MATERIALS SCIENCE AS A VEHICLE FOR TEACHING MAINSTREAM CHEMISTRY

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ABSTRACT

For almost 30 years, the Department of Materials Science and Engineering has taught one of the subjects that satisfies the freshman chemistry requirement at MIT: Introduction to Solid State Chemistry (MIT subject number 3.091). This subject teaches basic principles of chemistry, and shows how they apply in describing the behavior of the solid state. The relationship between electronic structure, chemical bonding, and crystal structure is developed. Attention is given to characterization of atomic and molecular arrangements in crystalline and amorphous solids: metals, ceramics, semiconductors, and polymers (including proteins). Each lecture ends with a five-minute segment presenting a “real world” application of the subject matter. Examples are drawn from industrial practice including the environmental impact of chemical processes, from energy generation and storage, *e.g.*, batteries and fuel cells, and from emerging technologies, *e.g*., biomaterials. Enrollment is between 300 and 400. The class meets as a whole three times a week for 50-minute lectures. Twice a week the class meets in groups of 15 to 20 students in so-called recitations presided over by either a faculty member or a graduate student teaching assistant. For many students this is their first exposure to materials science and engineering, and as a result this subject has the potential to awaken latent interests. Substantial departmental resources (staff time and money) are dedicated to this teaching enterprise to ensure quality.

Keywords: *general chemistry, materials science, science core, freshman year*

INTRODUCTION

For almost three decades, the Department of Materials Science and Engineering has taught one of the subjects that satisfies the freshman chemistry requirement at MIT: Introduction to Solid State Chemistry (MIT subject number 3.091). Not long after the end of World War II MIT adopted a curriculum that was based upon the thesis that modern engineering rests on a scientific foundation. Hence, all students were required to complete a core course of study comprising mathematics, physics, and chemistry, regardless of choice of major. At MIT, even students majoring in linguistics, music, or political science all must complete the “science core” in order to graduate with a bachelor’s degree. These subjects were taught by faculty from the School of Science, i.e., physics was taught by physicists – there was no such thing as “physics for engineers.” The science core was originally designed to be completed by the end of the sophomore year. Although there have been modifications over the years, this “science core” remains the basis of an MIT undergraduate education to this day. Table 1 below shows the current composition of the “science core” which is now typically completed at the end of the freshman year at which time students declare their major.

Table 1. Science core requirements at MIT

mathematics:	2 semesters
physics:	2 semesters
chemistry:	1 semester
biology:	1 semester

By the mid 1960s there was growing dissatisfaction in the School of Engineering with some components of the “science core.” With specific regard to chemistry, faculty felt that there was an imbalance between theory and application. Student interest was being quenched by a combination of subject content and lecturing style. The level of frustration was so great at one point that there was even discussion of abolition of the "science core"[1]. Into this debate stepped John Wulff, Professor of Metallurgy. In the early 1960s with the sponsorship of the Ford Foundation Wulff had led a team of colleagues in a textbook writing exercise that culminated in a series of books that helped define materials science as a discipline at the undergraduate level[2-5]. Wulff believed that materials science was an excellent platform from which to launch a presentation of the rudiments of chemistry. He called the subject Introduction to Solid State Chemistry, and within several years it had earned its place along side subjects offered by the Department of Chemistry in satisfying the freshman chemistry requirement at MIT.

For many students, 3.091 was their first exposure to materials science, and the number of students majoring in MS&E rose proportionately to the number taking 3.091 as freshmen.

CONTENT

Over the years 3.091 has undergone a number of changes, but certain components remain unchanged from the original concept espouse by John Wulff. The central idea is that the principles of chemistry can be taught via the solid state. This results in a syllabus that consists of two sections:
1. General Principles of Chemistry and
2. Solid State Chemistry: Basic Concepts and Applications. Table 2 shows the syllabus for the fall 1998 semester.

It should be clear that the modern version of 3.091 is an ambitious undertaking. In just 13 weeks, the students are exposed to the general principles of chemistry as well as the basic concepts and applications of materials science (a.k.a. solid state chemistry). What emerges is a paradigm that mimics the structure-properties paradigm of MS&E: electronic structure determines chemical bonding which, in turn, governs crystal structure. Thus, the central paradigm of MS&E (structure ⇨ properties) falls under a higher rubric.

Table 2. 3.091 Syllabus

1. General Principles of Chemistry

* **Introduction:** elements and compounds, chemical formulas and reactions
* **Evolution of atomic theory:** Bohr model of hydrogen, Bohr-Sommerfeld model and multi-electron atoms, atomic spectra, Heisenberg, de Broglie, Schrödinger
* **The Periodic Table**, aufbau principle, Pauli exclusion principle, and Hund's rules
* **Primary Bonding:** ionic, covalent, metallic, van der Waals
* **Secondary Bonding:** dipole-dipole, dipole-induced dipole, London dispersion, hydrogen
* **The Shapes of Molecules:** electron domain theory
* **Organic Compounds:** nomenclature

2. Solid State Chemistry: Basic Concepts and Applications

* **Crystal Structure:** 7 crystal systems, 14 Bravais lattices, cubic crystals
* **Characterization of Structure:** x-rays, electrons, neutrons
* **Band Theory**, semiconductors, and devices
* **Imperfections in Solids:** point, line, surface
* **Amorphous Solids:** inorganic glasses (oxides, metallic) organic glasses (polymers)
* **Liquids and Solutions:** solubility rules, acids, bases, pH, buffers
* **Biochemistry:** amino acids, peptides and proteins, lipids
* **Oxidation-Reduction Reactions**
* **Reaction Kinetics:** rate laws, Arrhenius equation
* **Diffusion:** Fick's first and second laws
* **Phase Stability:** unary and binary phase diagrams

Here is a snapshot of 3.091 in the fall semester of 1998. Enrolment was 370 students, which amounts to over half the total number of students taking chemistry at MIT (There are about 1000 freshmen in total. About 200 come to MIT with advanced placement credit in chemistry. About 700 of the remaining 800 take chemistry as first-term freshmen (The other 100 take chemistry at a later date.). The class meets three times per week in a large lecture auditorium (Mondays, Wednesdays, and Fridays from 11 a.m. to 12 noon). Twice per week the students attend so-called recitations (on Tuesdays and Thursdays) where the size of the class is limited to about 20. Recitations are led by either a faculty member or a graduate student teaching assistant. Each week the students receive sample problems with model solutions. In lieu of problem sets to be turned in for grading, students take weekly 10-minute quizzes in recitation based upon material covered in the homework. Every month there is a major test to which students are allowed to bring an aid sheet. There is a three-hour final (aid sheet permitted).

Substantial departmental resources (staff time and money) are dedicated to 3.091. Everyone associated with the class understands that the overall success of the enterprise hinges upon the coordinated efforts of many people. As lecturer in charge, the author conveys to everyone associated with 3.091 his expectation of their total commitment to delivering a quality education. In view of the fact that 3.091 is a freshman class, there may be a tendency on the part of some to underestimate the teaching skills needed to teach such a subject. Fortunately, at MIT, 3.091 has always enjoyed strong administrative support with the result that in some years over half the recitation sections are staffed by faculty, many of them senior faculty. In contrast, recitations in other freshman subjects are staffed almost exclusively by graduate students, most of them in their first year at MIT.

3.091 is distinguished not only by its course of study, but by a number of special features that make it unique among freshman classes at MIT. First, a good deal of effort goes into illustrating concepts by examples from industrial practice, energy generation and stroage, and emerging technologies. The last five minutes of each lecture is devoted to *Chemistry and the World Around Us*. Table 3 lists some of the topics covered in the five-minute segment at the end of lecture. Throughout the semester the lectures make reference to music, art, and literature. As well, attention is given to the historical development of science including people and times. In short, much effort is devoted to putting the subject matter in context.

Table 3. Topics for the last 5 minutes of class.

Aluminum – energy saver when used in transportation but energy intensive to produce.

Copper smelting and acid rain.

Recrystallized glass or glass ceramics.

Magnetoelastic resonators & theft prevention.

Compound semiconductors in traffic signals.

Thomas Midgley and designer molecules: freon and tetraethyl lead.

Rechargeable batteries and electric vehicles.

Students meet a variety of famous scientists in class. For example, the Bohr model is introduced to the class via Bohr's paper published in 1913 in *Phil. Mag.* J.J. Thomson's paper in *The Electrician* disclosing the discovery of the electron or the "corpuscle of electrically charged matter" is also presented, as is Fick's paper on diffusion published in 1855 in *Annalen der Physik und Chemie*. X-rays are introduced via Röntgen's observation of the mysterious glow on his scintillation screen and the subsequent irradiation of his wife's hand (medical radiography), his box of standard weights (airport security), and his rifle (quality assurance) – in those days it was a short distance between scientific discovery and practical application. Röntgen, Thomson, and Bohr were all recipients of the Nobel Prize. Students enjoy learning about the human side of scientific discovery, especially when it is accompanied by a description of the life and times of the main players. Table 4 lists Nobel Prize winners who are mentioned in 3.091.

Art is used to illustrate a number of points. Escher prints are used to show periodicity in 2-dimensional lattices. The use of x-rays in examining paintings is demonstrated via Millet's Angelus which was investigated at the request of Salvador Dalí[6]. It was found that Millet had indeed repainted the canvas – what is seen now to be a basket of potatoes was previously a child's coffin. The theater is also a venue for bringing forth science. A historical drama entitled "Copenhagen" by Michael Frayn is playing the London stage[7]. The story is set in 1941 when Werner Heisenberg visits Neils Bohr in occupied Copenhagen. The physics is accurate. Major moral issues occupy center stage.

Table 4. Nobelists we have met in 3.091

Physics		Chemistry	
Röntgen	1901	Arrhenius	1903
Zeeman	1902	Rutherford	1908
the Curies	1903	Haber	1918
J.J. Thomson	1906	Urey	1934
van der Waals	1910	Debye	1936
von Laue	1914	Hahn	1944
the Braggs	1915	Seaborg	1951
Planck	1918	Pauling	1954
Einstein	1921	Libby	1960
Bohr	1922		
Millikan	1923		
de Broglie	1929		
Heisenberg	1932		
Schrödinger	1933		
Davisson	1937		
Stern	1943		
Pauli	1945		
Bloch	1952		
Born	1954		
Shockley	1956		

Music also plays a big role in the class. Before and after each lecture music is played as students file in and out of the lecture hall. In many instances there is a link to the subject matter of the lecture that day. Table 5 gives examples.

Table 5. Musical selections.

acid-base equilibria: *Water Music, Acid Queen*

de Broglie, Heisenberg, Schrödinger: *Mack the Knife; Catch a Wave; Smooth Operator*

band theory of solids: *In the Mood*

Moseley's law: *Rondo alla Turca; Istanbul not Constantinople*

x-rays: *Love Theme from Superman*

quasicrystals: *Take Five*

polymers: *Chain of Fools, When the Nylons Bloom Again*

diffusion: *Crosstown Traffic*

ASSESSMENT

MS&E has proven to be an excellent vehicle for teaching the fundamentals of chemistry. Student reaction has been highly favorable as evidenced by strong course evaluations over the years. This approval has translated into recruitment of majors into the department. The faculty reaction has also been positive, even in the School of Science where it is appreciated that an understanding of 3-dimensional atomic structure is valuable for the subsequent study of molecular biology and organic chemistry. The experience of 3.091 has shown that MS&E facilitates curricular integration, which is due in large part to the interdisciplinary nature of the field. This has been recognized even by chemists who have embraced the teaching of chemistry with examples drawn from materials science[8].

In summation, it is the opinion of the author that MS&E belongs in the college core. The thesis of this article is that materials science is a vehicle for teaching the rudiments of chemistry (albeit under the guise of solid state chemistry). However, why should it end with chemistry? Can materials science not serve as a vehicle for teaching the rudiments of physics, i.e., mechanics, electricity, and magnetism? It should come as no surprise that students become interested in the subject matter of these introductory college classes when the principles are illustrated by practical examples. MS&E is a gold mine of such examples. It is simply a matter of making the commitment of time and resources to develop the curriculum and to present it as an alternative to the somewhat sterile presentations by traditional science departments. It's time for MS&E to move out of its historical subordinate position teaching service courses for engineers and to seize center stage in the college core. We owe it to our students, and we owe it to ourselves.

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