable examples. Advances in materials such as composites could play important roles in replacing materials such as structural steel. This development, of course, would make the car more efficient and conserve energy.

Materials are central not only in the transportation industry but even in electronics. The rate of progress in hardware is determined by materials and their processing. Nothing in the laws of nature that says that we cannot build a device that is about 700 atom diameters wide. In fact, we have built devices smaller than these and they all operate well. But this achievement was a laboratory demonstration. To manufacture these devices, we need a steady advance across a broad front of materials processing, new tools and techniques, and materials properties.

These observations apply not just to traditional industries, but even to those that are still evolving and in which the United States has a commanding lead. For example, the biomaterials industry is in its infancy compared to the transportation and electronics industries. I expect it to become a major industry in the future.

This is all well and true for the past and present, but are exciting developments happening in materials science now that could change the future? The scanning tunneling microscope (STM), a great tool for making very precise measurements of surfaces, is an example. It is used extensively for surface topography. Recently scientists have been able to pick atoms up, deposit them where they want to, and write images such as the 35-atom image of IBM. Why is this interesting? It demonstrates not only that we can deliberately change a surface at the atomic level, but also that we are reaching a level of complexity that allows use of the STM or the atomic force microscope (AFM) to store information. Researchers at the Almaden laboratory are enthusiastic about this possibility and have demonstrated high-density storage.

The STM is a demonstration of spatial control and resolution. Comparable advances in temporal resolution have been accomplished by using, for example, the pulse compression technique. As a pulse of light propagates through an optical fiber, it responds (if the pulse intensity is large enough) in a nonlinear way. The output pulse is chirped, similar to the chirping of a bird. The red component of the pulse appears first and the high-frequency blue end later. This pulse is then passed through a grating, which forces the red component to traverse a longer path. Given that the speed of light is constant, the frequency components pile on top of each other, resulting in pulse compression.

This technique will allow compression of a 100-femtosecond pulse down to 12 femtoseconds or even to 8 femtoseconds. (A femtosecond is a millionth of a billionth of a second or 1×10^{-15} s.) Pulse compression can be used to study chemical reactions, particularly intermediate states, at very high speeds. Alternatively, these optical pulses can be converted to electrical pulses to study electrical phenomena. This aspect, of course, is of great interest to people in the electronics industry because of their concern with the operation of high-speed electronic devices. It also is of great interest to people who are trying to understand the motion of biological objects such as bacteria.

In addition to these two examples of very short temporal pulses and very short spatial resolution techniques, other notable advances have been made. For example, many new materials have been discovered over the past decade, for example, the quasi-crystals with their unique and totally unexpected fivefold symmetry, the fullerenes, and the new high-temperature superconductors. Progress in the use of high-temperature superconductors for wires is entirely dependent on how well we can understand grain boundaries and the role of other defects that control the critical current density. We still do not understand the pairing mechanism responsible for this class of superconductors, and we have no idea if today's 125 K value is the limit or simply a limit until we exceed it. Most recently, interest in the fullerenes has been growing, now that their structure has been unraveled, and their properties are demonstrating a variety of interesting phenomena. These few examples hint at the sense of vitality and of excitement that we tried to capture in the study.

After the Study

A very important aspect of any major study is the follow-up activity. It affects three communities, each of which speak a "different language". The message is the same, although the words and the emphasis differ for each group. The three communities are as follows:

1. The technical community; it is important to communicate to them the scholarly aspect of your findings because their support and agreement are important.
2. The policy makers; in the United States, this means the agency heads and Congress.
3. The public—particularly the business community.

The second group may not respond unless the third group takes an interest.

In dealing with the technical community, we spoke at national meetings and also organized regional meetings. We divided the United States into four regions and asked the local industry, university, and Government groups to tell us what made sense for materials science in that particular region. The report from these regional meetings, published by the Materials Research Society, was used by the Federal Coordinating Council for Science, Engineering, and Technology (FCCSET) as part of their analytical process.

We also saw a number of policy makers, starting with Allan Bromley. Allan was convinced of the importance of this field before we finished our talk, and he subsequently provided the leadership that led to Bob White overseeing the FCCSET initiative. We also went to see Eric Bloch. He responded positively, and NSF took the initiative and proposed an increase in their 1992 budget. We also met with Admiral James D. Watkins, the Secretary of the U.S. Department of Energy (DOE) and with a host of congressmen and senators.

For the public, we made a video documentary of materials science education in which the National Academy of Sciences collaborated with WQED. This program was broadcast on public television as part of the Infinite Voyage series. The video on materials science education, called "Miracles by Design", is useful for showing to students who are not sure what this field is all about. It covers the spectrum: physics, chemistry, metals, ceramics, and polymers. An article in *Business Week* called "The New Alchemy" covered this field in some detail for the business community.

All of this activity culminated with the presidential initiative that Robert White described in the previous section. The follow-up activities are not over, and much still remains to be done. In particular, money has to be appropriated by the legislative bodies and made available to the funding agencies. In these uncertain times we cannot take for granted that a presidential initiative will automatically result in new funding. We need our community to continue to convince our congressmen of the national importance of this field.

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The National Science Foundation's Program in Materials Science: New Frontiers, New Initiatives, New Prospects

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IN WASHINGTON, REPORTS ARE PLENTIFUL. Most of them are on important topics and reflect careful analysis by well-informed, thoughtful people. But there are too many: with few exceptions, these reports conclude with a request for new programs and more money from agencies, departments, and legislators that hear the same litany over and over again; only the supplicants change. Rarely, a report commands major attention and holds it over some period of time. Praveen Chaudhari and Merton Flemings produced a report that has received the attention it deserves. *Materials Science and Engineering for the 1990s* (*1*), published by the National Research Council in 1989, has been the foundation for planning on a coordinated and sustained level not often seen in Washington, outside of major national efforts such as the space program or the superconducting supercollider.

The importance of materials science in tomorrow's world cannot be overstated. Technologies from microelectronics and nanostructures to spacecraft and biomedical prostheses depend absolutely on amazing materials created through the ingenuity of scientists and engineers. Kevlar composites, high-temperature superconductors, and buckeyball-based structures did not exist a short time ago. But we are already on the edge of an even more astonishing materials fixture: Just in the past few years, we have developed techniques to assemble materials molecule by molecule and atom by atom; we literally have the ability to move single atoms and place them where needed. Imagine the possibilities that power brings to the design, synthesis, and processing of newer, "smarter" materials for applications we have not yet considered. Truly, the opportunities are not only mind-boggling, they are also only mind-limited.

The socioeconomic impact of materials in the United States is no less staggering. The eight industries of aerospace, automobiles, biomaterials,

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[†] Deceased

chemicals, electronics, energy, metals, and telecommunications—all critically dependent on materials—together generate $1.4 trillion in sales (1987 figures) and employ 7 million people. No wonder that *Materials Science and Engineering for the 1990s* attracted such attention!

Robert White, chair of the Federal Coordinating Council for Science, Engineering, and Technology (FCCSET) Committee on Industry and Technology, has already discussed the materials research and development activities of 10 federal departments and agencies that were coordinated into a coherent, cross-agency 1993 Presidential Initiative known as the Advanced Materials and Processing Program (AMPP). The AMPP Initiative as proposed for fiscal year 1993 was roughly a $2 billion enterprise, including both the existing base and the proposed 1993 increases. This section will focus on implementation of the AMPP at the National Science Foundation (NSF).

Early Precursors to AMPP at NSF

Although the NSF has had a Division of Materials Research (DMR) and has supported a network of materials research laboratories (MRLs) since 1972, additional recognition of the emerging opportunities on the molecular scale in materials science prompted a 1984 workshop at the NSF. Sponsored by NSF's Divisions of Chemistry and Materials Research, the conference explored the scientific opportunities and programmatic needs in the area of materials chemistry (MC), roughly defined as the region of overlap between the macroscopic frontier of chemistry (the molecular science) and the microscopic frontier of real materials (a macroscopic science). Out of that workshop report grew a small but catalytic program to support collaborative projects involving both chemists and materials scientists or engineers, trying to bridge the gap between the colligative and molecular worlds. The role of chemists in materials science is now as it was then: To synthesize next-generation materials atom by atom, the chemist must understand all dimensions of molecular interactions and their impact on macroscopic properties in order to know which atoms to put where. Moreover, synthesis is the heart and soul of chemistry. Physicists, mathematicians, and engineers analyze, characterize, and process materials; chemists synthesize them.

Materials chemistry proposals were jointly reviewed and split-funded, and in 1987 and 1988, 33 cooperative research projects were initiated. In 1989, the partnership was expanded to include the Division of Chemical and Thermal Systems (NSF's home for chemical engineering), and the program was renamed Materials Chemistry and Chemical Processing (MCCP). In 1989, 1990, and 1991, each of the three participating NSF divisions invested about three-quarters of a million dollars in additional projects, most of which were later mainstreamed into existing program rubrics, and a high fraction of which have been successfully renewed.

The total 5-year investment in the materials chemistry programs (MC and MCCP) was more than $18 million. That number might be considered modest, but MC–MCCP accomplished two things: (1) it initiated about 60 collaborative research projects in the chemistry research community, where individualism was the overwhelming norm; and (2) it established within NSF a paradigm for interdivisional cooperation in the review and funding of interdisciplinary research.

NSF's 1992 Materials Synthesis and Processing Initiative

During 1990–1991, while the FCCSET Committee on Industry and Technology was carrying out the extensive analysis, coordination, and planning necessary to implement a Presidential Initiative, the NSF was carrying out its own component of this analysis. An inventory of support for materials science and engineering at NSF (1991 actual expenditures) includes the following:

- $216 million for materials research and development (R&D) research project support, principally in DMR, the Engineering Directorate (ENG), and the Chemistry Division (CHE)
- $31 million (additional) for national user facilities (nanofabrication, synchrotrons, magnet labs, and supercomputers)
- materials research laboratories (nine) and groups ($47 million)
- science and technology centers (7 out of 25 have materials as their focus)
- engineering research centers (6 out of 18 have materials as their focus)
- industry–university cooperative research centers (15 out of 26 have materials as their focus)

Recognizing the criticality of materials science and engineering, the NSF moved to get a head start on the materials programs being planned through FCCSET by establishing its own Materials Synthesis and Processing (MS&P) Initiative for fiscal year 1992. An increment of $25 million was requested in the 1992 budget as the first phase of a 5-year effort to strengthen research in materials synthesis and processing. The 1992 MS&P Initiative had two aims: (1) molecular-level approaches to the design and synthesis of new materials based on fundamental principles and a developing base of molecular structure–property–performance relationships; and (2) new and improved processing methods, including reactor design, kinetics, and applications to manufacturing, looking to produce materials with improvements in efficiency, properties, and quality.

The MS&P Initiative was launched as planned in 1992, although the 1992 congressional appropriation was less than requested. Features of the program (*2*) included the following:

- They focused on synthesis and processing (including relevant theory and characterization).
- They included five eligible materials classes, two favored (electronic–photonic and biomolecular) and three others (structural, magnetic, and superconducting materials).
- They included single- and multidisciplinary projects.
- They accepted proposals from single investigators and groups.
- Nine NSF divisions cooperated in review and funding.

Biomolecular materials were defined as those substances, natural or synthetic, with novel materials properties that use or mimic biological phenomena. A sample menu of ideas was generated to provide some sense of the envisioned scope of the MS&P program:

Electronic and Photonic Materials

- new materials with unique properties (semiconductors, superconductors, insulators, and composites)
- methods for deposition and growth (films, layered structures, bulk crystals, and fibers)
- low-temperature synthesis and preparation
- combining materials growth and processing techniques
- laser, electron, ion, and plasma-assisted processing
- real-time, in situ diagnostics

Biomolecular Materials

- genetic modification of natural synthetic pathways
- biomolecular self-organization and phase behavior
- novel catalyst, sensor, and transducer materials
- materials aspects of in vivo biopolymer processing
- synthetic structures mimicking natural composites
- biodegradable or biorecyclable materials

Structural Materials

- new metallic alloys, polymers, ceramics, and composites
- origin and evolution of phases, defects, and microstructures
- solid-state behavior controlling multiphase materials properties (phase transformations and grain boundaries)
- processing methods (particle consolidation, sol–gel conversions, rapid solidification, and powder synthesis)

- direct conversion of precursors to finished forms (reaction bonding and injection molding, microwave sintering, and net-shape manufacturing)

Magnetic Materials

- design and synthesis of new magnetic materials
- artificially structured multilayer magnetic materials
- enhanced properties in hard and soft magnets, thin films, and magneto-optics
- surface and two-dimensional magnetic behavior
- new processing methods for magnetic materials

Superconducting Materials

- superconduction in bulk materials, thin films, and reduced-geometry structures
- low-temperature, in situ processing and fabrication methods
- improved structure–property relationships and theory
- single-crystal growth of superconducting materials
- properties of surfaces and interfaces: connections, contacts, and passivation
- crystal structure, microstructure, and morphology

All multi-investigator proposals were due by November 1, 1992, because it was anticipated that the large majority of them would have to be co-reviewed and co-funded by two or more disciplinary NSF divisions. Single-investigator proposals were accommodated within regular programmatic boundaries and guidelines. A matrix-managed review procedure was established. Proposals were to be addressed to the NSF division appropriate to the principal technical thrust of the proposal (its "center of gravity"), where a divisional coordinator carried out preliminary screening for suitability, negotiated with other divisions where required for joint review, and then managed the review itself. To a large extent, each NSF division used its usual review procedures, although several divisions reviewed all MS&P proposals with specially assembled review panels instead of using ad hoc mail review.

Approximately 700 proposals were received in response to the MS&P announcement in fiscal year 1992; some divisions had no deadlines for individual investigator proposals, so this inventory was not complete until the end of the 1992 fiscal year. The breakdown between collaborative proposals from groups and those from single investigators was approximately 2:1. About 50% of proposals had a center of gravity in the DMR (principally solid-state chemistry, polymers, and electronic materials) and were managed by DMR. Another 33% were managed by five engineering divisions, 12% by chemistry, and 5% by two biosciences divisions. As expected, most of the proposals fell into the categories of electronic and optical or photonic materials; fewer proposals than expected were received with a biomolecular materials focus.

Data for proposals and awards in which the Division of Chemistry was involved are as follows:

- Reviewed 122 out of 700 proposals; managed 82; 52 were single investigators; 70 were groups; 92 required interdisciplinary review; 30 were reviewed within CHE.
- Focus was on electronics (48%) and photonics (25%); biomaterials was 10%; magnetic was 8%; structural was 7% of the proposals.
- Funded 26 awards (21%), $3.1 million; 13 were single investigator; 13 were groups; 16 out of 26 were co-funded with four different divisions.

Data for proposals and awards in which the Division of Materials Research was involved are as follows:

- Reviewed 351 out of 700 proposals.
- Funded 57 awards and co-funded 28.
- Total investment was $6.4 million in 85 grants (16% success rate).
- Award distribution was as follows: 40%, electronics; 23%, optical–photonics; 18%, structural; 3%, biomolecular; 9%, magnetic; and 7%, superconducting.

What has been learned from MS&P about multidisciplinary program management? Program management must be kept simpler by taking a "varietal wine" approach to the labeling and review of proposals. It is quite cumbersome to matrix-manage a large number of proposals. In the future, NSF will have to assign proposals to a given program on the basis of the scientific "center of gravity", have that program solicit assistance as needed, but make review and award decisions more locally.

Looking Ahead to the AMPP

The AMPP is a coordinated interagency effort to exploit opportunities in materials research and development to meet significant national goals and to extend U.S. leadership in materials-dependent critical technologies. The goal (*3*) is "to improve the manufacture and performance of materials to enhance the Nation's quality of life, security, industrial productivity, and economic growth". To achieve this goal, a set of strategic objectives was established:

1. maintain U.S. leadership in advanced materials and processing
2. bridge the gap between innovation and application of technologies

3. support agency mission objectives to meet national needs
4. encourage university and private sector R&D related to AMPP

Implementing priorities were also established:

1. support strategic objectives through R&D effort
2. plan federal programs to incorporate needs of strategic, industrial, and social sectors
3. promote applications through university–industry–Government cooperation in generic, competitive technology development
4. support the human resource base to meet future needs
5. maintain healthy infrastructure (e.g., facilities)
6. focus R&D on materials and processes that are most important to achieving AMP strategic objectives

Although the AMPP is an R&D program, its purpose goes well beyond curiosity-driven research. Success is going to be measured not only by new discoveries, but also by successful application of new knowledge and technology. Thus, a significant ambition within AMPP is to strengthen productive interaction between the Government, industry, and academic sectors. All participating federal agencies share the same AMPP goals and objectives consistent with their missions. NSF's mission is the generation and dissemination of fundamental knowledge and the training and development of scientists and engineers.

The AMPP has three conceptual tiers: (1) an inventory of current materials R&D; (2) targeted program enhancements; and (3) conceptual opportunities for technical breakthroughs. The inventories are by agency, by materials class (the terms are familiar to chemists), and by program component. AMPP has four program components: (1) synthesis and processing; (2) theory, modeling, and simulation; (3) materials characterization; and (4) education and human resources. National user facilities are included in the inventories, but they are not a program component in the sense of being subject to the same priority-setting practices.

The priority-assigned program components increase roughly as their applicability to the national needs identified in the AMPP program goal. Within synthesis and processing, process integration takes a higher priority than basic research; similarly, application-specific theory, modeling, or simulation takes precedence over more fundamental research. Bigger budgetary increments were proposed for synthesis and processing than for materials characterization. These priorities are for the overall interagency program. In synthesis and processing, for example, process integration may be emphasized at the National Institute of Standards and Technology (NIST), and basic research would be emphasized at NSF. Or, even within NSF, process integration and applied research may be centered in ENG, and basic synthesis is centered in CHE or DMR.

The prioritization of research objectives and classes is is not necessarily what a "curiosity-driven" researcher likes to hear. However, these are Government-wide priorities. They apply to all participants in the AMPP, but not all agencies have exactly comparable missions. AMPP research carried out with NSF support will probably have a more fundamental flavor, on average, than R&D sponsored by a mission agency. Objectives for 1993 within the NSF component are

- synthesis of advanced materials
- fundamental physics and chemistry of materials
- links between synthesis and processing and materials structure, properties, and performance
- development of novel processing and manufacturing methods
- creation of linkages with industry for knowledge and technology transfer
- emphasis on academic research for education and training

The AMPP represents a major response to the needs and opportunities spelled out in the materials science and engineering (MS&E) report (*1*). Major opportunities exist for scientific breakthroughs in materials science, and many of them, perhaps most, will need chemists for the key finding or concept. Everyone who thinks about chemistry and materials can generate her or his own list. Some ideas and possibilities that seem particularly challenging and ripe for plucking by chemists are in the areas of polymers, biomolecular materials, and electronics–photonics.

New "natural" polymers based on synthesis from renewable resources, improved recyclability based on retrosynthesis to reusable precursors, and molecular "suicide switches" to initiate biodegradation "on demand" are the exciting areas in polymer science. In the area of biomolecular materials, new materials for implants with improved durability and biocompatibility, light-harvesting materials based on biomimicry of photosynthetic systems, and biosensors for analysis and artificial enzymes for bioremediation will present the breakthrough opportunities. Finally, in the field of electronics and photonics, the new challenges are molecular switches, transistors, and other electronic components; molecular photoaddressable memory devices; and ferroelectrics and ferromagnets based on nonmetals.

Although the AMPP represents a set of real opportunities—both intellectual and financial—for chemists, two important constraints must be recognized. The first constraint is also financial: The federal budget will not be everything the scientific community might hope for. Congressional spending caps and competition among many different funding demands will restrict budget growth. In some situations, agency or program budgets may not exceed those of 1992. At the NSF, at least, the AMPP will move ahead in 1993 at some level, because chemists and engineers are seizing on the fundamental intellectual challenges and basic questions posed by materials problems, whether or not funds are "set aside". In all three divisions that are the principal supporters of the chemistry aspects of materials, materials chemistry and chemical engineering have already been identified as major intellectual frontiers in long-range planning exercises. Hence, the AMPP represents an intellectual thrust as well as a fiscal one.

The other constraint is that AMPP is a goal-oriented research program. Even at the NSF, it is not quite "business as usual". Policy issues at the national level are pushing the NSF to take a broader view of its mission in education and research, relating those traditional strengths to national needs, especially in the area of economic competitiveness. NSF will increasingly look for opportunities to contribute to the nation's priorities through its unique programs. NSF, for example, is particularly well-suited to support fundamental research at academic institutions because that activity couples the research and education missions; that is, NSF is contributing to the nation's human resource infrastructure through research support.

However, NSF is also moving to contribute to more effective partnership in research between Government, industry, and academia. This partnership is important to speed knowledge transfer from the basic research laboratory to application and commercial development, and maps well onto the strategic priorities of the AMPP. For example, some quantitative measures of performance have been proposed to exist in monitoring the effectiveness of NSF programs and activities, such as the number of interdisciplinary research projects, the number of industry–university collaborations, the number of centers and groups, and the number of Memoranda of Understanding or Cooperative Research Agreements with other Government agencies.

The number of interdisciplinary projects supported is a useful indicator because it is in keeping with the AMPP goal to bridge the gap between different disciplines. An increase in the number of industry–university collaborations might speed knowledge transfer between those research sectors. The very existence and purpose of a fair number of centers hinge on industry–university partnerships. Extending the partnership concept from industry–university to include Government research laboratories is important to get maximum return on investment from these national treasures of scientific talent; that step, too, is already underway. Such criteria are not substitutes for the old standbys of important results and education of tomorrow's students, but they may be viewed as value-added measures for some situations.

Within the Division of Chemistry, several initiatives to improve intersectoral cooperation have already been established. New in 1992 were (1) a cooperative program with the Electric Power Research Institute on electrochemical synthesis: joint review and joint funding; and (2) a cooperative program with the Council for Chemical Research (CCR) on environmentally benign chemical synthesis and processing. In this CCR–NSF activity, university-based research projects are required to have industrial intellectual partnership in order to speed knowledge transfer and to ensure applicability of the research to real-world problems. Other new and experimental ventures are likely to follow. Many of today's important fields of chemistry grew out of basic research carried out in the years after World War II to answer important practical questions. Those applications of chemistry to the real world made chemistry the central science that it is today. The AMPP will be an important force for renewing existing links between basic research and application and for building the new ones for chemistry's tomorrow.

Acknowledgments

This chapter represents only the views of the author and is not intended to represent official views or policy of the NSF. Data cited are drawn from NSF sources and publications.

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Development and Commercialization of Advanced-Performance Materials

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Bringing a new, advanced-performance material into the marketplace as a profitable article of commerce presents many problems. However, I'm reminded of a cartoon I have saved over the years that has two scientists in white lab coats looking at their test tubes, and one of them says, "Remember, our job is to push science to the state of the art and make a buck in the process." So, my remarks will be directed to the problems associated with "making a buck" out of all this forefront research in materials science.

I define advanced-performance materials, development, and commercialization for the purposes of this chapter as follows:

- *Advanced performance materials* are materials (metals, ceramics, polymers, etc.) whose functional and structural properties impart improved performance to specific products, that is, an enabling technology.
- *Development* is the "proof of principle" of material design and product applications.
- *Commercialization* is scale-up, process development, and marketing either as a material or as an integral part of a product.

Thus, advanced-performance materials are not necessarily a product in their own right, but rather an enabling technology that allows the design of new products with new utility or the improvement in performance of an existing product. As we progress from the research needed to discover a new material, to the development of a prototype product, to the commercialization of the product, the associated cost goes up exponentially with each step. The research is relatively inexpensive, development will cost on average 10 times the research costs, and a commercial launch can easily cost 10 times the development expenses. So, the issue is that a $200,000 piece of research may require a $2 million development program culminating in $20 million for a commercialization launch. Thus, if we are to capitalize on our research activities, we need to understand the system totality for commercialization. So, although we talk about the research base, unless we have an economic model for the development and commercialization phases, the competitiveness issues are moot.

To understand the system, let's look at the generic characteristics of advanced-performance materials and their utility. These characteristics can be summarized as follows:

1. Specific properties such as heat resistance, strength, and inertness are "designed in".
2. Utility depends on product applications and proof of superior performance.
3. Initial applications are usually niches and require a limited amount of material.
4. Attractive commercialization schemes require a material of intrinsic value that will justify a high margin or applications for which the value can be captured from end-product margins.
5. The dilemma then is high development costs and high-risk returns.

Examples of the utility and need for new, advanced-performance materials are numerous. For example, in turbine engines today, the need is to be able to increase operating temperatures by 100–150 °C. The laws of thermodynamics allow significant fuel efficiency to be gained as the temperature increases. However, the material, particularly for the turbine blades, must be able to handle these increased temperatures. This material need illustrates the connection between product application and material performance.

Development of Advanced-Performance Materials

One of the unique issues in the development of advanced-performance materials is that they are very product-specific, and their development requires expensive prototype iteration and performance testing. The product development is people- and design-intensive and usually results in a niche market for the material; that is, the specific product slate for which the material has been designed and tested. Many of the applications are in high-tech industrial products like aerospace components, so the total volume of material used will be small. Thus, attractive commercialization schemes require that the material have intrinsic value that will justify a high margin, or there must be a product application for which the value can be captured in the end product.

Designing materials for a proprietary product as a vertical integration process, in many cases, provides a superior product for which the material development costs are derived from final product margins. In this area, the Japanese manufacturers seem to have an edge. They frequently target material development for specific products and use a "market pull-through" philosophy to get the right properties to enhance their product line. This approach is in contrast to many materials efforts that are "technology-push", that is, new performance materials are looking for a product home. In this case, the material development costs are high with high risk returns. Most chief executive officers do not favor these odds in their prioritization of development resources.

These *life-cycle dynamics* for advanced-performance materials were described in 1987 by Eckstut (*1*) (Figure 1). His model still has relevance to the commercialization dilemma of advanced-performance materials. In Figure 1, development costs are going up from the molecular invention to material utilization steps. Early on, the new molecular system may have a specific application in a small and fragmented market in this technology-push model in which a new material with unique properties is "looking for a home". If this small market materializes and processing costs are successfully driven down, new applications can be found that contribute to other products' functionality or product life when direct substitution of the material can be made in existing part or product designs. An example is a new light-weight composite that is substituted directly for a metal in a weight-sensitive part.

If the material has sufficient intrinsic property enhancement, newly designed parts can allow for the optimal utility of the material. Again, if sufficient market develops, resources can be deployed to optimize the

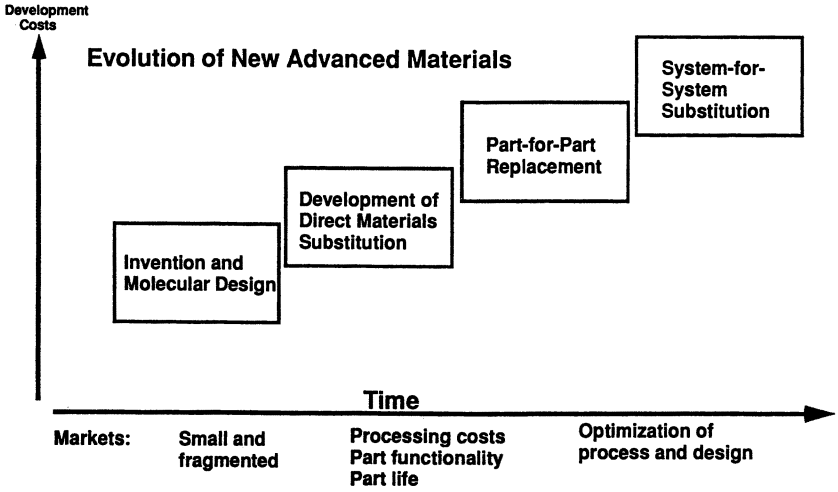

Figure 1. The life-cycle dynamics of advanced-performance materials. (Reproduced with permission from reference 1.)

material processing and the final product design. Now the possibility exists for system-for-system substitution using the new material as the foundation for a superior performance substitute system. An example of a new material that was successfully commercialized through these stages is optical fiber. Currently, communication systems are being designed on the basis of optical fiber technology, which has little relationship to copper wire systems. Optical fibers have become a major materials business in which there is intrinsic value in the material itself and the volume demand has grown to the extent that processing costs, including capital, can be recovered from material sales.

The number of such examples, however, is not high. In many other examples of advanced-performance materials, such as DuPont's Kevlar and Allied Signal's SPECTRA, the volume applications associated with system-for-system substitution has not yet occurred at a level necessary to pay back the development and commercialization costs already expended. High-performance ceramics is another area in which the early promise has yet to materialize. The consequences of Eckstut's life-cycle dynamics have been overcapacity and severe rationalization in high-performance carbon fiber businesses, some specialty alloy activities, and high-performance polymer composites. Thus, with critical technologies that involve advanced-performance materials, we need to better understand how to exploit their value in a commercially viable way.

Areas of Opportunity for Advanced-Performance Materials

To begin to understand the need and the areas of opportunity for advanced-performance materials, we need to analyze where they fit. First, several unique "drivers" exist for advanced-performance materials for which enhanced properties translate into next-generation products:

- aerospace industry (structural materials): military, space, and civilian aircraft
- electronics–communications (electronic materials): miniaturization, higher performance, and new technologies (electronics–electro-optics–optical)
- ground transportation:/ automotive, ships, and shipping containment

Clearly, aerospace has been a major driver for advanced structural materials. It will continue to be a driver, although perhaps at a slower pace, particularly for weight reduction and higher temperature reliability. The slowdown of military aircraft development presents a unique problem because many of these programs, such as the advanced tactical fighter (ATF), were "test beds" for advanced-performance materials for which

U.S. Government funds were used to defray research and development costs. The aerospace plane is another opportunity for companies to develop new materials with Government support. However, military support for advanced-performance materials development is rapidly decreasing, both in appropriate test beds and in manufacturing support such as the U.S. Defense Department's Mantech program.

Space technology development has also provided advanced-performance materials test beds in both communications and structural areas. The value of these programs has been passed on in many cases from space and the military to civilian aircraft. Many of the advanced-performance materials in the new generation of airline transports, such as structural composites, were first developed for spacecraft or advanced military aircraft.

In electronics and communications, the drivers are the need for further miniaturization, higher performance, and new optical technologies that provide entirely new products. For example, in aircraft, control systems have progressed from mechanical hydraulic components to fly-by-wire electronic systems to the new concept of fly-by-light optical systems. This progression has depended on the development of the appropriate materials to design the performance systems.

In ground transportation, the push for advanced-performance materials has been less dramatic because cost is the discriminator in the selection of components and systems. However, incremental improvement in automotive materials has been substantial in many areas, particularly in structural steels and plastics.

The list of high-performance materials currently in some stage of development or commercialization is quite extensive. Some of the most promising in terms of potential product enhancement include high-temperature and high-strength ceramics, rapidly solidified metals (metallic glasses), high-temperature and high-strength fibers, electronic polymers, optical polymers, inorganic electronic materials, high-strength polymer composites, metal matrix and ceramic matrix composites, and high-temperature alloys. All of these areas have specific products of high promise in terms of product enhancement. However, many of them are offered by small, start-up companies who have yet to truly capture the markets they seek, and others have been developed by "deep pocket" chemical companies who are reassessing the long-term opportunities. The disincentives for continued development are high:

- Users are not generally the developers.
- High development costs and extensive product application work are required for market entry.
- Initial markets are small and specific.

- Long development times are required for certification and market penetration.
- Capital costs for production can be large.

When the users are not the developers, a major mismatch can result between the material design and the end use. Thus, the developer will have extensive product application development to do, which is both expensive and time-consuming. Initial market potentials can be small, and manufacturing capital costs can be high. Thus, the development of new performance materials as the foundation of a materials business does not look very attractive to materials suppliers. Yet, these enabling technologies are very important to the future development of many basic industries. Some models for the successful development of advanced-performance materials are the following:

- U.S. Department of Defense (DOD) development and demonstration of performance products
- NASA programs
- in-house development of proprietary materials for vertical integration of new product development
- joint partnerships between materials developers and users

The DOD and NASA programs generally involve an aerospace firm that works with material suppliers to develop a material for a specific performance goal. In addition, the Government provides some research and development (R&D) funds so the risk to the materials developer is minimized. In a sense, this is a case of vertical integration in which DOD or NASA is the end user and manages the complete product development.

Cases of the development of proprietary materials for in-house use are found in certain industries. For example, Pratt–Whitney initially developed high-temperature alloys for their own jet engines. Since that time, they have licensed some of their materials technology to other manufacturers, but the market advantage to them early on was significant.

In-house materials development is most prevalent in the microelectronics industry, even down to polymer substrates for circuit lithography. Here, companies such as AT&T and IBM have established some of the most impressive polymer science laboratories in the world to design and develop polymer systems for their own microelectronic products. They recover their development costs from the margins on final products.

However, in today's world of rapid cycle time and cost-efficient manufacturing, perhaps the best examples are in joint development partnerships between chemically or materials-based companies and the end users. One such example is the joint composite development partnership between the Dow Chemical Company and Sikorsky, a subsidiary of United Technologies. Here is a clear case of materials know-how being used in a technology-pull environment guided by the performance needs of the end users. Clear targets are provided to the materials designers, and product application and testing can be iterated rapidly with the user.

A look at the current commercial scene in advanced-performance materials is not very encouraging. Although a great deal of R&D resources have been used for materials development, and materials research is very strong in universities and Government laboratories, the commercialization of the results has been disappointing. For example, structural ceramics has received essentially no play in the United States; most components are from Japan. Carbon fibers are at the point of excess capacity. Many players getting out of this area because of strong Japanese competition. Advanced composites are also at the point of excess capacity. Players are dropping out, and fabrication is still too expensive for mass markets. Advanced metal products is receiving mostly small efforts by users and start-up companies. Electronic materials are mostly developed by in-house R&D by component manufacturers.

Some notable exceptions to these generalities have occurred, especially in electronic materials. Several chemical companies, including DuPont and Hoechst–Celanese, have major successful businesses in electronic materials.

The lessons to be learned are to determine the requirements for success. These include the following:

- Early integration of material modification, product application, and process optimization. This integration reduces cycle time and up-front risk. Today's fast-moving markets cannot accommodate a 20-year development cycle and still ensure commercial success. Concurrent engineering with discovery and manufacturing is required to be a leader.
- Understanding of markets and the need for a supplier–user partnership. Where is the value added? If the market needs are understood, the value of the performance material can be estimated, and market-pull will ensure that the technology is cost-effective and commercially viable. This result will almost always require a working partnership between the material developer and the end user.
- Improved processing technology. In many cases, properties are conveyed to advanced-performance materials through specific processing routes, for example, single-crystal alloys and molecularly oriented polymer films. Sometimes, the ultimate cost structure of the materials depends on processing parameters. When the demand is relatively small, it is difficult to improve cost position through economies of

> scale. Another issue relates to the manufacturing processes to make the final product. For example, the use of polymer composites has been hampered by the lack of cost-effective lay-up equipment and rapid prototyping capability. These processing questions beg for new approaches to materials production and their subsequent processing into final products. The solutions will include new, flexible production systems in which plant overheads are carried by several materials' products and new concurrent product design processes that are optimized for the material of choice. Process research in both areas should be priorities for chemical and mechanical engineering departments.

I conclude with a few suggestions. First, continued Government support for advanced-performance materials test beds, processing, and manufacturing should be a high-priority item for the Department of Defense and for Government laboratories. The potential for civilian spillover should also be a high priority. To be successful, these programs must be joint partnerships with industry so that concurrent R&D can rapidly create new product opportunities. Materials processing and product development must be of equal (or greater) importance to basic materials research.

Second, partnerships between materials developers and end users must be facilitated and encouraged. In some cases, this step may mean an R&D consortium between university researchers, a chemical or materials company, and a product manufacturer. The National Institute of Standards and Technology's Advanced Technology Program (NIST ATP) is a good model that should be expanded. Several projects that have been funded are examples of this integration of research–development–commercialization by universities, a materials supplier, and an end-user product manufacturer.

Third, engineering education should be reconsidered in both product design and materials processing. Most design engineers have limited materials expertise. Thus, their ability to optimize product designs to use an advanced-performance material (normally a substitute for metal) is not high. In addition, real "hands-on" experience in property enhancement through processing is minimal for most students. Thus, new materials-design courses should relate design parameters to materials properties and explore the materials property enhancements that can be obtained by controlled processing.

These issues should be regarded as an important part of research policy and Government support of critical technologies involving advanced-performance materials. In addition to basic research support, other mechanisms should foster the engineering and development activities that will make the materials candidates for commercialization. The next generation of high-technology products will, undoubtedly, require the enabling technology associated with advanced-performance materials. Our competitive position will, in many cases, depend on our ability to put together all elements for a successful commercial product—research, development, and commercialization—in a coherent, integrated fashion. This ability will require creative scientists, innovative engineering, and "street smart" commercial launches. Generally, no one organization has all of the necessary components, so partnerships and "concurrent engineering" will be the "name of the game".

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Partnerships with Universities

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RESEARCH UNIVERSITIES ARE IN THE MIDST OF MAJOR CHANGE. Historically, the research universities have been supported by the Government with two theories in mind: (1) national security is important, and science and technology are critical to a strong defense; and (2) human health is important. The interest in human health persists, an interest in national security persists, but the adversary has given up. The Soviet Union no longer exists. The question now is, What is the rationale for the support of universities—support in the post-Cold War era? The Department of Defense, which has nurtured an important set of activities, has a role in electronics and devices, structural materials, and high-performance or advanced-performance materials.

Support by the Department of Defense

Academic institutions have been included, and in many instances, there have been commercial consequences, although that has not been the mission of the Department of Defense. The Department of Defense mission is defense and national security, not the development of compact disk players. But in fact, for example, in electronics and devices, fundamental materials research was sponsored by the Department of Defense. Various organizations and activities in parallel in industry (at Lincoln Laboratory, IBM, and General Electric) led to the development of the semiconductor laser in the early 1960s.

The Department of Defense encouraged long-term efforts that led to this practical development. In 1962, no one had the vision that for a few dollars, every compact disk player would have a semiconductor laser as an important component.

What have we learned about the modus operandi of the Department of Defense that should prove useful as we move through a transition to a new era for support of science and engineering in the universities? First, the Department of Defense, despite its mission-oriented character, has had a very long-term view. It has consistently supported research and development (R&D) in support of its mission, and it has included in that mission the support of education. Many highly educated individuals have stepped out of the university scene and made important contributions in the industrial sector. A number of people as well stepped out of one university and right into another and continued in the footsteps of their research mentors.

There is a recognized need for continuity in support of research by the Department of Defense. National security is something that we have embraced as a nation. Moreover, the Department of Defense has provided a substantial level of support consistent with the nature of the project under investigation. This fact stands in striking contrast to programs supported by other agencies, in which all are leveraged, one against the other, no one of which is providing adequate support to accomplish very much of anything. An extreme view, but the Department of Defense has been better in terms of long-term consistency and providing more than subcritical support for its projects.

Finally, the Department of Defense has in fact has taken the posture that planning, integration, and systems orientation are important. The Department of Defense probably will maintain "tech base". That means that we will have a strong science and technology base, which should bode well with the universities. However, a tremendous down-sizing has already occurred in active forces, and more is planned. Moreover, the larger projects that had been awarded to industry contractors are dissolving, and less R&D funding is available to those industries. This decrease in funding in turn means that there will be more competitors at the resource table to perform the basic science and technology efforts for the Department of Defense. More "players" for the same dollar means a more competitive world.

Why should we maintain strength in science and technology? Science and technology are critical for a variety of reasons. Science and technology are critical to solving international conflicts. Our ability to determine whether airplanes are moving around southern Iraq hinges on advanced science and technology and communications capability. Furthermore, solving global-scale problems will rely more and more on science and technology. Pollution is a global-scale problem, but telecommunications is another, and energy systems is yet another. Achieving and maintaining economic vitality and economic viability and enhancing the quality of life are important reasons for maintaining strength in science and technology.

The entire federal policy is predicated on the notion that education and research are tightly coupled and intertwined, and that language is in the pamphlet that describes how universities are funded by the Federal Government. Here are the products and services of the research universities. Our most important set of products and services is the people we educate and our commitment to human resource development.

Contributions of Chemistry

Chemistry really should be at the heart of this revolution in materials. Chemistry is the discipline that has been associated with the study of matter; that is the science of chemistry. Moreover, chemistry is also the discipline associated with the purposeful manipulation of matter at the atomic and molecular level. But, in terms of materials chemistry, the time is right because of the ability to do analysis at an unprecedented level of resolution. However, our academic system has not yet responded for our students because our laboratory and lecture subjects have not yet included the dramatic advances in analytical capability. This is an important charge to the academic community.

One unique contribution for chemistry is analysis. Analysis is really making it possible to make giant strides. It is fueling the revolution. Chemistry has one important thing in its educational belt that the other disciplines do not have, and that is synthesis. Synthesis and processing relative weaknesses in the area of materials in the United States. This is an area of unquestioned strength in chemistry, but synthesis has not been brought to bear, at least as we see it as molecular scientists, to the potential possible, especially by the most gifted and talented people in the area.

Fundamentally, chemists have not been educated or have not learned on their own where chemistry plays a role in materials systems. Educational laboratories, including those at the most expensive universities, are lacking state-of-the-art equipment that would introduce young people or people who are going to enter college later in life to state-of-the-art technology that would intrigue them with the opportunities about complicated systems like materials.

Finally, too many leading chemists have dismissed materials chemistry as too applied. In a chemistry department, generally the largest subgroup is the organic chemists. The leading people in the department, the people most highly regarded, and most highly rewarded are organic chemists who have in mind a practical synthesis. They want to develop a method, or they actually have a target in mind, something that looks good, smells good, and tastes good, like flavorings, fragrances, molecules with a purpose, or a method to obtain them. That's practical. Synthesis is the heart of chemistry. But these individuals, the most capable people, need to be turned on to the opportunities in these complicated, messy materials systems where progress is just being made because of our ability to establish structure and to relate that to function.

Need for Partnerships

The traditional academic units that might be called on to contribute here, chemistry first, but also chemical engineering, physics, electrical and mechanical engineering, and materials science, are all standard academic departments at institutions that have strength in science and engineering. All of these in their own way have an educational prospective to bring to bear on this materials chemistry issue. One can quite legitimately ask if there are better ways to organize ourselves to address these problems. Materials research laboratories that are a quarter of a century old have served us well in some ways, but new organizational structures are needed to assist in executing research programs.

For example, there is an increasingly important role for parallel input to both communities of the social sciences and the physical and engineering sciences. That is particularly true in the problems I mentioned earlier, global environment, telecommunications and information, and energy systems. Dean Lester Thoreau of the Sloan School of Management points out quickly that two organizational systems have survived for about a thousand years: the Catholic Church and the university. Our longevity and strong traditions are our strengths, and our curse is that we change slowly. Despite opportunities for change, some important strengths that are associated with our current structure should be maintained. The most important is that this large number of academic units that can be brought to bear on these complicated problems includes people with unique educational perspectives, each of which would be necessary to solve some of these problems. The current structure is not so bad, provided that we are able to learn each other's language and to see the other contributions that others might make.

We have been very weak in fostering teamwork in universities. In interdisciplinary or multidisciplinary collaborative projects, individual contribution can be recognized, appreciated, prized, and nurtured. But we have done a very poor job at developing systems for teaching teamwork. This is something that we can learn from industry and from other organizations that work in a mode that promotes teamwork. I said that our greatest product is the people we educate. The majority of our graduates will go into the private sector, and this is where they are going to need to know teamwork.

There is a need to develop renewed partnerships, and particularly so when the technology for doing certain kinds of science and engineering is so expensive. If for no other reason, we must develop working relationships that work. At one time it was possible for every university to have gas chromatographs, IR spectrometers, and NMR spectrometers. But it is not possible for every university in the nation to have a full complement of complicated and expensive instrumentation for the study of complicated materials.

I have come to appreciate a role for social sciences, and I also believe there is an important role for the business community. The kinds of solutions that we are trying to find in science and engineering are not going to be implemented in a vacuum. For example, Mario Molina at MIT is associated with studies that led to an understanding that chlorofluorocarbons might be a problem. But doing something about that problem is much more complicated in some ways than doing the fundamental science that led to that observation.

Finally, we need to form partnerships while maintaining our traditional values, meaning that we must remain committed to this notion that individual scholarship is something to be nurtured in the university setting. Ideas and knowledge are creations, not unique to universities, but that are happening everywhere. However, in universities, there still needs to be the opportunity for people to pursue what would apparently be the useless, because discovery and innovation stem from the unexpected. The best examples of this truism are in materials chemistry: high-temperature superconductors from ceramics, weird; a new form of carbon, I thought everything had been discovered, but now we have C_{60}. These are just two of many examples of where unfettered investigation needs to be nurtured and continued. There is a great basis for optimism as we move through a period of enormous change.

Materials Education for and by Chemists

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Introduction: A Historical Perspective

The empirical fact is that the science of chemistry began as the science of materials—inorganic at first, then organic. Extractive and process metallurgy (recall alchemy, too), the preparation of the vast tonnages of industrial chemicals from ammonia and soda ash to fertilizers—this was what chemists did for 150 years. At the beginning of this century, they turned to the organic world. Perkin's dyestuffs, aspirin, Salvarsan, and rayon led to the giant organic chemical industries of today: polymers, pharmaceuticals—all materials. And on that economic base chemistry had the luxury to start studying the fine structure of matter and its interactions at the subatomic level. The progression of the content of what was taught by "chemistry departments" in the United States (very different from Europe and Asia), which is not by any means the same as what constitutes chemistry, can be summarized in Table I. At the turn of the century the study of chemical reactions and their fundamentals embodied in the phase rule was firmly in the purview of chemistry departments. Applications were directly linked to the basic science that the applications "pulled." Josiah Willard Gibbs, arguably the country's greatest chemist, recipient of Yale's first Ph.D. (in engineering), taught Latin for 3 years before embarking on understanding steam engines. Thermodynamics owes more to the steam engine than vice versa. Van't Hoff and his study of phases was concerned with the extraction of pure salts from mixed solutions for industry.

By the 1930s, the fragmentation of American academic life was in full swing. As far as the inorganic world was concerned, the chemistry of the earth, of metals and ceramics, all became the province of new specializations that eventually called themselves departments, even "disciplines". In chemistry departments, inorganic (materials) chemistry became equated with the chemistry of coordination compounds. Although the profound impact of DuPont's discovery of nylon and the opening of the polymer world was felt throughout the world, by 1948 (when I finished my Ph.D.) U.S. chemistry departments had opted out of the world of materials science and engineering.

Table I. Teaching and Research in Materials Chemistry in the Twentieth Century

1900	*1930*	*1950–1990*
Chemists • Extraction of metals and ores, heavy chemicals • Physical and inorganic chemistry of the earth • Analysis of all matter • Phase rule (thermodynamics)	Metallurgists • Chemistry, physics, and properties of metals and alloys	Physicists • Theory of properties of solids • Utilization of new materials
	Ceramicists • Preparation and uses of nonmetallic compounds	Materials Scientists • Structure–composition–property relations • Synthesizing new materials • Characterization of materials • Utilization of one or more classes
	Geochemists • Analysis of solids • Fundamental physical chemistry and synthesis of earth-forming solids	
	Mineralogists • Crystallography • Structural analysis of solids	Mineralogist–Geochemist • Synthesis and stability under extreme pressure and temperature conditions • XRD and characterization of-structure
	Chemists • Coordination complexes • Thermochemistry	Chemists • Crystal field theory • Surface and specialty characterization

Although the emphasis on organic chemistry and synthesis was very suitable for the pharmaceutical industry, and although hundreds of graduates and Ph.D.s went to work for the polymer materials industries, astonishingly, for 15–20 years, essentially all faculty in chemistry departments with notable exceptions like C. S. Marvel and Paul Flory ignored the field or, worse, regarded it as second-rate chemistry. It was no wonder then that when the semiconductor revolution started, physicists and electrical engineers took over the chemists' role of synthesis, structure, and property analysis of this defining new class of materials.

By 1960, when the Materials Research Laboratories of the Pennsylvania State University were formed, the role of chemistry departments was minor. Indeed their funding agency, the Advanced Research Projects Agency (ARPA), had to fund a special program to do materials synthesis and processing research in its new interdisciplinary laboratory, which was not in the chemistry department. Since the early days of the development of the materials research field, the relevance of chemistry education to the materials field has improved with respect to polymers. In metallurgy, semiconductor science, and ceramics, U.S. chemistry departments do not contribute significantly. Participation by many chemistry departments has been on the increase as money has become tighter and "materials" has appeared to become a desirable label. However, there has been a disappointing and largely unsuccessful effort to force-fit materials into the mold of pre-existing specializations in chemistry.

Two examples stand out: research on ceramic precursors and research on biomaterials via so-called "biomimetic" approaches. I had started the systematic organometallic precursor work for making ceramic powders in a series of a few dozen papers starting in 1948 (*1, 2*). By the mid-1950s I had shown that inorganic sols did essentially as well and were orders of magnitude cheaper. The very sophisticated ceramic precursor work, now a decade old, has yet to demonstrate a special niche for itself in any real examples with unique properties.

The biomimetics theme is more current. Here again, E. W. White et al.'s (*3–5*) early success in making the only genuinely biomimetic commercialized material used both in human prostheses and in electroceramic technology is more than 20 years old. Work on a wide front summarized by Heuer et al. (*6*) is singularly innocent of any success in making a real material with special properties or potential use in science or technology. Indeed not one other real biomimetic material has ever been prepared. Furthermore, in a remarkable concession, the dozen authors of this paper (*6*) conceded that the use of the term "biomimetics" was an exaggeration, but instead of choosing an accurate term, they suggested that a special dispensation be granted them to let the word mean something other than what it does!! I suggested an accurate term: "materials derived from biognosis", that is, using learning or knowledge from nature. Here also the only real example of technologically significant materials, based on biognosis, are the transducers and actuators by Newnham et al. (*7*).

I cite this history including these two recent examples of attempts to "insert" chemistry into the thicket of materials research already densely populated by physicists, ceramists, metallurgists, and chemical and civil engineers, because they form the background for my recommendations in the following sections. It is, of course, directly relevant to the initiative in education of the American Chemical Society. First let me list good reasons for such an initiative:

- To make the proper contribution of chemical sciences to the materials research community, noting the fact that chemists outside chemistry departments have already been doing this for decades.
- To inform and educate chemistry faculty and students in materials science.
- To compensate for the fact that, for the past 50 years, U.S. chemistry departments (uniquely in the world) have ignored the chemical science of solids.

There are also poor reasons for the ACS to launch such an initiative without proper assessment of the real situation:

- There is money available under the label "materials".
- The materials research community is unaware of particular insights or research now being done in chemistry departments and should be exposed to them. (This erroneous view ignores the facts that every industry utilizes all disciplines in attacking research problems, and chemists are already fully involved in industry.)

The problems confronting the ACS initiative in 1992 were very, very substantial.

1. Very few chemistry faculty (perhaps 2–5%) are interested in, and even fewer are appropriately trained in, the chemistry basic to materials research (discussed later).
2. Who will retrain the professoriat and how? (Indeed, who will admit that they need retraining?)
3. There is an oversupply of very adequately trained personnel in materials research, although the situation may not be as severe in chemistry.

A Balanced Content for Degrees in the Science of Solids

In 1959, Pennsylvania State University launched the first Ph.D. degree program in the United States that was administered by an interdisciplinary committee of the graduate school through participation by senior faculty from all departments. Chemistry was represented by J. G. Aston and J. J. Fritz and me (counted as a "geochemist"). This very successful program, the largest such in the nation, continues to the present (renamed the "materials" degree in 1991–1992). It defined the content of the field and broke it up into appropriate courses (*see* Table II).

Chemists clearly contribute to both synthesis and analysis of materials, less so in the physical and mechanical properties of materials and their applications in systems.

In the three loops of Figure 1, modified from my paper written for the physics community (*8*), the role of chemistry is dominant in the "preparation" and "characterization" functions.

The role of materials chemistry education will therefore have to have as its core the knowledge base adequate for

1. preparation
    - the theoretical basis in crystal chemistry and phase equilibria
    - the experimental capacity to synthesize new materials (including those that never existed before, which has expanded enormously in the past 20 years). The chief variables used are pressure (to ~1 megabar) and temperature (to 4000 K). These are combined in many families of apparatus.
2. characterization
    - the appropriate characterization of solids demands a rational scheme based on the level of detail needed (*see* ref. 8).
    - theory and practice for the use of tools for analysis of composition.
    - theory and practice for the use of tools for analysis of structure.

Basic Subject Matter Chemists Must Acquire To Work in Materials Chemistry

Materials Synthesis or Preparation. It would be regarded as foolhardy for any physicist to attempt to work in materials physics without a grounding in quantum mechanics and the standard 1-year course in solid-state physics. The chemistry community does not fully appreciate that the equivalent courses to be grounded adequately in materials chemis-

Table II. Contents of Solid-State Science Ph.D. Program

Subject Matter	*Usual Courses To Cover This Subject Matter*
1. Preparation: synthesis, growth, special forms	• Crystal chemistry • Phase equilibria • Kinetics of (solid-state) reaction mechanisms
2. Characterization: position and nature of atoms and ions (chemistry and structure)	• Optical microscopy • X-ray diffraction theory and practice • Elemental analysis: XRD, emission spectroscopy • Defect structure determination
3. Properties: their relation to composition and structure	• Quantum mechanics, statistical mechanics • Introduction to solid-state physics (Kittel) • Relation of properties to structure and composition

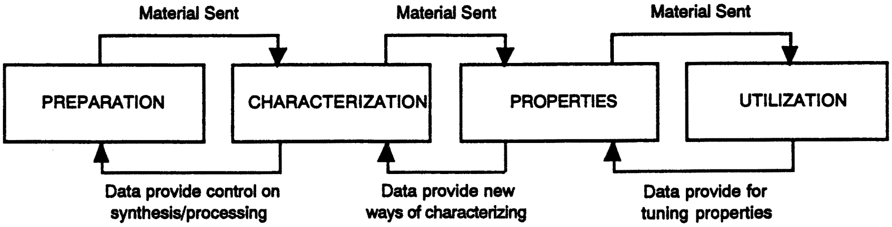

Figure 1. The logical idealized structure of materials research.

try are crystal chemistry (not only crystallography) and phase equilibria. Crystal chemistry deals with the relationship of (crystal) structure to composition and (thermodynamic) environment. It can be distinguished from crystallography, as shown in Figure 2. Crystallography, the study of the analysis of crystal structure, is a necessary prerequisite for crystal chemistry but is far removed from it. Linus Pauling laid the groundwork for crystal chemistry and, together with V. M. Goldschmidt, clearly defined the general field. The power of crystal chemical concepts can be illustrated by the fact that Goldschmidt's 1926 book, *Geochemische Verteilungsgesetze der Elemente*, lists on page 144 all the structural analogues of Si and Ge and the III–V and II–VI compounds, which were laboriously discovered one by one by the semiconductor community. Likewise, Pauling's structural chemistry of the silicates provides insights still current in today's synthesis research. It is inconceivable that a materials chemist not be grounded in this material.

The second major component of the education of a modern materials chemist in materials synthesis is, of course, in phase equilibria, possibly through the treatment of quaternary systems and P–T–X (pressure–temperature–composition) equilibria. This subject was essentially eliminated from chemistry departments and is taught in the materials and geological science departments. Every student (and professor) aspiring to be a materials chemist will have to master this subject.

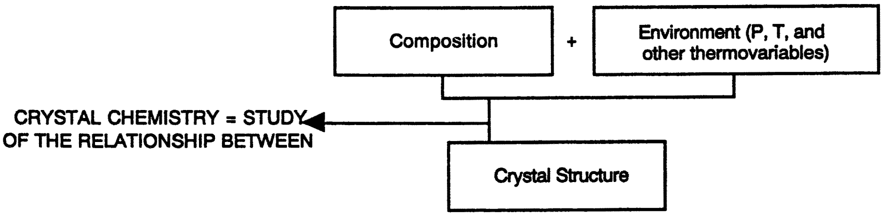

Figure 2. A representation of the field of crystal chemistry.

The information contained in a phase diagram is as follows:

1. number of compounds formed and stoichiometry: whether one or more phases form from a given composition
2. absolute magnitude of one-component solid-liquid, solid-vapor curves: bond strength and bond nature
3. data on crystalline solubility (CS): defect concentration and its temperature dependence; CS with vacuum
4. solidus and liquidus: heat of formation ΔH_f, "strength" of "compound", liquid structure; "clustering" in crystalline solutions
5. pressure–temperature curves for solid–vapor reactions in binary systems: nature of defects—anisodesmicity of bonds and energy relations
6. pressure–temperature curves for solid–solid reactions: sign of the change of volume (ΔV); magnitude of the change of enthalpy at the transition (ΔH) or ΔV; nature of phase transition

Unfortunately, many of those who can read the thermodynamic aspects of the phase diagram do not realize the enormous amount of quantitative crystal chemical information that is contained (or is it concealed?) therein. In two reviews (*9, 10*), I detailed my view on the intellectual processes necessary for successful materials synthesis.

Materials Characterization. Regarding education in the characterization or analysis of materials—a central topic of materials chemistry—there is a similar hierarchy of importance of subjects that chemistry students (and faculty) will need to have learned. Reference 7 treats this topic systematically, and Roy and Newnham (*11*) presented a comprehensive (albeit somewhat outdated) presentation of the architecture of materials characterization. Thus Rutherford backscattering and extended X-ray absorption fine structure (EXAFS) are excellent characterization research tools, but in the sequence of tools used every day on every sample, they are insignificant. Thus for structural characterization, X-ray powder diffraction reigns supreme, yet the full power of the modern automated search routines that can be universally applied are taught only to a minuscule fraction of even the materials science student body.

Pedagogical Aids for Teaching Materials Chemistry

The Pennsylvania State University is the base for the Materials Education Council (MEC), the national and international center for the creation, collection, and distribution (at not-for-profit prices) of teaching aids for college-level students.

Two classes of materials will be invaluable to any group contemplating teaching materials chemistry:

1. print
   - The *Journal of Materials Education (JME)* is a must for the departmental library. It is in fact a continuously changing textbook of teaching modules on new and emerging materials topics. Free reprint rights make the articles easily available.
   - Clusters of modules (from *JME*) on selected topics such as polymer experiments or cement chemistry are available as short textbooks.
   - Special autotutorial modular texts on crystallography and on phase diagrams are available. (Nearly 10,000 units are sold every year.)
   - The materials science and engineering of wood is thoroughly covered in four texts.
2. video
   - The National Materials Science Film series includes an excellent treatment of ternary phase diagrams and of mechanical and electrical properties.
   - TV and text courses on materials synthesis and related topics are available. The use of such offers by far the most cost-effective way to give faculty the wherewithal to teach new topics.

Recommendations for Improvements in Materials Chemistry Education

Most chemistry faculty will not undertake a serious study of materials science. Hence I propose the following:

- Those few chemistry departments interested in materials chemistry should start hiring faculty trained in materials sciences.
- Chemistry departments should start offering a concentration area in materials chemistry, and the requirements for this degree include the substitution of 15 credits of phase equilibria, crystallography, crystal chemistry, and materials characterization to be taken in the materials or geoscience departments. Where local chemistry faculty can teach

these topics, students would, of course, take them under chemistry labels.

- Beyond these beginning basics, the local chemistry or materials faculties' own specialization will determine both the research and specialized courses that may be available to the student.

At this time, the interdisciplinarity of the materials field is being emphasized as much as the topic itself. Materials chemistry will bring to the academic chemistry community an excellent opportunity to practice what they often preach (or agree with) regarding the importance of interdisciplinarity, as they incorporate more courses from the materials science and physics departments as part of their requirements.

Acknowledgments

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Industrial Perspective on Materials Chemistry Education

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A STUDENT STARTING AN INDUSTRIAL POSITION in a materials-based manufacturing company will find a vastly different environment from the one that existed 10–15 years ago. The pressures on most companies to compete in today's global marketplace demand that they operate differently. In a high-technology business such as Kodak's, innovative products are essential. Today we must bring those innovations to market as quickly as possible. Once the concepts are proven and a manufacturing route is determined, the manufacturing process must be competitive to produce products with the required features at the lowest possible cost. Product technologies change rapidly compared to the career lifetimes of the employees, so the work force has to remain flexible to adapt to new technologies.

The views expressed here are my own, and they are based upon 17 years of industrial experience, 12 of which were in research management, so they should prove representative, as they are driven by a common set of pressures present in the current industrial climate. The three basic questions that I address are

1. What does industry seek in new hires?
2. What do we find we need to provide after hiring?
3. Where would a materials chemistry background help?

Needs of Industry

Innovation has historically been a strength of U.S. industry. In recent years, the United States appeared to be losing its position to foreign competition, particularly the Japanese. Table I (*1*) illustrates, for 1991, the number of patents obtained by several firms. Japanese companies hold the top few positions, but several U.S. companies have shown continued progress.

Table I. Number of U.S. Patents in 1991

Company	*Number*
Toshiba (Japan)	1156
Hitachi (Japan)	1139
Mitsubishi Electric (Japan)	959
General Electric (U.S.)	923
Eastman Kodak (U.S.)	887
General Motors (U.S.)	863
Canon (Japan)	828
Philips (Netherlands)	768
Fuji Photo Film (Japan)	742
Motorola (U.S.)	631
DuPont (U.S.)	631
Subtotal, U.S. companies	3935
Subtotal, Japanese companies	4824
Subtotal, Netherlands	768
Total	9527

Although a good record of innovation is a key ingredient for success, the progression from innovation to successful manufacturing is perhaps even more important. A product such as photographic color film, where multiple layers of material are coated onto a plastic support, where literally hundreds of materials are involved, where the photographic system shows a high sensitivity to impurities, and where the product must be manufactured at high rates in dark conditions, presents unique challenges to a materials chemist and engineer. An effective development cycle from innovation to manufacturing will require careful attention to all aspects of manufacturing, starting at the design phase.

Reducing the development cycle time will depend upon talented, well-trained people. Employees must possess a broad knowledge of the entire manufacturing process, whether their job is product design or manufacturing process research and development (R&D). They must focus on understanding, not empiricism. Workers must understand all aspects of the product's behavior, and they must integrate their knowledge with that of others on the team and work well within the team. Individual excellence is a key ingredient for success, but teamwork is essential. Today's emphasis on quality requires that employees understand statistical principles and tools and use them. Problems that show up in parts per million or parts per billion require special experimental plans to detect and to correct. Today's environment really requires workers to integrate their materials knowledge throughout all aspects of the process to achieve the desired levels of system performance in ways that were not required several years ago.

As a simple example of this integration, consider a new product design engineer who might be given the problem of designing a plastic part for a new camera or film system. Starting with the development of customer requirements and specifications, the individual must design the part, choose the appropriate materials, select a manufacturing process, and then demonstrate that the new part and manufacturing process work, leading to a final verification that the part functions as the customer requires. To reduce the product development cycle, both analysis and testing become crucial ingredients in the concept stage rather than after the part is manufactured, as has been the case in the past. The key notion is get it right the first time and not spend time and money fixing it later. To perform a proper analysis, the engineers must understand all aspects of the system from start to finish.

Job Skills Required

Getting back to the issue of people and materials chemistry training, consider the job skills required for functional excellence in the type of environment described. Four key dimensions come into play:

1. technical
2. business
3. quality—statistics and planning
4. people—teamwork and communication

Of these, the academic environment seems to concentrate on the first two, technical and business. To be sure, for students in technical curricula, exposure to business concepts and training often is minimal. The other two areas, quality tools and people skills, are seldom formally addressed.

D. Kezsbom (*2*) conducted a survey of some 285 managers and project specialists who were asked to list the sources of conflict in their current projects and to assign a prioritized rating to each. Table II illustrates one set of results from the survey. Technical options is found very low on the list, twelfth of thirteen. According to the prioritized ratings, technical problems are not an issue, but goal-setting, people problems, communications, and politics play a much larger role in project conflict. The findings of this work differ greatly from the typical notion of academic training.

Table II. Causes for Project Conflict

Cause	*Score*
Goals–priority definition	1877
Personality	1201
Communication	1182
Politics	655
Administrative procedures	633
Resource allocation	571
Scheduling	527
Leadership	453
Ambiguous roles–structure	185
Costs	174
Reward structure	151
Technical options	132
Unresolved prior conflicts	96

Need for Materials Chemistry Background

One way to examine the problem that academia faces in preparing one of its products, students for industry, is to compare the preparation in terms of the environment found in industry today. In Table III, I attempt to compare the academic preparation students receive to what they will find in industry.

The contrast in environment versus preparation is interesting. Education has a lot to do with the creation of habits, and students do receive considerable technical input, but they are not generally given the chance to develop people skills and to practice them in a nonthreatening environment. The academic focus on correct answers to problems is at odds with industrial practice, because most industrial problems do not have correct answers, meaning that many approaches are doomed to failure. The pain of failure has been cited as one impediment to learning in an organization (*3*). Individuals will become defensive and stop listening or communicating with each other if they feel their projects may fail.

As suggestions for the future, the following are opportunities for materials chemistry training. My suggestions certainly are not specific to materials chemistry but should be germane to other technical disciplines that train students for industrial careers.

1. Start by providing a solid foundation, one that will suffice for a career of learning.
2. Develop the habits required for continuous learning.
3. Teach from the system perspective from the outset.

Table III. Academic Preparation versus Industry Environment

Academic Preparation	*Industry Environment*
Individual performance is tested	Team performance is essential
Problems have correct answers	Problems have solutions
Projects have short time lines	Projects can take years
Constant performance feedback	Feedback is much less frequent
Courses are independent	Problems require integration
Failure is painful	Failure happens
Statistics are not routine	Statistics are essential

4. Encourage flexibility in thinking about alternative solutions to problems. Perhaps it might be possible to develop a set of open-ended problems, much like the case-study approach used so effectively by business schools.
5. Provide experience and training to develop group work skills. This is happening in grades K–12 where it is known as cooperative learning.
6. Finally, teach and require the use of statistics.

A focus on materials chemistry will lead to more system-oriented thinking and integration. It should be possible to build curricula in a way that encourages the development of the people skills needed in the industrial environment.

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Funding Opportunities for Materials Science Education

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SUPPORT FOR THE DEVELOPMENT AND IMPLEMENTATION of new courses and laboratories in materials science is available through National Science Foundation programs in both the Division of Undergraduate Education and the Division of Materials Research. The Division of Undergraduate Education has separate programs targeting laboratory, curriculum, and faculty.

The Instrumentation and Laboratory Improvement (ILI) Program aids in the purchase of laboratory equipment for use in undergraduate laboratories at all levels. Annual funding has been $23 million for the past 5 years and is anticipated to remain at this level for the near future. Typically, 2300 proposals are received, resulting in approximately 600 awards per year. ILI has two components: The major one accepts proposals for equipment only; the other, known as Leadership in Laboratory Development, seeks to support the development of exemplary national models for laboratory curricula by providing funds for personnel and supplies as well as for equipment. Five percent of the ILI budget is devoted to Leadership projects, and preliminary proposals are required. A 50% institutional match for equipment costs is necessary for all ILI proposals. The maximum allowable request from NSF is $100,000. In the 1992 competition, 60 proposals to initiate or improve materials science laboratories were received; 15 were from departments of chemistry, the remainder from engineering units.

The Undergraduate Course and Curriculum (UCC) Program focuses on the development of introductory courses for both science and nonscience majors. Eligible activities include the production of textbooks, lecture modules, software, and other media materials and the pursuit of alternate teaching strategies. The program is funded at $18 million for fiscal year 1992. Typical awards are for 2 years with annual budgets in the range of $75,000–$150,000. Two materials science projects supported by UCC are (1) "Development of a Materials-Oriented General Chemistry Course," under the direction of A. B. Ellis; and (2) "Development of Instructional Materials in Polymer Chemistry for General and Organic

Chemistry Courses," under the direction of J. P. Droske. These projects are described elsewhere in this chapter.

Short courses and workshops for college faculty primarily engaged in undergraduate instruction are supported under the Undergraduate Faculty Enhancement (UFE) Program. The purpose of the program is to ensure the vitality of the teaching faculty by assisting them in learning new ideas and techniques in their fields and using the knowledge gained to improve undergraduate instruction. Several short courses devoted to the study of polymers have been sponsored by the program during the past several years. Proposals for the development of more broadly based materials science workshops suitable for chemistry faculty are encouraged.

The Division of Materials Research launched the Undergraduate Materials Education Initiative during the spring of 1992 with a closing date of May 15. The goal of the Initiative is the development of advanced undergraduate courses, including laboratories, in materials synthesis and processing. The courses should focus on fundamental principles, modeling and simulation, characterization, and property evaluation. Subject to the availability of funds, the Foundation expects to make 7–11 3-year awards with annual budgets of $150,000.

Chemistry of Materials Courses at Rensselaer Polytechnic Institute

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FRESHMAN CHEMISTRY is arguably an important course, one that needs to be viewed as a contribution beyond a "service" level. It affords the opportunity to make the case, to many students of varied disciplines, of why chemistry is the central science and is responsible for virtually all of the high-tech developments they encounter or read about. The course should be a vehicle to attract more students to chemistry. More importantly, it should instill greater respect for and appreciation of chemistry by students who will not necessarily specialize in it. In our view, this function is particularly important for engineering students, as they will frequently use the basic ideas in freshman chemistry in their professional lives, yet they often wonder where the connection is while they are exposed to these ideas in the classroom.

To make the connection between chemistry and engineering more immediate, we have developed, with support from Rensselaer's administration, the General Electric Foundation, and NSF, a two-semester freshman course that emphasizes solid-state chemistry and materials science and that is now taken by all of our engineering freshmen. The course is cotaught by faculty from the chemistry and materials engineering departments, and is in the truest sense a cooperative venture. Here we briefly summarize our motivations for moving in this direction and outline the course as it is now constituted.

The Shift toward Materials Chemistry

Chemistry and materials science are inextricably linked. In fact, in the National Research Council's "Opportunities in Chemistry," familiarly known as the Pimentel Report (*1*), can be found the following definitions from Webster: A material is "the substance or substances out of which a thing is constructed," and chemistry is "the science that deals with the composition, properties, and changes of properties of substances." However, a common perception is that chemistry is concerned primarily with microscopic phenomena. Nowhere is this attitude more evident than in a freshman chemistry textbook. Occasional chapters on the solid state can be found, but these typically dwell on atomic packing. Virtually no mention is made of material properties such as modulus, electrical conductivity, and transparency, and how these are dictated by atomic and molecular composition and structure. If solids are discussed, imperfections such as point and line defects are almost never mentioned, and yet these dictate, for example, mechanical properties.

This approach is unfortunate, as it has been pointed out quite clearly that tremendous opportunities exist for chemists to participate in the exciting area of materials science. For example, in the Pimentel Report, materials chemistry played a prominent role, and the interdisciplinary nature of materials chemistry was stressed. It was stated that "chemists are increasingly joining and expanding the specialist communities concerned with glasses, ceramics, polymers, alloys, and refractory materials." Furthermore, the report predicted that "coming years will see entirely new structural materials, liquids with orientational regularity, self-organizing solids, organic and ionic conductors, acentric and refractory materials." A companion report, "Frontiers in Chemical Engineering" (*2*), expressed similar opportunities in the materials area for chemical engineers.

The fact that more and more chemical research activity is indeed being directed toward the materials area was responsible for the American Chemical Society's launching of a new journal, *Chemistry of Materials*, in 1989. Mary Good, former ACS President, edited a book published by the American Chemical Society that directly addresses the point, *Biotechnology and Materials Science: Chemistry for the Future* (*3*). To meet these challenges, changes in chemical education may be needed "to keep chemists in the center of revolutions in materials and biological sciences" (*4*). Changes are also necessary to thwart the decline of interest in science by prospective students and, more broadly, by the public at large. What is being done to respond to this particularly serious need has been nicely summarized in a *Chemical and Engineering News* article (*5*).

Perhaps the most compelling argument for at least considering a shift toward a more macroscopic focus in freshman chemistry comes from engineering faculty. At a number of institutions, engineering faculty have complained that introductory chemistry is not terribly relevant to the needs of their undergraduates. What they mean (in part) is that their students are not learning enough about the solid state and, hence, about materials. For example, many electrical engineering faculty believe that students should be exposed to semiconductors and how simple devices can be constructed from them. Another way of saying it is that freshman chemistry is not applied enough for engineering needs. But is it not, after all, the application of chemistry that fascinates chemists?

The reluctance of chemistry faculty to respond to these needs has led to the initiation of alternative chemistry courses taught by engineering faculty. For example, for the past approximately 15 years, freshmen at the Massachusetts Institute of Technology (MIT) may elect to take their one-semester requirement in chemistry in the form of Introduction to Solid-State Chemistry. This course is taught exclusively by the Materials Science and Engineering Department. Roughly one-half of the freshman class takes this course instead of the Chemistry Department's offering. Northeastern University now teaches a second-semester freshman course emphasizing materials chemistry for honors students. At the University of Pennsylvania and the University of Arizona, freshmen engineering majors can take their second-semester chemistry course in solid-state chemistry, again taught by materials science and engineering faculty. Most likely many more such programs are in progress or in the planning stages.

Should this shift toward materials chemistry be taken seriously? Yes, because materials topics bring vitality to freshman chemistry, which should be fascinating but many times has fallen short of this goal.

An Approach to the Microscopic–Macroscopic Merger

We strongly believe in a hierarchical approach that begins with the structure of the atom and continues to molecules and then collections of atoms or molecules into various superstructures (i.e., condensed phases). This idea is not new, as such an approach can be found in the first few chapters of Pauling's classic introductory text (*6*). The fundamentals of thermodynamics, kinetics, and the solid state are discussed next to prepare students for the remainder of the course. Students learn, for example, in detail why metals are electrical conductors and malleable, whereas most ceramics are insulators and are brittle. They also learn why structural metals are not as strong as one might predict on the basis of an ideal (perfect) crystal lattice, and how it is possible for solid-state chemical reactions to alter the strength of an alloy. We then move onto ideal and real (i.e., defect-containing) solids, phase diagrams, kinetic processes in solids (e.g., diffusion and sintering), and a discussion of the materials classes, and conclude the course with a few case studies that underscore most of the course material. Two examples include the fabrication of semiconductor devices and the synthesis of diamonds. The response of previous students has in general been supportive of this approach (*7*).

No single textbook is adequate, but we have had success using a first-year chemistry text along with a materials science text, although more recently we are placing heavy emphasis on lecture notes that we have written. Concerning operation, students now meet for two lectures per week, two 1-hour recitations, and a 3-hour lab every other week. Many traditional experiments can be readily employed, but the course content also calls for new experiments. Several experiments that have been developed are relevant to the lecture material and can be performed with the large throughput of students in a freshman course. Examples include the growth of a metal–semiconductor junction and its electrical properties, absorption spectroscopy of transition metal ions in glasses, and construction of a phase diagram. Each is intended to provide a conceptual link between a macroscopic property and its atomic–molecular level origin.

Long-range goals include the development of a textbook along with a laboratory manual, modification of lecture notes, demonstrations, and experiments for use in high school science courses. The latter goal is particularly important to us in view of the declining interest of students in science. Students frequently find high school chemistry (and other science courses) to be too abstract; in short, they are demanding more immediate relevance to the real world. Perhaps a dose of a microscopic–macroscopic merger can meet this demand.

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New Curricular Materials for Introducing Polymer Topics in Introductory Chemistry Courses

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INFAMOUS QUOTES that are purported to be advice that was given to H. Staudinger in 1925 told him to "Leave the concept of large molecules well alone," and "There can be no such thing as a macromolecule" (*1*). Today we know that much of our world is made of macromolecules and that they are an integral part of today's science. Whoever gave the advice to Staudinger probably is glad that the quotes are anonymous. It is unlikely that anyone would feel slighted by not having it attributed to them. Even though the existence of macromolecules is well-established today, macromolecules have been largely ignored in the chemistry curriculum. Fortunately, this situation is changing, but the first part of this quote has been all too true of the treatment that polymers received, until recently, in the chemistry curriculum.

Another oft-quoted line is the advice given to Dustin Hoffman in the movie, "The Graduate". He had just graduated from college, and a friend of his parents gave him this advice: "I want to say one word to you, just one word: plastics" (*2*). This remains good advice today, yet, like Dustin Hoffman, most of our undergraduates still do not hear about polymers until after they graduate.

Action by ACS Divisions

Recognizing that insufficient attention was being given to polymer topics in the chemistry curriculum, the ACS Division of Polymer Chemistry (POLY) formed the Polymer Education Committee in 1972. Shortly thereafter they were joined in this effort by the ACS Division of Organic Coatings and Plastics (now known as the Division of Polymeric Materials: Science and Engineering or PMSE), and the committee was called JPEC, the Joint Polymer Education Committee. Over the years, the Polymer Education Committee was very active and instituted a variety of programs targeted toward including polymers in the chemistry curriculum. In 1989, recognizing that there continued to be a need for pro-active efforts in polymer education, the two divisions (POLY and PMSE) renewed their commitment to polymer education. To reflect this renewal in both financial as well as human resources, the committee was renamed POLYED.

Today, POLYED has more than 50 active members serving four Directorates: Pre-College Faculty, College and University Students, College and University Faculty, and Government and Industrial Professionals. Each of these Directorates offers polymer education programs for these groups. Within the Pre-College Directorate, POLYED sponsors an annual Excellence in Polymer Education Award which is given to an outstanding high school teacher. These awards typically are presented at national ACS meetings, which often feature symposia for teachers that are organized by POLYED.

The College and University Students Directorate offers several awards programs, including an award for outstanding performance in undergraduate organic chemistry courses, an award for excellence in undergraduate research, summer research scholarships, and awards to graduate students such as the Sherwin–Williams Award and the Unilever Award.

The College and University Faculty Directorate has been offering hands-on polymer chemistry demonstrations and experiments workshops for faculty for nearly a decade. In addition to this active program, the Directorate also oversees the Curriculum Development Award as well as the Textbook Author Program. Both of these programs are targeted toward increasing the availability of curricular materials in the polymer area.

The Government and Industrial Professionals Directorate is expanding its activities and recently published a Short Course Catalog listing institutions that offer short courses in the polymer area. This Directorate also is working closely with the new ACS Division of Chemical Technicians.

Because of the wide variety of POLYED programs, in 1989 the POLYED National Information Center for Polymer Education was established at the University of Wisconsin—Stevens Point. The purpose of the Center was to serve as a clearinghouse for POLYED programs and, in particular, to provide a single site that interested individuals could contact to obtain information about POLYED programs. Since its inception, about 800 faculty have contacted the Center for information regarding the inclusion of polymers in their courses. Letters to the Center from college and university faculty show that schools are developing new courses in the polymer area and that there is considerable interest in including polymer topics in existing courses. However, these communications also frequently cite limitations in realizing these goals, such as administrative constraints on the number of new courses that can be offered, an already very heavy course load for students, insufficient room in existing courses for introducing new material, as well as faculty concerns about their limited familiarity with polymers and the time involved in "getting up to speed" in this area.

Scholar Program To Develop Lectures

These concerns led to a grant proposal to the National Science Foundation from the POLYED Center entitled, "Incorporating Polymeric Materials Topics into the Undergraduate Chemistry Core Curriculum." The purpose of this grant was to address the need for new curricular materials in the polymer area that were ready to use and that provided the necessary background information for faculty. With primarily NSF support as well as some matching funds from POLYED, the Center named a team of five NSF–POLYED Scholars. The Scholars were college and university faculty, from assistant to full professors, with a range of experience in the polymer area. Some of the Scholars had considerable prior experience with polymers, and others were relatively new to the field. All of the Scholars had experience in the development of curricular materials for college chemistry courses.

Implementation of the program began in the spring of 1992 with each of the Scholars reviewing the University of Massachusetts video course, "Introduction to Polymer Chemistry." In May, the five NSF–POLYED Scholars (Guy Mattson from University of Central Florida, Ann Nalley from Cameron University (OK), Karen Quaal from Siena College (NY), Chang-Ning Wu from the University of Massachusetts—Dartmouth, and Joe Young from Chicago State University) met in Stevens Point, WI with their host–mentors: Lon Mathias from the University of Southern Mississippi, Gary Wnek from Rensselaer Polytechnic Institute, and me. During this meeting, the Scholars and host–mentors set goals for their 4-week summer residencies to be held at the three host institutions.

The Scholars, working with their mentors, did an outstanding job during their residencies, and many laboratory experiments and new "lecture snapshots" were developed. Lecture snapshots are short discussions of timely or fundamental polymer topics. They are designed to minimize the time necessary for faculty to familiarize themselves with the topic and to prepare their presentation on it. In general, the lecture snapshots require only a few minutes of lecture time and setup and interface with topics that already are covered in general chemistry courses. The snapshot format is as follows:

- title
- keywords
- context

- brief description
- packet contents
  - — transparency masters
  - — demonstration(s)
  - — sample questions, problems, and solutions
  - — related experiments
- approximate lecture time, with and without demonstrations
- background
- transparency masters
- demonstration(s), with details
- related topics and suggested extensions
- references

The following lecture snapshots were prepared:

- molecular weights of polymers
- solutions of macromolecules
- physical properties of matter
- small molecules vs. large molecules
- thermal properties of polymers
- rubber-like elasticity and entropy
- effects of temperature on vinyl polymerization
- calculation of degree of polymerization
- silicon, silicates, silicones
- adhesives
- common polymeric materials
- transdermal drug delivery
- chitosan, a natural polymer
- composites, manufactured and natural

In addition to the lecture snapshots, a variety of experiments suitable for general chemistry lab classes were developed:

- microscale bulk polymerization of styrene
- dependence of film quality on molecular weight of polystyrene
- recycling by selective dissolution
- determination of molecular weight by thin-layer chromatography (with recycling of plates)
- molecular weight determination of polyethylene glycol by titration
- film casting
- molecular weight determination of a urethane prepolymer by titration
- preparation of a synthetic metal
- a kinetics experiment on the effect of temperature on the curing of an epoxy resin
- water-proofing filter paper with a silicone polymer

- PCMODEL, molecular structures laboratory exercise
- separation of metal ions using a natural biopolymer, chitosan
- preparation of nylon 11, fiber drawing, and tensile properties
- thermal properties of polymers

The experiments were tested by student assistants at the University of Wisconsin—Stevens Point with good success. Most of the experiments do not require any special equipment beyond that found in a typical general chemistry lab.

The next phase of this effort will involve three steps:

1. review of the snapshots and experiments by an expert advisory panel, comprising 14 leading polymer scientists and educators
2. editing of the manuscripts
3. field testing

The new curricular materials probably will be disseminated by publication in the *Journal of Chemical Education* and by distribution from the POLYED Center at the University of Wisconsin—Stevens Point.

We hope that these new curricular materials will not only facilitate the introduction of polymer topics into introductory chemistry courses but, in conjunction with other general chemistry curricular efforts, will also serve as a catalyst for revitalization of our introductory chemistry curriculum.

Acknowledgments

The fine efforts of many individuals, especially the NSF–POLYED Scholars and their host–mentors, have contributed to making this endeavor a success. They are greatly appreciated. Also, the financial support of the National Science Foundation (Grant Nos. 91–50497 and 92–54351) and POLYED is gratefully acknowledged.

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General Chemistry as a Curriculum Pressure Point: Development of *Teaching General Chemistry: A Materials Science Companion*

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IN 1989, A PANEL CONVENED BY THE NATIONAL SCIENCE FOUNDATION examined introductory college chemistry courses and concluded that "the historic bias of chemistry curricula toward small-molecule chemistry, generally in the gaseous and liquid states, is out of touch with current opportunities for chemists in research, education, and technology" (*1*). Moreover, the report noted that "the attractiveness of chemistry and physics for undergraduate majors could be enhanced by greater emphasis on materials-related topics which would help students better relate their studies to the real world."

A Materials Chemistry Resource Book for Teachers

Shortly thereafter, the NSF solicited proposals for projects that would bring about comprehensive curriculum reform in introductory chemistry courses. During this period, a group of about a dozen chemistry researchers and teachers, many of whom were working in various areas of modern solid-state research, had organized themselves into what was subsequently called the Ad Hoc Committee for Solid-State Instructional Materials (SSIM). With funding from the American Chemical Society's Society Committee on Education (SOCED), the group met for the first time at an ACS National Meeting in the spring of 1990. As a result of the meeting, the Ad Hoc Committee decided to submit a proposal in response to the NSF solicitation. The thrust of the proposal would be to help revitalize introductory chemistry courses by providing examples from materials chemistry that would illustrate basic chemical concepts. Pooling the committee's collective expertise led the group to conclude that, in fact, essentially all of the concepts typically covered in introductory chemistry courses could be illustrated with solids, be they polymers, ceramics, semiconductors, superconductors, or biocompatible materials, to list a few examples.

In many respects, the NSF solicitation for projects affecting introductory chemistry courses provides an ideal strategy for effecting broad curricular change: pre-college chemistry courses have traditionally reflected the content of the freshmen chemistry course, and upper-level collegiate courses use this course as a foundation. Thus, the introductory collegiate chemistry course can sensibly be regarded as a curriculum "pressure point" because it influences the entire curricular content.

Moreover, the introductory chemistry course, along with introductory calculus, serves as a foundation course to technical careers. Unpleasant experiences in these courses or poor performance in them often results in the loss of these students from the future technical labor-force pipeline. Enhancing the appeal of these courses is a viable strategy for kindling interest in technical careers across the spectrum of student "customers". For the many students who will not pursue technical careers, a materials-oriented chemistry course can provide a sense of relevance by connecting chemistry to advanced materials and devices that we increasingly encounter in everyday life.

Both the NSF and the Camille and Henry Dreyfus Foundation provided funding for the project proposed by the Ad Hoc Committee. The committee recognized that several problems had to be overcome if materials chemistry were to be mainstreamed into the chemistry curriculum. First was the recognition that most college teachers of general chemistry have been trained as molecular chemists. Much of the language of solid-state chemistry is unfamiliar to this teaching community, coming as it does from other disciplines, including physics, engineering, and materials science. The jargon associated with solids thus needs to be translated. Second, solids typically involve extended three-dimensional structures that can be hard to visualize for students and teachers. These structures need to be made comprehensible. Finally, even if these problems can be solved, a critical question is how to convince teachers to try the new materials!

A multifaceted strategy was developed to overcome these obstacles. Rather than writing a textbook on materials chemistry suitable for introductory chemistry courses, the committee determined that a resource volume was needed. Entitled *Teaching General Chemistry: A Materials Science Companion*, this volume was written for teachers and presents solid-state examples to complement the molecular examples typically given in introductory chemistry courses. The Companion covers topics paralleling those in traditional chemistry texts, facilitating incorporation of the materials in "traditional" chemistry courses. At the same time, a matrix connecting materials and devices with core concepts is provided to serve as a guide for use of the materials in unconventional course treatments. For example, light-emitting diodes could be used to illustrate spectroscopy, substitutional stoichiometry, bonding, and periodic properties.

The objective of the Companion, published by the ACS in 1993, is to empower teachers by providing them with exciting examples from materials chemistry that students can see, hear, and touch, firmly grounding the introductory course in concrete examples. Moreover, these examples can illustrate the key role chemistry plays in developing high-tech materials and advanced devices. The philosophy of the committee is to make it possible to obtain a balance in the introductory course between molecular and solid-state examples. By using both to illustrate concepts, teachers can also demonstrate the universality of scientific thinking.

Other Instructional Materials

The committee recognized that supporting instructional materials for the Companion would be needed. The Institute for Chemical Education (ICE), a NSF-funded entity whose mission is the enhancement of chemical education, is serving as the distribution arm for supporting instructional materials. The first product is an Optical Transform Kit that shows how diffraction is used to determine relative atomic positions. The kit essentially scales up the X-ray diffraction experiment by use of a small laser as a visible light source and 35-mm slides bearing photographically reduced, laser-written patterns that mimic atomic packing arrangements (*2*). (For ordering information, contact ICE, Department of Chemistry, University of Wisconsin, Madison, Madison, WI 53706.)

A second product is the ICE Solid-State Model Kit, developed by L. A. Mayer and G. C. Lisensky, which makes it possible to build extended three-dimensional structures: Using a base with holes, templates for some 60 different structures, rods, and four sizes of spheres in radius ratios, common crystal structures can be assembled in a matter of minutes (*3*). Furthermore, many structures can be assembled from different perspectives by teams of students: For example, the cubic NaCl unit cell can be assembled with its orientation on the face of the cube or on the body diagonal. Natural cleavage planes can be found with the kit: Lifting one sphere will separate atomic planes from one another. (Contact ICE for ordering information.)

Suppliers for other products are collected in the Companion. An example of a "smart" material that is rapidly gaining popularity among teachers is "memory metal," a NiTi alloy. This solid has several remarkable features derived from a martensitic phase change. Thin wires of NiTi are easily bent. After bending, the wire can be gently heated to restore the initial linear shape. Heating to higher temperature in a candle flame permits the wire to be "re-trained" to remember a new shape. Rods of the alloy, also commercially available, have strikingly different mechanical and acoustical properties in the two phases: the high-temperature phase is rigid and "rings" when dropped; the low-temperature phase is more flexible and "thuds" when dropped. (Samples of memory metal are available from ICE, which can be contacted for ordering information; or from Shape Memory Applications, Inc., 1034 W. Maude Avenue, Suite 603, Sunnyvale, CA 94086.)

As noted, light-emitting diodes can be used to illustrate a variety of basic chemical concepts. Substitutional solid solutions like $GaAs_xP_{1-x}$ ($0 < x < 1$) effectively extend the periodic table by providing a tunable band gap, which translates to tunability in the color of emitted light (*4*).

Re-entrant foam provides a counter-intuitive demonstration of processing (*5*). Polyurethane can be isotropically compressed in a mold and heated to about 170 °C. The microstructure of the resulting solid yields a material that bulges in cross section when stretched! More information on polymers will be available from John Droske's complementary NSF-funded project (described in the preceding section).

Even given this new and user-friendly package of instructional materials represented by the Companion, the critical question is still how to get teachers to try it—how to have them "buy in". Several strategies are proving to be effective methods for acquainting the academic community with this project. First, the broad constitution of the committee itself has provided substantial visibility for the project; as new interested participants were identified, the committee's membership grew to its present size of about two dozen, comprising individuals with a broad range of research and teaching expertise. Second, field testing has provided a sense of ownership of the project for participating institutions. The structural model kit, for example, was tested at some dozen colleges and universities. User comments not only provided valuable feedback, leading to improved kit design, but made faculty at the institutions aware of and willing to try the kit.

A particularly effective way to identify potential users of these materials has been through presentations at professional meetings and informal networking. Individuals have volunteered to field-test the materials at a variety of institutions across the country that will expose some 5% of all students taking introductory chemistry courses to the material this year. Moreover, colleagues in other disciplines—physics, engineering, geology, and biology—have also expressed interest in and begun to use materials from the project that are of particular interest to them.

In short, momentum for the project has been established. Publication of the Companion by the ACS represents a key step in making this material an integral part of the curriculum. The ACS will encourage use of the instructional packet not only by teachers, the primary targeted audience, but also by textbook authors and publishers. Incorporation of materials chemistry throughout introductory chemistry texts will be a certain sign that the discipline has entered the mainstream. As one of our committee members noted at the outset of this project, if 10% of all of the examples used in introductory chemistry courses are solids, this project will have accomplished a lot. It remains to be seen whether the project will achieve this goal, but we believe that the infrastructure is now in place to make it possible.

Acknowledgments

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How Scientists and Engineers Can Enhance Science Education in Grades K–12

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MATH AND SCIENCE EDUCATION IS A CRITICAL ISSUE. Scientists and engineers are learning that the technical community can make a real difference.

We at Sandia have always had educational outreach programs. Until several years ago, these programs were relatively small. Then Admiral Watkins issued a Department of Energy (DOE) directive: "We must expand our involvement in science education to inspire the youth of America to either enter, or feel more comfortable in, the fields of math, science, and engineering. With our labs and facilities, we are uniquely well positioned to provide major assistance in strengthening science and engineering motivation and education, making it come alive for the main body of students who too often fear these disciplines or who cannot relate to them. I intend to lead this effort personally." (*1*)

School Partnership Program

This proclamation encouraged the national laboratories and DOE facilities to become more heavily involved in pre-college education. On the basis of my experience working with youth groups, I was asked by management to initiate our expanded effort of science and math education enrichment. I first gathered together a small group of our technical staff who had experiences similar to mine and who were experienced in working with kids through activities such as youth work, coaching, or scouting. We asked ourselves the following questions: What are the problems, and how can we affect them? We decided that our goal should be to inspire increased student interest in math and science. This decision was based on our belief that two keys to learning are positive impressions and excitement—if you get kids interested and excited, then learning will happen.

A strong point of our School Partnership Program is that it does not consist solely of exciting programs that we imposed on the schools. Instead, we teamed with teachers and emphasized that we wanted to fit in with their curriculum. We asked them, "What science topics will you be covering, and what types of activities might we do to get kids excited about them?" We learned through our discussions and experiences that there is a big difference between the needs in elementary and high schools. Elementary school teachers frequently had very little background in science, and as a result, often avoided science instruction. However, they recognized their shortcomings in this area, and were eager for any kind of help we could give. High school teachers, on the other hand, were well versed in science content, but had more need for activities that demonstrated real-world applications of particular topics. Middle school teachers were highly varied; some had elementary school and others high school credentials. Key to our success was that, in all cases, we designed our activities around the curriculum and the expressed needs of the teacher.

Albuquerque Public Schools picked three pilot schools for implementation. They had a good ethnic mix and were below the 50th percentile in socioeconomic level. My assignment was in a middle school with the highest turnover rate in the city. I contacted the middle school teacher for physical science classes and said, "I'm from the government and I'm here to help you." Initially she was not enthusiastic. After explaining to her that I wanted to know about her curriculum and intended to develop some exciting activities to go along with her topics, she reluctantly agreed that I could try an activity on Newton's law—force and acceleration.

As I thought about developing a demonstration, I remembered that Sandia had been involved in the design of nuclear waste shipping containers and had some videotapes of dramatic crash tests, such as tractor trailers running into concrete bridge abutments. Knowing that middle school kids are fascinated by destruction, but would be bored by a 45-minute videotape, I knew I had to incorporate some additional activities that engaged the students in fun and exciting ways. We accomplished this goal by wrapping the kids up in bubble wrap, outfitting them with helmets, and then putting them on skateboards and letting them run into the wall. This got their attention!

Discussions afterwards focused on how the levels of pain would vary, how the force would change, and how the suddenness of the change in speed would vary with the number of layers of bubble wrap. Out of this directed discussion we developed and discussed the formula $F = ma$ (force equals mass times acceleration), and then used it to do a simplistic calculation of what the force would be on a skier running into a tree. We then viewed the most dramatic 10 minutes of the video of the crash tests of nuclear waste shipping casks. Afterward, I explained that each test cost hundreds of thousands of dollars, but that using Newton's law we were able to calculate the forces and damage that would occur in each crash. After doing a few tests to make sure our calculations were correct, we were then able to do many subsequent "crashes" on the computer. These are the elements of a good in-class activity. I first got them excited and actively involved, helped them develop the key principle in their own minds, applied it to a situation that they could relate to, and finally, showed them a concrete real-world application. I was invited back!

Out of experiences like this, we developed continuing relationships with the teachers and students at our pilot schools. We conducted in-class activities to complement major curriculum topics every 3 weeks or so. In addition, we assisted in other ways, such as helping elementary school teachers understand science content and working with science fairs.

We evaluated our effectiveness through a questionnaire designed to assess attitudes toward science. We administered this questionnaire to the students prior to any of our activities and again following one semester of activities. The "before" results were consistent with previous studies, indicating that substantial declines in attitude occur between grades 3 and 7. The "after" results showed substantial improvements in attitudes toward science following our semester's activities with them. In addition, more than 95% of the students at every elementary and middle school grade level said they would like us to continue and expand our program next year.

When we considered how to expand this program, we decided that we could have an impact on a much larger number of schools by concentrating on teacher support, rather than direct interaction with students. This approach also broadened the range of potential Sandia participants, as most of our staff are more adept at communicating with adults than interacting motivationally with students. Prior to the first year of this Science Advisors Program, we wrote letters to all elementary and middle schools in Albuquerque and offered to assign a technical employee to work with their teachers 1 day a week doing whatever they thought would be helpful. About 80% responded positively; in the second year the others also joined.

We prepared our "science advisors" with training on how to interact effectively with teachers and students, and we developed an Education Resource Center where they could borrow both activity plans and equipment to help their teachers do interesting hands-on science activities in their classes. This resource center was stocked both with commercial educational materials, as well as selected surplus equipment. Computers turned out to be particularly popular items—we now loan out on an annual basis about 200 computers that are outmoded for our technical purposes, but that the schools are delighted to have. At the request of teachers, our science advisors have ended up doing many of the same things as the School Partnership participants. About 50% of them do at least some activities directly with students. Others provide help in understanding science content, coordinate access to the resource center, assist with science fairs, and provide support for teachers in a variety of other ways.

In addition to the School Partnership and Science Advisor programs, we also sponsor efforts in which women's and minority outreach groups provide mentoring and science enrichment activities with students who have been historically underrepresented in the technical community. High school students receive tutoring from our staff, and high school students can be mentored through part-time or summer employment experiences. One of the reasons so many of our employees are involved is that we offer them this variety of options.

We are also involved in attempting to propagate programs in which technical professionals enhance grades K–12 science education in areas beyond Albuquerque. We have assigned science advisors to 80 public and Bureau of Indian Affairs schools in rural portions of New Mexico. In addition, we are helping other communities set up their own science advisor programs. Finally, we are working through technical professional societies to involve technical professionals in their local communities nationwide.

How Scientists Can Help Teachers

One of Sandia's primary contributions to the national effort involves helping technical professionals understand how to be effective. On the basis of our experiences, we have developed training materials that we are making available to technical professionals through the coordinated grades K–12 education programs of a large number of professional societies. Some of the key points made in these training materials are outlined in the following list.

- Adopt a productive attitude. Don't go into schools with an attitude that tells the teachers you think they're doing a bad job. The fact is that most of our schools and teachers are doing a terrific job with limited support and resources and in spite of a lot of societal baggage. Don't alienate the teachers—try to help them make a good thing even better.

- Do activities that complement and enhance the existing curriculum. Don't waste time with things that aren't curriculum-related. Teachers have goals and competency requirements imposed on them. If you help them meet these they will be appreciative. If not, you are failing to help them where they most need it. Remember, they are your customers.

- Make teachers' lives simpler, not more complex. Teachers are pulled in many different directions and are very busy. If you become a time and work saver for them, they will love you. If you become a time sink and another person competing for their attention, they are likely to resent you.

- Help integrate excitement and fun into science education. We should not mislead people to believe that science is nothing but excitement and fun, but neither should we start off with a hard-line diatribe about science requiring great personal sacrifice and self-discipline. Instead, begin by doing a fun activity that illustrates the scientific principle, such as the skateboard experiment. Then make the transition into topics activities that require greater concentration. Once interest is aroused, concentration becomes more achievable.

- Promote hands-on, discovery-based activities. Kids learn by doing! And hands-on activities that let kids discover things for themselves are the best of all. Kids forget most of the things their teachers tell them, but when adults lead kids in experiences where they wrestle with an interesting personal observation and then figure it out "by themselves", kids remember those things forever.

- Help integrate principles and applications. Our traditional educational paradigm says, "First you learn the principles and theory, then you learn what it's good for and how to apply it." That is boring! Very few of us are motivated to learn in this sequence. Applications are not only more interesting than theory, they also provide a concrete context through which we are better able to understand abstractions, particularly when we are first learning about a topic. I wish that when I was first learning differential calculus someone had helped me understand that the first derivative was velocity and the second derivative was acceleration. It not only would have given physical meaning to what seemed to me to be nothing but an abstraction, but it would have helped me understand why it was important to learn it. We need to help change the teaching paradigm to give much greater emphasis to applications.

- In working with students, do activities that are age-appropriate. This is second nature to most teachers, but we technical professionals violate this principle frequently. Scientists and engineers who work with the schools need to understand the basics of Piaget and the progression of the way kids learn. Most importantly, they need to know that essentially all elementary school students are concrete thinkers—they understand what they detect with their physical senses, but not abstract representations of reality, such as graphs and algebraic equations. Only in middle and high school do students begin to develop abstract thinking abilities. Even there, it is best to start with the concrete and move toward the abstract to the extent that the students remain engaged.

- Emphasize activities in which everyone can succeed. Don't do things that you think will be challenging and rewarding only to the top 20%.

The others will be discouraged and decide that science is just too hard for them.

- Plan in advance to eliminate sources of confusion and demotivation. Don't try to impress students or teachers with how much you know; that attitude results in intimidation and discouragement. Deal with topics to which students can relate. (Fifth graders are not engaged by integrated circuits, no matter how important and exciting we think they are.) Consciously scrub your language of technical jargon and acronyms. Remember that familiarity with technical content isn't all that is needed. To teach in a clear and compelling way takes careful planning.

- Take advantage of existing educational resources. Lots of outstanding hands-on activity plans are available. Take some time to learn about and become familiar with some of these. (I'll send you a listing and descriptions of some of the ones that we've found most useful if you request it.) Avoid the syndrome of reinventing all your activities from scratch; they probably won't be nearly as good as if you capitalized on the ideas and experiences of others. We hope that at some point in the future, a database will be available for searching existing materials by topic and age level.

- Emphasize scientific method and logic, not just science content. Science is not knowing all of the right answers. Science involves wondering what would happen if …, making guesses, doing experiments, figuring out what the results mean, and changing your mind when the experiment proves you wrong. These are the type of logical process skills that all citizens need to develop and employ. Helping promote such technical literacy is perhaps the most important challenge the scientific and engineering communities face. The alternative to a society that uses logical thinking to arrive at conclusions is one in which policies are set and resources are committed on the basis of who has the slickest advertising or the most emotionally heart-rending appeal.

- Be an encourager. Praise people when they get something right. Take advantage of opportunities to turn even incorrect answers and hypotheses into something positive. When people are encouraged to share and discuss their reasoning, they frequently uncover their incorrect assumption or logic flaw themselves—then you can praise them. And if they don't, use an experiment to help them discover where they are wrong. Remember, science is doing experiments and figuring things out, not knowing all the right answers.

- Build positive relationships and be fun to be with. Your best technical efforts probably won't be very effective unless you also build positive relationships. Learn the teachers' and students' names. Eat lunch with them. Get to know their hobbies and interests. Give them lots of positive feedback. Laugh with them. Convey with your time, attention, and attitudes that you like them and value them. Pretty soon they will start to like you, too. Then you will have won the important "right-to-be-heard."

- Maintain control when working with students but without stifling fun. It's best to have an agreement with the teacher that he or she will always be present and will take responsibility for any disciplinary problems. Discuss with the students your expectations, and expect them to behave responsibly. If criticism is needed, criticize the behavior rather than the person, and never embarrass kids in front of their peers.
- Finally, make a long-term commitment and follow through on it. Don't do a one-shot presentation with a school and then disappear; you'll never get beyond the steepest part of the learning curve or build the trusting relationships out of which the most important interactions occur. The beginning activities are usually the most difficult. Subsequent interactions become more relaxed and fruitful as relationships develop and your understanding of their real needs increases. Remember that improving the educational process is a marathon, not a sprint.

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