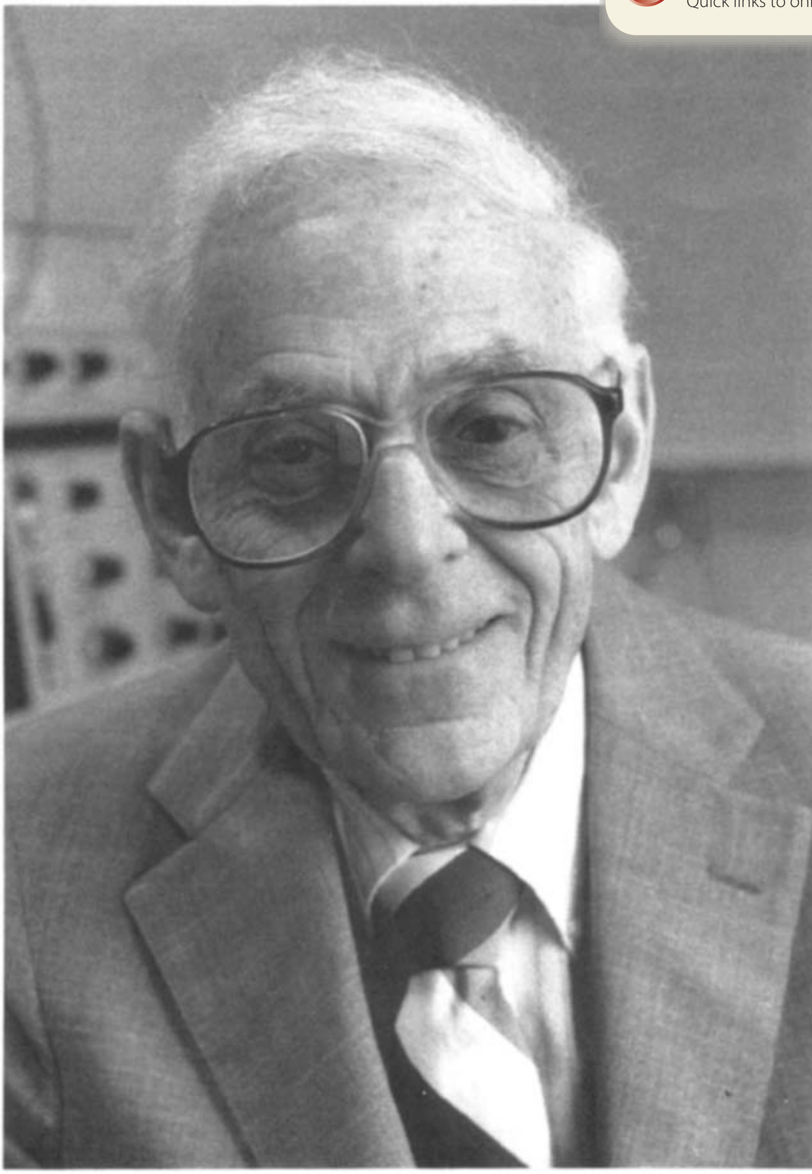

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MATERIALS SCIENCE AND ENGINEERING, AN EDUCATIONAL DISCIPLINE

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INTRODUCTION

"In this age of specialization, it is comforting to realize that basic typical concepts apply to a wide range of seemingly diverse problems. Progress made in understanding one area may often be applied in many other fields. This is true not only for various fields of materials science but for the structure of matter in general." Thus wrote Bardeen in the 1980 volume of the *Annual Review of Materials Science* (1). This has been the guiding principle for the teaching of materials science.

In the late 1940's and early 1950's one found separate departments of metallurgical engineering and ceramic engineering. Polymers were taught in chemistry and chemical engineering. Solid state physics was a well established branch of physics. Electronic materials was already of great interest and specific areas were taught in many departments. This was true of many other aspects of materials such as mechanical properties, corrosion resistance, and processing of materials. Important materials such as wood and concrete were mostly ignored except in civil engineering.

As it should, research, of necessity, often does not recognize boundaries between disciplines. In Arthur Von Hippel's laboratory for insulation research at MIT, electrical engineers, physicists, chemists, and ceramists worked together. The interdisciplinary research at the Bell Telephone

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Laboratories on semiconductors, which led to the development of the transistor, is perhaps the best known example (of course, John Bardeen was a key member of this team). Turnbull's chapter in the 1983 volume of the *Annual Review of Materials Science* (2) discusses the "emergence and evolution of 'Materials Science' as a research field."

The establishment of the Interdisciplinary Laboratories (IDLs) for materials research at a number of universities by the Advanced Research Projects Agency (ARPA) did much to push universities into educational programs in materials science. The early history of these laboratories is reviewed by Sproull in the 1987 volume of the *Annual Review of Materials Science* (3).

Two modes of education in materials science and engineering have emerged. In some schools, the full area is covered in one department, while in others, education in materials science is a multi-disciplinary program involving many departments. The University of Texas at Austin is an example of the latter. Northwestern University is an example of the former. Of course, teaching of limited areas of materials science and engineering takes place outside the jurisdiction of either program. The objective of this chapter is to describe and compare these two modes of education. There are many successful programs in materials science and engineering at other universities in this country, but our comparison will be mainly of the programs at the University of Texas at Austin and Northwestern University.

WHAT IS MATERIALS SCIENCE AND ENGINEERING?

Before describing and discussing educational programs, it is useful to explain what we mean by materials science and engineering. Turnbull (2) defined materials science as "the characterization, understanding, and control of the structure of matter at the 'ultramolecular' level and relating of this structure to properties (mechanical, magnetic, electrical, etc.)." Our definition includes a broader range of structural levels from macroscopic, such as in composites, to the atomic level, and it includes synthesis and processing. The continuum approach, which does not emphasize structure, has also been highly useful as a first approximation for many materials related problems and is included in our definition. Adding engineering to the field title brings in processing, design, and utilization of materials, but knowledge and control of structure remains central to the field. The relationship among performance, properties, structure/composition, and synthesis/processing can be visualized by the tetrahedron shown in Figure 1 (4).

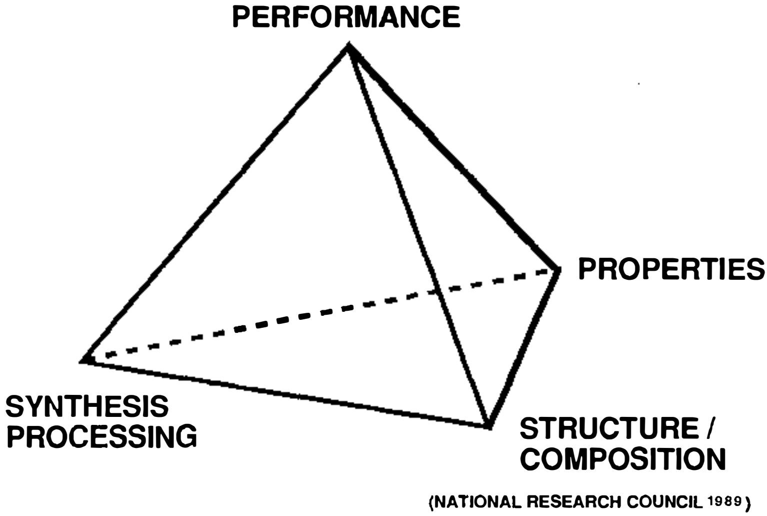

Figure 1 The materials science and engineering tetrahedron showing the four related elements of all materials (4).

IN THE BEGINNING

More than 2000 years ago Vitruvius (5) stated that "a machine is a continuous material system." He described a number of machines, and they were made of wood, rope, some steel, and occasionally bronze. Of course, stone was used for grinding. Interestingly Granger (5) pointed out that the Latin word *materia* has been translated as wood by other translators of Vitruvius's *The Ten Books on Architecture*. Since that time, a great many more materials are at the disposal of the design engineer and materials permeate all fields of engineering.

What were some of the factors and events that led to materials science or materials science and engineering becoming university departments or programs? Several streams led to this development. The kinds of materials courses that should be taught to engineering students in general were being debated ca 1950. The role of science in winning World War II, i.e. the atom bomb, radar, etc, and the role of science in the development of new technologies such as the transistor had a strong impact on engineering education. Engineering sciences were increased as a component of engineering education. In 1952, the American Society of Engineering Education appointed a Committee on Evaluation of Engineering Education. Linton E. Grinter was the chairman, and the report produced by the committee was commonly known as the Grinter report (6). It recommended 36 semester hours of engineering science in the engineering curriculum. Engineering materials as well as physical metallurgy were listed as engineering sciences. Some time earlier the concept of a unified materials course for all engineering students based on principles (rather than cataloging the properties of the different materials) began to take form. Daniel Rosenthal at UCLA was a pioneer in organizing and teaching such a course and Frankel's book *Principles of the Properties of Materials* (7) was an early text that grew out of the UCLA course. Frankel taught the course at Northwestern, where the book was written.

An important question was who should be given responsibility for teaching and developing unified materials courses with strong science underpinnings to replace largely descriptive courses. On many campuses this fell to the metallurgical engineering departments or programs, on others it fell to ceramists. Courses in metallurgy and ceramics already had strong scientific bases, and it was logical for suitable courses in ceramics or metals to be broadened to include all materials of interest to engineers. Wulff's course at MIT on materials for non-specialists is perhaps the best known example. This course developed over a ten-year period and culminated in publication of the four volumes of *Structure and Properties of Materials* in 1964 (8). At The University of Texas at Austin, a unified materials course had its origin in ceramics engineering. Joseph Weiss initiated the effort and Hugo Steinfink carried it forward.

We have already mentioned multidisciplinary materials research. Engineering teams designing new products or reaching for solutions to critical design problems to improve existing products need to consider all classes of pertinent materials. Thus metallurgists, ceramists, "polymerists," and other materials specialists were frequently required to broaden their materials perspective. Industry and government exerted pressures on universities to educate people with broader backgrounds in materials. Many advances in products as well as in energy production and defense systems were limited by the materials available, thus materials science and engineering could be considered an enabling discipline.

The strong push by United States government agencies on the universities to revise their offerings in materials is detailed in Sproull's chapter (3). The Atomic Energy Commission's Metallurgy and Materials Branch (Frederick Seitz was chairman) recommended new buildings and facilities at universities for materials research and education in its first report (1956). The office of Naval Research's Solid State Sciences Advisory Panel under the leadership of Seitz and Harvey Brooks also issued a report on opportunities in solid state sciences research after studying the Navy's materials problems. A study by the National Academy of Sciences, chaired by J. Herbert Holloman (who had assembled a materials department at the

General Electric Research Laboratory), recommended creation of a National Materials Laboratory. In September of 1959, these and other considerations led the Advanced Research Projects Agency of the Department of Defense to issue an invitation to all major universities in the United States to submit proposals for funding to establish interdisciplinary materials research laboratories (IDLs) with education of graduate students through a doctorate to be a major component. Many proposals were submitted because most universities were already discussing what they should do about materials. A few universities had already established educational programs in materials science. Northwestern University was one of these institutions.

While there werc cxternal forces, the emergence of materials science and engineering as an academic discipline was a logical pedagogical development. The scientific base and the experimental methods are largely common for all materials. It is more efficient to teach courses in solid state physics, thermodynamics, kinetics, molecular and crystalline structure, diffraction, microscopic examination, etc, generalized for all materials, than to teach separate courses for each class of materials. Of course, advanced courses are needed that deal with specific material types.

The forces that led to formation of materials science and enginecring as a discipline are summarized by the tetrahedron shown in Figure 2, where the four forces, industry, government, the general unified materials science course taught in most undergraduate engineering curricula, and the com-

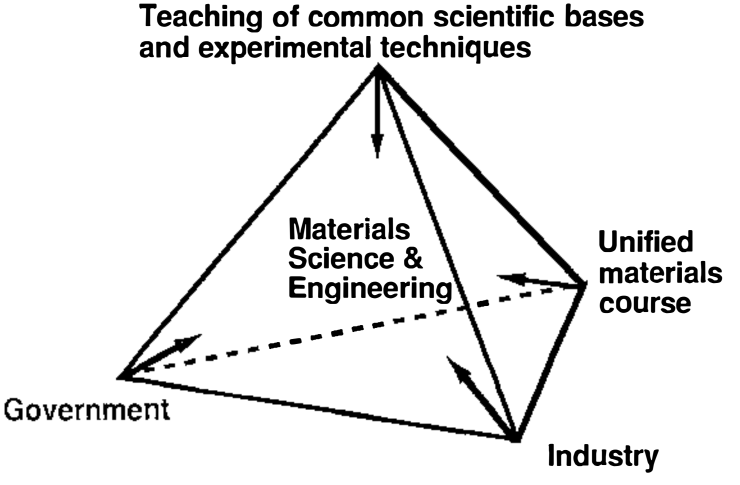

Figure 2 The four forces that led to materials science and engineering being established as a teaching discipline.

mon scientific bases and experimental techniques applicable to all materials, are at the corners. All are pointing toward materials science and engineering at the center of the tetrahedron, which acts as the unifying body to absorb these forces.

THE MATERIALS SCIENCE AND ENGINEERING DEPARTMENT AT NORTHWESTERN UNIVERSITY

In 1954 a Department of Metallurgy was formed at Northwestern under the leadership of Donald Whitmore, previously a member of the Chemical Engineering department. The original faculty, including one of the authors, had broader interests than metals. This was also the time that unified materials programs were being discussed in university, government, and industry circles. Based on discussions beginning in 1954, Northwestern's administration endorsed development of a Materials Science department instead of a Metallurgy department, and in January 1959 this change was approved by the University's Board of Trustees. Engineering was added to the title later to better recognize the character of the department that had been formed.

Northwestern's Materials Science and Engineering department identifies four areas of concentration: metals and ceramics, electronic materials, surface science, and polymers. Northwestern is on the quarter system and the students are required to take 48 courses for a bachelor's degree in Materials Science and Engineering. The students take Principles of the Properties of Materials and Applications of Thermodynamics as part of the basic engineering requirement. This is followed by the required courses: Science of Engineering Materials, Physical Properties of Polymers, Introductory Physics of Materials, Crystallography and Diffraction, Physical Properties of Polymers, and Mechanical Behavior of Solids. A variety of other courses in materials are taken as technical electives along with courses in other departments to form an area of concentration. Each student must also do a senior project under the direction of a faculty member. The projects vary from basic research to materials engineering. This is an ABET (Accreditation Board for Engineering and Technology) accredited curriculum that satisfies all of their criteria. Currently there are approximately 60 students in the undergraduate program.

On the Ph.D. graduate level, seven core courses are required. These are Chemical Thermodynamics of Materials, Symmetry and Physical Properties of Materials, Statistical Thermodynamics of Materials, Imperfections in Materials, Phase Transformations, Deformation and Fracture, and Physics of Solids. The student is assumed to have sufficient undergraduate preparation to take these graduate level courses. The core course program is a recent addition. Previously there were no required courses, but the student was required to take nine graduate level courses in the department. There are elective graduate level courses in all four areas of concentration as well as in electron microscopy, X-ray diffraction, phase transformations, stereology, physics of materials, and dislocations. A student majoring in one area of materials is required to satisfy a minor requirement, and this may be in another materials area or in another department. The student's examination committee consists of three faculty members in the department and one from another department or from outside the university. There are currently approximately 125 graduate students enrolled in the department.

Two opposing tendencies seem to have reached an equilibrium. One tendency is for each sub-area to develop separately and the second is to foster interaction between and among areas. The latter is assisted by the use of common facilities: one mechanical properties laboratory, one X-ray diffraction laboratory, one ceramics processing laboratory, three common electron microscope laboratories, and so forth. These laboratories are open to all properly trained members of the university community. A limited amount of service personnel time is available to assist those who are not trained in the use of the equipment. This is particularly useful for researchers who are not in the department. There is a charge for use of the equipment for research purposes, but not for teaching. The Materials Science and Engineering department and the Materials Research Center (a Materials Research Laboratory sponsored by the National Science Foundation, one of the first IDLs established by ARPA in 1959) share responsibility for the facilities. Some equipment is available for undergraduate teaching in a separate laboratory.

Teaching of the unified materials science service courses is rotated among faculty in all areas in the department. Because these courses are not team taught, faculty members whose field, for example, is primarily polymers must teach about ceramics, metals, electronic materials, and so on. The faculty members responsible for the central facilities in particular do research on several kinds of materials, and their courses relating to the facilities are aimed at covering all kinds of materials. This is true of the core graduate courses as well. The atmosphere in the department is conducive for students to freely consult with faculty other than their advisors and with other advisors' students as well. It is common for students to have joint advisors.

Of course, a good deal of teaching and research of materials occurs in other departments at Northwestern. Polymers is the joint responsibility of the Chemical Engineering and the Materials Science and Engineering departments, and all polymer specialist faculty members are joint appointments. There is also a joint appointment with the Civil Engineering department for a faculty member in the science of cementitious materials. A joint graduate program on electronic materials has been developed with the Electrical Engineering department. Condensed materials is also an important subject in Chemistry and Physics at Northwestern, and there is collaboration among faculty members in Materials Science and Engineering and these departments. Much of the collaboration is through the Materials Research Center. The Center's research is organized into thrust groups consisting of faculty members from several departments. The Center has no teaching responsibility and all members are full time members of departments.

All of the engineering departments, physics, chemistry, and the biological sciences are located in interconnected buildings at Northwestern. This is extremely helpful in fostering multi-departmental research and education, especially in the winter. While the Materials Science and Engineering department is coherent, with a unified educational program, materials as a whole at Northwestern has many characteristics of an interdepartmental program.

THE COLLEGE-WIDE INTERDISCIPLINARY MATERIALS SCIENCE AND ENGINEERING GRADUATE PROGRAM AT THE UNIVERSITY OF TEXAS AT AUSTIN

The primary task of any center for higher learning is the education of students in an environment conducive to the open exchange and dissemination of ideas and knowledge. Traditionally, the university has approached this task by assembling scholars with common foundations of expertise into a collective group, the department. However, there are liabilities to the departmental structure, since the natural tendency is to compartmentalize knowledge with concomitant academic provincialism. This mindset poses a particularly serious problem for a number of subject areas that are intrinsically interdisciplinary. Materials science and engineering is an example. The interdisciplinary graduate program provides a mechanism for accommodating these cross-disciplinary fields within the framework of an existing departmental structure. The interdisciplinary Materials Science and Engineering graduate program at the University of Texas at Austin is a relatively mature but still evolving example of such a program (9) and provides the student working toward an M.S. or Ph.D. degree with the opportunity to combine traditional fields of natural sciences and engineering to study the relationships between the structure and properties of materials.

After several years of informal interactions, the Materials Science and Engineering graduate program was formalized in 1972 under the leadership of Steinfink to allow for the interaction of the ten faculty members in the College of Engineering whose primary research interests were in materials science and engineering. Most of the faculty members were located on one floor of a building housing the Electrical Engineering department. The affiliated laboratories were also located there.

This program has the equivalent status within the university of all other graduate programs, whether departmentally based or interdisciplinary in nature. At the University of Texas at Austin all graduate programs are structured to report to the Vice-President for Research and Dean of Graduate Studies. All other academic responsibilities, including undergraduate programs and faculty appointments, are structured to report through the college deans to the Executive Vice-President and Provost.

The concept of a graduate materials science and engineering program has its most significant impact when the faculty size is subcritical in the subdisciplines, and only through a cooperative effort can an environment be made that is conducive to keeping a strong research program in the area. This was true at the start of the program. During the 1970's and early 1980's, the program was targeted as one of the critical areas in several departments and was consequently moved into two floors of a new building shared with the Mechanical Engineering department. The intent was to consolidate most of the materials science and engineering faculty members in the new facility. Shortly thereafter Materials Science and Engineering was defined as a major thrust area within the College of Engineering. The net result of this accelerated growth was to redisperse the faculty and laboratories associated with materials science and engineering away from a single facility. At this stage several of the sub-areas were critical in size, and the nature of the faculty affiliation with the program, which had reached the size of a large department, was modified. To support the increasing research effort, additional research space was constructed in a new building at the University of Texas Balcones Research Center located a few miles from the main campus. The long range effect of this move, which is taking place at the time of this writing, has yet to be determined.

The program now has 38 full-time faculty members predominantly located in four departments in the College of Engineering. The 90 students participating in the program earn their M.S. or Ph.D. degrees in Materials Science and Engineering. Approximately 150 additional students working with these same faculty members on materials science and engineering-oriented research are pursuing their graduate degrees in the home department of their faculty advisors.

There is no undergraduate degree offering at the University of Texas at

Austin in Materials Science and Engineering. The engineering departments have materials areas or options where the student can take up to four upper division courses as technical electives in addition to the required entry level materials course(s). All degrees are granted in ABET accredited curricula in the home departments of the student's major.

The graduate Materials Science and Engineering program has recently defined four required semester courses that also serve as the primary course material for the written qualifying examination required for admission to candidacy for the Ph.D. degree. These courses are Thermodynamics of Materials, Introduction to Phase Transformations, Mechanical Behavior of Materials, and a solid state course, either a traditional course in solid state, or one closely coupled with device physics. In addition there are a wide range of courses in each of the subdivisions of Materials Science and Engineering, as well as experimental technique courses such as electron microscopy, surface spectroscopy, and X-ray diffraction. All courses are listed with the offerings of the home department of the faculty member teaching the course. In comparing course requirements at the University of Texas at Austin and Northwestern, it should be noted that the former is on the semester system, while the latter divides the year into quarters.

In addition, the student must meet the Ph.D. requirements established by the graduate school plus those established by the student's committee and approved by the chairman of the Materials Science and Engineering graduate studies committee. The student's committee has four or more members with at least one from outside the area of the student's specialization. Committee members are often from outside the university community.

Faculty members in the program are actively engaged in funded research programs. Faculty expertise and graduate student research efforts are concentrated in the areas of materials processing, solid-state chemistry, polymer engineering and science, X-ray crystallography, biomaterials, structural materials, theory of materials, and solid state materials and devices. The major portion of the research is reported through three research centers that are part of the Bureau of Engineering Research, which reports to the office of the Dean of Engineering. There are two specialized materials centers: the Microelectronics Research Center and the Center for Polymer Research. The third is the Center for Materials Science and Engineering wherein a range of materials research is done including research in structural materials, continuum mechanics, computational materials science and engineering, ionic materials, rheology, tribology, corrosion, crystallography, as well as synthesis and processing. Integrated into the Center for Materials Science and Engineering are the Laboratory for Smart Materials and Devices and the Laboratory for

Interconnects and Packaging. Students in the Materials Science and Engineering graduate program and students enrolled in degree programs of the home departments of the faculty members participate in the above research.

DISCUSSION

Two successful materials science and engineering programs have been described in detail. The authors do not wish to imply that the programs at the University of Texas at Austin and Northwestern University are the best. They were selected because the authors are more familiar with them.

A Variety of Materials Programs Exist in Universities

Besides the materials programs at the University of Texas at Austin and Northwestern, there are many other combinations of departments and multi-departmental programs. The programs, departments, and combinations of these in the universities were determined by local interests that determined how each university responded to its needs and opportunities. Where there were long established departments in metallurgical engineering or ceramics engineering, a materials department required a longer time to develop than in a university such as Northwestern where no previous department existed before 1954. In some universities, materials science was combined into the metallurgical engineering department. Departments devoted to one class of materials still exist and are needed because they satisfy important needs. In universities where there were strong materials components in the chemical, civil, electrical, and/or mechanical engineering departments, a multi-departmental educational program in materials was a natural development rather than a separate materials-oriented department. As already discussed, materials permeates all of engineering and all engineering departments have a legitimate interest in the subject.

The many materials programs at Pennsylvania State University are an example of how both strong departmental and strong multi-departmental programs can exist side by side. Beginning in 1957, a group of faculty members under the leadership of Rustum Roy advanccd thc argument that a "new intellectual center of gravity was forming around the preparation, characterization, and properties of solid matter" (R Roy, private communication). In 1959, a graduate degree program in Solid State Technology within the graduate school was created, with faculty drawn from a half-dozen departments. There are now four materials degree programs in parallel at Penn State. Three are based on kinds of materials, i.e. metals, ceramics, and polymers, and a fourth interdisciplinary program deals with the generic science of materials (applied physics and chemistry). In the current Solid State Materials program there is a required core curriculum in theory, materials preparation, materials characterization, and materials properties. The strong Geochemistry department at Penn State, which specializes in phase diagrams and synthesis, is a major force. Currently there are about 100 graduate students enrolled in the program (R Roy, personal communication).

University Administration Support

Strong sustained commitment by the university administration is needed at all levels for a successful materials program or department. The cartoons in Figure 3 illustrate the importance of the university administration's

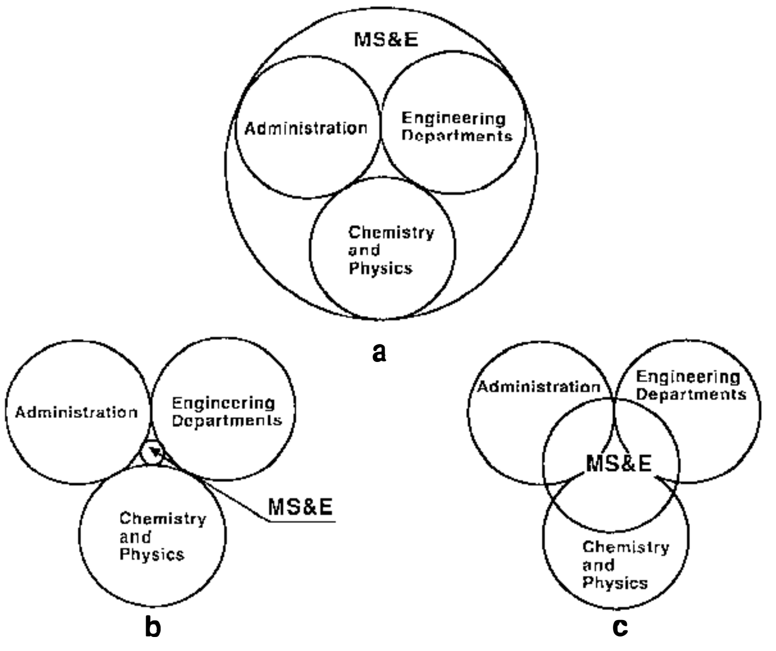

Figure 3 The role of the university administration in the success or failure of a Materials Science department or interdisciplinary program. (*a*) The university administration support for materials science and engineering is shown inside the materials science and engineering circle, which represents the synergism in the interdisciplinary program. (*b*) Materials Science and Engineering is a small circle between the administration and the departments interested in materials education. These represent the conditions for a constrained program or limited size department in materials science and engineering. (*c*) The Materials Science and Engineering department is represented by a circle of equal size to the other circles. This represents the conditions for a successful department overlapping the other materials interests.

commitment. For any multi-departmental program to be successful, faculty in the departments must strongly support the program, and the administration must commit sufficient resources to add needed faculty and to assist in maintaining the infrastructure. Thus the cartoon in Figure 3a shows administration inside the circle with chemistry, physics, and the engineering departments. In this case, the strong administrative support of materials science and engineering leads to a strong synergistic interdepartmental program. A separate materials science and engineering department cannot flourish if it is too small, nor can a college-wide or university-wide program prosper if administrative support is not sustained. Both of these situations are depicted in Figure 3b, where the efforts are severely contained and limited. A materials science and engineering department or program with sufficient resources, however, can play a strong role in the university's education and research activities as depicted in Figure 3c. In each case, where there is a successful materials program at a university, faculty members have spent much time in assuring the administration's continued commitment. The administration, of course, evaluates the productivity of the program or department, i.e. enrollment and research, and a weak entity is threatened by reorganization or extinction.

Some Requirements for Successful Programs

The University of Texas at Austin materials educational program is a pure interdisciplinary multi-departmental one, while that at Northwestern is a strong departmental one plus some specific inter-departmental graduate programs. In both universities, the courses are all in departments and the faculty members have departmental bases, although there are some joint appointments at Northwestern. There have not been any problems at either university in developing and approving of the needed courses. One of the concerns, however, is that faculty members who spend much of their time in multi-departmental activities may not receive full credit for these activities in their home departments. This could affect promotions and salary increases. Joint appointments also present special pressures. Such concerns need continual attention to prevent them from becoming critical problems.

The interdisciplinary multi-departmental graduate program defers much administrative power to the home departments, and this tends to blur the program identity both internally and externally. Many decisions are made at the department level and the available resources are decentralized. Externally, continual explanation of and justification for an interdisciplinary graduate program must be made to prospective students and faculty. On the other hand, undergraduate students with interest in materials, but who are working towards degrees in another field, are likely to be more attracted by an interdisciplinary program.

Where both departmental and multi-departmental programs in materials exist side by side, there is danger of destructive rivalry. Every university has probably experienced this problem, at least to a limited extent, and care must be taken that such rivalry does not become ruinous. There are natural areas of conflict between multi-departmental programs and research centers, on one hand, and departments on the other. There are turf problems. Who should be responsible for facilities? Is the credit for research accomplishments and research funding given to the department, to the program, or to the center? Are the graduate students credited to the departments or to the center or program? For a healthy center or inter-departmental program, all such matters must be decided openly in a spirit of congeniality and compromise, with guidance from the deans and higher administrators. The reports of the various university units (departments, centers, programs, schools, vice president for research's office, etc) need to be careful to give full credit to all players.

The problem of obtaining and maintaining an adequate enrollment of materials department majors has often been troublesome, and much faculty time is required for recruitment and other related enrollment activities. This is a consideration when deciding to establish a department or a multi-department materials program. Low enrollment, for example, was responsible for the demise of the Metallurgical Engineering department at the University of Minnesota, where one of the authors (MEF) went to school. At the University of Minnesota, materials is now combined into a Chemical and Materials Engineering department, which includes mechanical properties as an area of specialization.

Some Benefits of a Multi-Departmental Materials Program

A major advantage of the multi-departmental graduate program structure is that faculty with a common interest in a broad technical area may be easily gathered from various departments and even colleges. In materials science and engineering, as already discussed, the field encompasses mechanical behavior and structural materials (mechanical engineering), continuum and applied mechanics (engineering mechanics), polymers (chemistry and chemical engineering), electro-optical behavior (electrical engineering and physics), and the fundamental nature of materials (physics). This is the same set of disciplines required to attack the four parts of the materials science and engineering tetrahedron (Figure 1): synthesis/processing, structure/composition, properties, and performance. The multi-departmental Materials Science graduate program facilitates collaboration and identity as a materials group with a common educational objective, all with a minimum of administrative overhead.

A multi-departmental materials program also has the ability to focus the materials effort within the institutional level of the college or university. Faculty whose interests and research identity lie principally in materials science and engineering have a vehicle for speaking collectively on academic and administrative matters that impact the field. The graduate program is a focal point for addressing materials science and engineering issues within the university as well as externally. A materials department cannot do this alone because of the legitimate interests of other departments. The materials faculty in all departments must pull together and present a common front to receive the needed recognition and support from the higher university administrative officers.

A tangible benefit to a department such as mechanical or electrical engineering borne out of the multi-departmental graduate program is that expertise vital to the undergraduate educational mission of the department resides locally rather than externally. For example, mechanical engineering students at both undergraduate and graduate levels may take materials courses from materials scientists and engineers who are well versed in the various aspects of structural materials, have an appointment in the mechanical engineering department and, in addition, participate in an interdisciplinary materials program. Electrical engineers learn electronic behavior of materials from materials scientists who reside in the department and are therefore aware of and responsive to the curriculum needs in electrical engineering. From the perspective of a graduate student in such a program, a remarkable freedom exists for creating a widely diverse program of study, compared to any single department, while remaining squarely within the confines of materials science and engineering.

Final Discussion

Universities have responded in different ways to the challenges of providing education in materials, i.e. how and to what extent materials are covered varies from university to university. There is a large spectrum of needs and many different kinds of programs are required to respond to these needs. In the final analysis, a program that is done well, regardless of its orientation, is a satisfactory program and will maintain continued support of the university administration.

THE FUTURE

It is interesting to speculate about the future. Great advances in the biological sciences have taken place in recent years. How will this affect the field of materials? Of course, wood has been an important material since the beginning of civilization. The importance of wood for the manufacture of machines was well established in the time of Vitruvius (5), approximately 2000 years ago. While wood is now infrequently used for machines in developed countries, it remains one of man's most important materials. The increasing importance of renewable resources means an increasing role for cellulosic materials. Improving renewable materials through biological engineering seems to be a certainty, and inclusion of biological materials in the materials science and engineering department or program of universities may be anticipated. Should a biological science course be required in the undergraduate materials engineering curriculum?

Concrete's raw materials occur widely, and old concrete can be used as aggregate in new concrete so there is no disposal problem. Modern research techniques are leading to a much better understanding of the cement-forming reactions. Study of cementitious materials is beginning to take its rightful place in the materials science family. High performance concrete is a vision of the future.

On the high technology side, improved understanding of relations of properties to structure is increasingly making materials by design possible. In this regard, electronic materials has a substantial lead over structural materials and corrosion-resistant materials. The increasing trend of developing new materials by a design strategy is certain to continue with greater use of computer-generated phase relations, crystal imperfection dynamics and reaction rates to predict structure and composition distribution as they depend on processing. This information will be used increasingly to predict properties.

The development of more and better smart materials is a certainty. These materials maintain stability in changing environments, or signal the approach of failure. Using layered structures, combinations of materials may be prepared to carry out smart functions.

Materials programs have often not paid sufficient attention to processing and one expects this to receive more attention in the future. Much of manufacturing involves materials and the tie to the broad field of manufacturing engineering may need to be strengthened. The same need holds true for management. Too often people in decision making positions know too little about the product being manufactured and decisions are based on only short term considerations.

Another question concerns teaching physics of materials at the undergraduate level. The authors are of the opinion that entering graduate students are less prepared in this area than in former years. Physics of materials remains a basic underpinning to the materials field and should not be neglected. The greater emphasis in education on manufacturability, quality control, and other important applied topics is not a reason to lessen education in the scientific bases of the materials field.

Finally, materials is certain to remain an important field. Whcn one of the authors (MEF) began working at the Bell Telephone Laboratories in 1946, he worked on thermal conductivity and coefficient of expansion mismatch problems in vacuum tubes. While vacuum tube engineers may be superannuated, thermal conductivity and thermal stresses resulting from expansivity mismatch are as important topics today as they were in 1946. This is true for essentially all of the properties of concern to one in the field of materials science and engineering. The concepts, phenomena, and problems endure as the materials systems to which they apply evolve. It is equally true that traditional metallic, ceramic, polymeric, electronic, and ionic materials and their composites will be as essential in the foreseeable future as they are today, and their importance will continue to be emphasized in any program in materials science and engineering.

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