APPROACHES TO AN INTEGRATED UNDERGRADUATE EDUCATION IN MATERIALS SCIENCE AND ENGINEERING

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General Comments

This is an era of great excitement and opportunity in the materials field, particularly for those of us in universities. Our field has expanded greatly in recent years. Materials scientists and engineers have joined forces with physicists, chemists, electrical engineers and others to pave the way for major technological advances. Remarkable strides in instrumentation have brought insights unimagined a decade ago. The realization is growing in so many other fields of research and education that further advances are limited largely by the capabilities of materials. There is no field of engineering that could not improve the efficiency or performance of its products, if better materials were available.

The restructuring of industry and of trade patterns throughout the world has created tensions and difficulties, but they also provide us new challenges and new opportunities. Perhaps most importantly, our field is aided in its forward momentum by the development of Materials Science and Engineering (MSE) itself which provides the intellectual foundation and the organizational framework for a new type of education, as well as a new focal point for interdisciplinary research and study.

Materials Science and Engineering comprises the generation and application of materials-related knowledge which can be summarized in two statements. First, the properties of a material are determined by its structure, i.e. microstructure and composition, and secondly, processing can exercise control over microstructure and composition to achieve a specified level of performance in a material. This is illustrated in Figure 1, which also shows the close linkage (and overlap) of our field with basic science at one extreme, and with the needs of society and with experiential knowledge at the other. The close coupling of theory to practice, and the turbulence resulting from interaction of scientific ideas

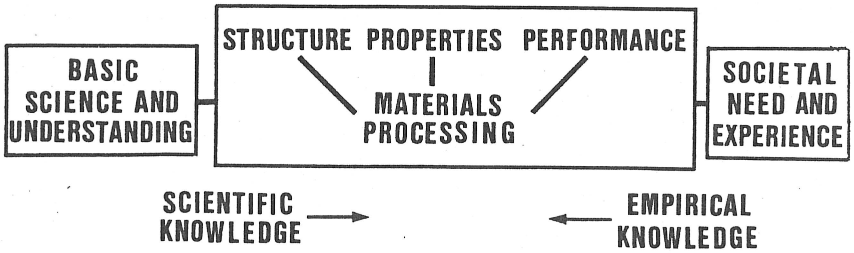

Figure 1. Schematic Diagram of Materials Science and Engineering

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with practical understanding, contribute to the vitality of our field. Our momentum is greatly enhanced today by our growing ability to understand and to work with materials as a whole as we learn to generalize the paradigms we have discovered with specific materials classes.

The ways we think about (and teach) our field continue to evolve in response to the changes occurring in the world around us. While our emphasis remains on structure, properties and performance, and their control through processing, we appreciate that our treatment of properties must extend beyond those associated with mechanical behavior. For example, we are increasingly concerned with electronic and optical properties. We see many of our students taking jobs related to electronic materials. Should we doubt that this will continue, we need only look at projections for the data processing industry which is today a $200 billion industry worldwide and is projected to grow to a trillion dollar industry in a decade or so. Today the industry spends 6% of its sales on research and development, and this projects to $60 billion a year, a significant fraction of which will be materials-related. Such growth in the R&D sector alone will create enormous demand for our graduates for the foreseeable future.

We have much to gain, and we believe little to lose, when we focus our educational program on principles and practices that cut across materials classes and that treat materials generically rather than specifically, i.e., metals, ceramics, polymers, or electronic materials. If we generalize much of our undergraduate program this way, then elective subjects can be used to teach the specific characteristics of a given class of materials and to provide insight into industrial practice.

But if our goal is truly to span science through engineering and to do so with reference to all materials classes, then we must enlist the help of scientists in related fields such as chemistry, physics and electrical engineering. This interdisciplinary nature of our field must continue to strengthen and grow in all respects, especially in our teaching and research. For example, the happy marriage of physics and materials science ushered in the modern semiconductor era. Continued and expanded interdisciplinarity with physicists, chemists, and electrical engineers can do much for our departments, our teaching programs, and our appeal to undergraduates in the years ahead. But we must take the lead.

We believe departments of materials science and engineering have much to gain in their teaching as well as their research from interacting with industry. Such interactions can take the form of visiting or adjunct professorships for industrial personnel, theses carried out in part in industry, student participation in industrial cooperative programs, etc. At the same time, our departments have something unique to offer industry, namely our rapidly evolving perception of materials in technology.

While we want our students to understand the beauty and perfection of simple, ideal materials, we want them also to appreciate how to deal with "real world" materials which are always highly complex, variable, impure, and imperfect. We want them to understand something of how to design and engineer new materials, and we want them to have an awareness of production problems and costs, and of market demands. We want, if possible, to let them have some exposure to facilities and equipment that are either too large or too expensive for individual departments to afford. All of these factors lead us to seek industrial interactions such as those mentioned above.

An Example of an Undergraduate Program

To illustrate the general ideas set forth above, we would like now to make some comments on the undergraduate program at MIT, developed by our

Undergraduate Committee under the Chairmanship of Professor Sadoway. Approximately three years ago this department began a major restructuring of its undergraduate program in response to the changes described above. The goal was to provide a comprehensive materials education at the undergraduate level - an education that is comprehensive in the sense that it is strong in fundamentals, teaches the relevant scientific principles, avoids over-specialization, and yet exposes students to all classes of materials.

Table I is an overview of our current undergraduate program indicating its division into five major categories: the General Institute requirements, the Humanities and Social Science requirements, MSE core subjects, MSE restricted electives, and unrestricted electives. We shall restrict our comments here to the MSE core subjects and restricted electives which together demand less than 50% of the student's time on campus.

TABLE I
SUBJECT CATEGORIES

	%
GENERAL INSTITUTE REQUIREMENTS	20
HUMANITIES AND SOCIAL SCIENCE REQUIREMENT	20
MSE CORE SUBJECTS	31
MSE RESTRICTED ELECTIVES	16
UNRESTRICTED ELECTIVES	13
	100

The Core subjects, shown in Table II, have been designed to be generic, i.e. not materials specific, and as a group to achieve a balance between science and engineering. The first six subjects listed are lecture subjects taught by our faculty. The seventh entry is differential equations, a subject required of our students but taught by the Department of Mathematics. The eighth entry is a laboratory subject and the ninth entry is the bachelor's thesis. The last entry, Thesis Seminar, is designed to help students prepare for their thesis research and to help them develop communication skills through preparation of the thesis document and through oral presentation of their research results.

TABLE II
CORE SUBJECTS

3.00	THERMODYNAMICS
3.01	KINETICS
3.185	TRANSPORT PHENOMENA
3.11	MECHANICS
3.13	STRUCTURE
3.10	CHEMICAL PHYSICS
18.03	DIFFERENTIAL EQUATIONS
3.081	LABORATORY
3TH	THESIS
3.041	THESIS SEMINAR

The restricted elective subjects are materials specific and build upon the knowledge presented in the Core. The subjects are grouped into materials "options" or areas of specialization. Students must choose six from the choice of sixteen such subjects. The selection rules balance "breadth" and "depth". The paradigm for curriculum design in the restricted electives is given in Table III. Each materials "option" has a

TABLE III
PARADIGM FOR RESTRICTED ELECTIVES

- MATERIALS SCIENCE: STRUCTURE-PROPERTIES
- MATERIALS ENGINEERING: PROCESSING-STRUCTURE
- MATERIALS LABORATORY

materials science subject treating structure-properties relationships in that materials class, a materials engineering subject treating processing-structure relationships in that materials class, and a laboratory subject. Table IV gives a complete list of these subjects. Their descriptions along with those of the MSE Core subjects appear in the Appendix.

TABLE IV
RESTRICTED ELECTIVES

CERAMICS	
3.07	INTRODUCTION TO CERAMICS
3.06	GLASS SCIENCE AND ENGINEERING
3.069	CERAMICS PROCESSING
3.075	CERAMICS AND GLASS LABORATORY
ELECTRONIC MATERIALS	
3.15	ELECTRICAL, OPTICAL, AND MAGNETIC MATERIALS AND DEVICES
3.146	ELECTRONIC MATERIALS
3.147	PROCESSING OF ELECTRONIC MATERIALS
3.083J/3.084	INTRODUCTION TO MICROELECTRONIC TECHNOLOGY/ ELECTRONIC MATERIALS PROJECT LABORATORY
METALLURGY	
3.02	CRYSTAL DEFECTS AND PHASE TRANSFORMATIONS
3.14	PHYSICAL METALLURGY
3.03	CHEMICAL METALLURGY
3.082	METALS PROCESSING LABORATORY
POLYMERS	
3.062	POLYMER CHEMISTRY
3.061J	STRUCTURE AND PROPERTIES OF POLYMERS
3.064	POLYMER ENGINEERING
3.065	POLYMER LABORATORY

A closer look at the curriculum reveals that the department has what we term a "two-tier" laboratory sequence. In the Core, all students must take 3.081, Materials Laboratory, which constitutes the first "tier". Like all Core subjects this laboratory is generic, taking examples from all materials classes. The laboratory deals primarily with materials characterization using a variety of techniques including optical spectroscopy and microscopy, electron microscopy and X-ray analysis. In the "second tier", each student chooses at least one of four materials-specific laboratories (see Table V). These laboratories deal with processing/structure/property/performance relationships. Students alter processing parameters to generate samples with varying microstructures which are characterized. The properties of these samples are in turn evaluated.

TABLE V

TWO-TIER LABORATORY

CORE:	3.081 (generic)
	MICROSTRUCTURE
ELECTIVE:	3.065 (POLYMERS)
	3.075 (CERAMICS)
	3.082 (METALS)
	3.083J/3.084 (ELECTRONIC MATERIALS)
	PROCESSING-STRUCTURE-PROPERTIES

Many of our students are enrolled in the department's Industrial Cooperative Program. The curriculum for these students is the same as above with the exception that they may substitute for the bachelor's thesis the reports of their industrial research performed during the summers following the sophomore and junior years.

Concluding Remarks

The field of MSE continues to evolve at a rapid rate. There are exciting new developments in materials, developments that challenge us to gain a deeper understanding of how materials behave. There are exciting new ways of viewing materials knowledge, and we expect to discover better ways to incorporate this new knowledge into our academic Core. For example, at the moment we teach four materials processing subjects: one each in metals, ceramics, polymers, and electronic materials. In each subject the same issues arise: what are the fundamentals of the process at different important structural levels, how does one control and optimize the process, what is the necessary instrumentation for monitoring the operation, what are the economic implications, etc. There is a commonality here that is under-exploited. In time we shall learn how to combine these four materials-specific processing subjects into one, or perhaps two, generic materials processing subjects.

In universities it is almost always easier to start something new than to phase out something old, but over the years we have succeeded in phasing out required subjects in mining engineering and later mineral dressing, and in eliminating subjects and subject matter that seemed excessively craft-based, or more properly put, seemed not to involve the appropriate balance between technology and science. And we have succeeded in combining and unifying many areas. This trend will continue, enhanced and made possible by increased emphasis on materials science and on materials engineering at the expense of materials classes.

Of all the fields of science and technology, surely none can surpass Materials Science and Engineering in its intellectual excitement, and few can approach it in its potential for contributing to the needs of mankind. The decades ahead hold much promise and excitement for all of us in the field, both on and off campus.

in terms of packing and coordination polyhedra. The nature of imperfections in real materials: point defects and the structure of line and planar defects.

3.185 Transport Phenomena in Materials Engineering

Definition of viscosity, simple overall mechanical energy balances, elements of laminar flow and turbulent flow. Thermal conductivity steady and unsteady conduction problems, forced and natural convection, heat transfer coefficient and radiative heat transfer. Definition of binary diffusivity, convection mass transfer, and mass transfer coefficient. Illustrative examples given throughout, chosen from the materials processing field.

RESTRICTED ELECTIVES

CERAMICS

3.06 Glass Science and Engineering

Glass structure and microstructure and their relation to processing and properties. Attention to glass formation, phase separation, viscous flow and relaxation, glass melting and forming. Consideration of applications such as: glass-ceramic materials, fast-ion conducting glasses, optical waveguides, amorphous semiconductors and thin glassy films, and glass matrix composites. Emphasizes recent developments and the present state of the particular technologies, including discussion of the relevant patent literature.

3.069 Ceramics Processing

Principles for processing technical ceramics based on an understanding of and application of fundamental principles for reliable and reproducible manufacturing. Case studies: ferrite magnets, alumina chip carriers, oxide varistors, and heat engine components. Topics: powder formation and conditioning, powder packing, densification and microstructure development, melt and vapor processing. Description of industrial manufacturing processes and how these relate to the fundamental concepts.

3.07 Introduction to Ceramics

Characteristics of the crystal structures, including crystal defects, of oxide materials and local atomic arrangements in silicate glasses discussed with regard to relative stability of alternate possible arrangements and influence of structure on properties. Applies phase equilibria, interface properties, atomic mobility, and phase transformations to development of structure to certain physical properties: individual study of a particular ceramic, ceramic property, or ceramic process selected by the student required.

3.075 Ceramics and Glass Laboratory

Laboratory investigates ceramic and glass processing by means of a series of laboratory experiments plus an extensive project. Laboratory experiments cover a range of powder and glass processing together with physical property measurements. Laboratory project is undertaken with faculty supervision.

APPENDIX A

CORE SUBJECTS

3.00 Thermodynamics of Materials

Essential features of first, second, and third laws of thermodynamics and their application to materials. Statistical interpretation of entropy. Experimental techniques used to measure the thermodynamic functions. Introduces phase diagrams, phase rule, and thermodynamics of solutions. Thermochemistry of homogeneous and heterogeneous reactions.

3.01 Physical Chemistry of Materials

Reactions involving pure condensed phases and gaseous phase, behavior of solutions, free energy-composition and phase diagrams of binary and ternary systems, reaction equilibria in systems containing components in condensed solution. Electrochemistry, corrosion, Gibbs phase rule, chemical kinetics, elementary mechanisms, reaction rate constant, activation energy, surface tension.

3.041 Thesis Seminar

Lectures on basic skills necessary for conducting thesis planning, research, analysis and preparation of final document. Included: library resources, how to plan experiments, departmental central facilities, laboratory safety, data analysis, technical writing, and thesis format. Seminar also requires that each student present an initial oral research proposal and deliver a lecture reporting on completed thesis.

3.081 Materials Laboratory

Introduces study of materials by light, X-rays, and electrons. Examines microstructures and investigates relationship of structure to mode of fabrication. Applies classical techniques of light microscopy and spectroscopy, and X-ray diffraction and the modern analytical tools of transmission and scanning electron microscopy.

3.10 Chemical Physics of Materials

Introduction to quantum physics of electronic structure and chemical bonding of atoms, molecules, and solids. Emphasis on those concepts which are basic to an understanding of the chemical and physical properties of materials. Topics: wave mechanics and Schroedinger's equation; atomic and molecular orbitals; the nature of the chemical bond; electronic structure of semiconductors and insulators; electronic structure of metals and alloys.

3.11 Mechanics of Materials

Aspects of solid mechanics necessary for understanding the response of polymers, metals, and ceramics to applied loads; static equilibrium, states of stress and strain, materials stress-strain-temperature relations, response to torsion and bending, stability. Subject includes an introduction to computational mechanics, including FORTRAN student projects.

3.13 Structure of Solids

Uses symmetry theory in the description of the atomic arrangement in crystals. Derivation of space lattices, point groups, crystal systems, and plane groups. Principles of space group derivation and equivalent positions and their use in specifying structure. Interprets structures

ELECTRONIC MATERIALS

3.083J Introduction to Microelectronic Technology

Introduces some of the basic techniques and processes used in the fabrication of silicon monolithic integrated circuits. Lectures and laboratory sessions on the theory and technology of device fabrication and integrated circuit processing, including wafer cleaning, oxidation, photoengraving, chemical etching, diffusion, thin film deposition, and device testing.

3.084 Electronic Materials Project Laboratory

Student use of facilities of Miocroelectronics Laboratory for individual or team projects. Projects illustrate processing-structure-properties relationships in electronic materials. Students participate in choice and design of projects which include fabrication and characterization phases.

3.15 Electrical, Optical, and Magnetic Materials and Devices

Electronic, optical, and magnetic properties of materials in terms of electronic structure, chemical composition, and bonding. Properties of metals, semiconductors, and insulators including electrical conduction, thermoelectric power, Hall effect, optical absorption and reflection, luminescence, magnetism related to microstructure, impurities, and degree of disorder. Manipulation of properties for incorporation into devices.

3.146 Electronic Materials

Various aspects of semiconductors such as crystal growth, impurity segregation, crystal structure, and electronic properties relevant to device application. Emphasizes relationships among structure, bonding, and properties in elemental and compound semiconductors.

3.147 Processing of Electronic Materials

Focus on preparation of electronic materials emphasizing elemental and compound semiconductors for device applications. Growth of single crystals from the gel, solution and vapor phase analyzed through respective phase equilibria. Studies of effects of heat and mass transfer on composition and defect formation. Discusses in detail processes such as epitaxy, junction formation, annealing, wafer oxidation, external and internal gettering in silicon.

METALLURGY

3.02 Crystal Defects and Phase Transformations

Structural, energetic, and kinetic properties of point, line, and areal crystal defects. General treatment of nucleation and growth. Examples of phase transformations in materials: condensation of vapors, solidification, recovery, recrystallization and grain growth, precipitation of a second phases in solids, martensitic transformations, spinodal decomposition, second-order transformations. Importance of phase transformations in the development and control of structure emphasized.

3.03 Chemical Metallurgy

Chemical principles of extractive metallurgy. Representations of heterogeneous equilibria. Unit operations and processes. Roasting of sulphides. Gaseous reduction of iron oxide. Reduction of zinc oxide and ferroalloy oxides. Reduction of halides. Smelting of iron ores, matte smelting of copper ores. Refining processes-gas-liquid, solid-liquid and liquid-liquid. Hydrometallurgy and electrometallurgy. Kinetics of high-temperature processes. Examples taken from industrial processes.

3.082 Metals Processing Laboratory

Introduces relationship between processing-structure-properties-performance of materials. Each student participates in three laboratory experiments drawn from metals processing. Includes instruction in safety, technical writing, oral presentation, and experimental design.

3.14 Physical Metallurgy

Relationship between structure and properties of engineering alloys presented and discussed in detail. Alloy systems covered include steels, stainless steels, aluminum and titanium alloys, and superalloys. Processing history, microstructure, and properties of each alloy system illustrated by case studies. Fracture analysis of alloys widely used in engineering application emphasized.

POLYMERS

3.061J Structure and Properties of Polymers

Structure and properties of bulk polymers. Design of engineering materials based on polymers. Molecular weight and configuration of macromolecules, rubber elasticity, deformation and fracture, electrical and optical properties, polymer-based composite materials. Relationship between processing and morphology. Amorphous and semicrystalline polymers treated.

3.062 Polymer Chemistry

Preparation of polymeric materials and their characterization. Topics: fundamentals of chain and step growth polymerization, chemistry of organic radicals and ions, synthesis-structure-property relationships and use of modern techniques for determination of polymer composition, molecular weight, and microstructure.

3.064 Polymer Engineering

Quantitative models for engineering analysis and design as applied to polymers. Includes linear and nonlinear viscoelasticity, yield models, homogeneous and flow models for fracture and fatigue, rheological properties of polymer fluids, governing equations for thermomechanical fluid processing, and models for industrially important processing methods.

3.065 Polymer Laboratory

Synthesis of typical plastics. Methods of processing. Techniques of polymer characterization: IR, DSC, viscosity, density, dynamic mechanical analysis, light scattering, microscopy, photoelasticity. Also modulus, strength, impact, creep, time-temperature superposition, environmental stress cracking.