Chemistry and Materials Science for All Engineering Disciplines: A Novel Interdisciplinary Team-Teaching Approach

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1 Abstract

A novel first-year course (Engineering Chemistry and Materials Science) was created to broaden the technical foundation in the BSE program at Calvin College. The content of the new course was drawn from two established courses – an engineering course in materials science (which was subsequently eliminated) and the second semester of first-year chemistry (which most engineering students did not previously take). In an innovative format, the course is team-taught by faculty from the engineering and chemistry departments. The material is integrated, so that the chemistry is motivated by relation to engineering properties, while the materials science is more thoroughly grounded in scientific principles. This allows greater conceptual depth for the materials science than was present in the previous stand-alone course. It also provides all engineering students with a greater chemistry background, and makes the chemistry seem more relevant and interesting. A weekly lab illustrates concepts, attracts the attention of hands-on learners, and is also integrative. For example, in one lab period students synthesize several polymers. The next lab period, they test various material properties of those polymers, relating these observations back to the structures they now know well. The course material is technical and challenging. Students enjoy the challenge, whereas the course previously taken by second-semester freshmen bored many students because they found it too simple, and repetitive of the first-semester freshman design course. The new interdisciplinary course has been successful in two years of being taught. Students particularly appreciate the lab, saying it makes the lecture more interesting, relevant, and easier to understand. Faculty see more student engagement with the material. Initial data indicate significant improvement in first-year-to-sophomore year retention rates.

2 Introduction

As engineering has developed in the late twentieth century the importance of chemistry has been rapidly increasing. As National Academy of Engineering president Bill Wulf has identified, "chemical … sciences are becoming fundamental to engineering" and need to be fully incorporated into the curriculum.[1] Calvin College recognized a need for more extensive chemistry preparation for all of its BSE graduates. Also, the recent addition of a Chemical concentration (joining Mechanical, Civil, and Electrical/Computer) presented an ideal opportunity to rework the common first two years of the program.

One desired curriculum change was to add a second semester of general chemistry for all engineering first-year students. Chemical concentration students need this anyway, and we believed all engineering students would greatly benefit. This addition presented several challenges. First, of course, room had to be found in an already full curriculum. Second, and perhaps more daunting, first-year chemistry tended to be the least popular course among engineering students. As taught to a general audience, they saw little relevance of the material to their careers and often just did not "get it" as material was traditionally presented.

Making room for chemistry began with eliminating a 2-credit, second-semester freshman design course. Assessment data indicated students found this course too simplistic and too repetitive of the first semester. We feared we were losing some top students due to lack of challenge. Our 3-credit materials science course had some significant overlap in topics with the chemistry we wished to add. By combining the courses, some room was saved. Even more importantly, we felt that the two disciplines would complement each other and enhance the overall education in both. In a novel approach, the course is team-taught by faculty from chemistry and engineering.

The next challenge was how to engage all first-year engineering students in a chemistry course. We made the course technically challenging, believing it was not rigor that turned off engineers to chemistry. However, we set out from the beginning to teach the chemistry in a different way. Recognizing the practical, "what is it good for and why do I care" nature of even first-year engineers, we decided to intimately integrate the course material of chemistry and materials science. Chemical concepts are presented as the background to explain a material property or other chemical aspect necessary for good engineering design. Finally, we strive to include examples from each of our four engineering concentrations, to constantly reinforce that today, chemistry is essential for *all* engineers.

3 Course Format and Goals

While many educators have recognized the value of interdisciplinary courses or team teaching,[2-8] we did not find examples of courses that take full advantage of the synergies between materials science and chemistry, particularly in an engineering course for multiple disciplines. At Calvin College, Engineering Chemistry and Materials Science is a four-credit hour, one-semester course for all first-year engineering students. It meets for four standard (50-minute) lecture periods a week and one three-hour lab period per week.[†] Teaching of both the lectures and labs is evenly split between the chemistry and engineering faculty (Table 1).

The course covers essentially all of the previous materials science course and about 50% of second-semester general chemistry. (Another 25% of general chemistry was distributed to a sophomore introduction to chemical engineering course that all engineering students take.) Five credits of lecture material were condensed to four, while adding labs. This was achieved by integrating course material to make use of overlapping content with chemistry. Also, the previous engineering course was taught at a relatively slower pace. A conscious decision was

[†] Although such a schedule would be a five-credit course at some institutions, many introductory-level science courses at Calvin College, including Chemistry, use this four-credit model.

made to create a rigorous course, with the idea that students are ready for a challenge and become bored without it. Also, this makes the transition to challenging sophomore engineering courses more gradual. The course goals are highlighted in Table 2.

Table 1. Schedule of lecture topics and lab topics for Engineering Chemistry and Materials Science. Shaded boxes indicate topics taught by the chemistry faculty; unshaded boxes are topics taught by the engineering faculty.

Week	Lecture Topics	Lab
1	Solid state chemistry and crystal structures	Mathcad software
2	Diffusion; Stress/strain diagrams	LED Chemistry
3	Mechanical properties of metals	Concrete I – create samples
4	Phase changes; Phase diagrams	Metal properties
5	Physical properties of solutions (including alloys)	Concrete II – test samples
6	Polymer structures and properties	Freezing point depression
7	Societal issues in Materials Science; Fatigue and fracture	Polymer synthesis
8	Chemical equilibria	Intro to design project
9	Chemical equilibria case studies	Polymer characterization
10	Acids and bases	Chemical equilibrium
11	Acids, bases, and solubility	Work on design projects
12	Electrical properties; Semiconductors	Titration I
13	Superconductors; Corrosion	Titration II

Table 2. Non-content educational goals of Engineering Chemistry and Materials Science.

Conceptual Goals

- Students should recognize the fundamental need for chemistry in the major fields of engineering.
- Students should begin to recognize the interdependence and continuity of science and engineering, rather than seeing science as an unrelated field.

Professional Development Goals

- Students should be introduced to the expectations of an engineering course, including the amount and pace of work.
- Students should start to take ownership of their education. They should learn to keep track of their own assignments and schedules and recognize when and how to ask for help.

The course is taught using a problem-solving approach. While this is common to engineering courses, it is not as much of an emphasis in general chemistry courses. Engineering students better engage the chemistry and materials science when it is presented as a tool, which they then must use to solve a problem. This is especially true in labs. All the chemistry labs differ considerably from the standard general chemistry ones in that their aim is not to complete a set of prescribed tasks, but rather to use a limited set of resources (chemical relationships, charts, websites, experimental setups, etc.) to accomplish one or two specific goals. Often the goal is simply to identify an unknown compound or composition, and the students have the freedom to solve the problem however they choose to do so. In the end, students come away with a much more thorough understanding of what they did and why it worked (or why it did not) because they have to be responsible for deciding on their specific path towards the goal and must engage the material to evaluate their choices. They learn very quickly the value of advanced planning based on accurate conceptual knowledge.

4 Integration of Engineering and Chemistry

The interaction of engineering and chemistry is used to motivate the student. A deliberate attempt is made to have one integrated course rather than two individual 2-credit courses stitched together. For example, the chemist first teaches about the crystalline structure of metallic solids, and then the engineering application is shown when the engineer subsequently teaches about slip planes and fracture mechanics. Phase diagram concepts are pulled in from the traditional chemistry course, but the emphasis is shifted to solid solutions in order to correlate with the materials science study of metallic solutions. Acid-base equilibrium is covered from the traditional chemistry course, and those topics are used to build a foundation for looking at half-cell potentials and corrosion.

The chemistry topics are taught in close conjunction with specific technologies in order to appeal to engineering students who typically need to see why certain knowledge is valuable. Solid state chemistry proves to be difficult for students as they try to conceptualize three-dimensional structures for the first time. Unfortunately, many of the standard examples (NaCl, ZnS, *etc.*), if simple, lack relevance for the students. More technologically interesting materials are generally too complex. For this course we try to elevate interest in atomic arrangements and crystallographic descriptions by teaching it within the context of semiconductors and LED technology. In the lab the students move from solid state modeling of semiconductor materials, to using diffraction to measure the wavelength of light from a range of LED's, to finally designing appropriate compositions of gallium based semiconductors for use in stoplights.

Equilibrium chemistry is another topic that often challenges the students. In this course, the focus is shifted from esoteric knowledge to the chemistry of automobile (engine and exhaust), explosion chemistry, and the Haber-Bosch process. These provide concrete and interesting examples to the students of how the chemical concepts of equilibrium are essential to producing useful technologies.

The focus of the materials science is on using materials in engineering design. Students are challenged to look at how material properties arise from the chemistry and processing of materials. The course includes a design project on injection molding of a car door panel. From the project they learn how to do an engineering design project (currently we have three projects, and plan to have five, distributed to the five engineering courses of the first two years) and how material selection and processing conditions influence product properties and cost. Students have a choice of four polymers and three fillers. They can choose a neat polymer, a blend of two polymers, a filled neat polymer, or a filled polymer blend. The use of polymer materials requires students to immediately apply some of their chemistry knowledge, and allows them to see concretely how the chemistry of the different materials results in differing properties. Although the project is challenging (especially for a first-year course) many students have said that they appreciated they project, that they learned a lot, or that it was the best part of the course because it helps them to understand how the course material comes together. Thus, engineers are motivated to learn chemistry when they see the relevance of chemistry to engineering.

5 The Laboratory Experience

The laboratory has been essential to the success of this new course. Evaluations of the previous materials science course indicated that lack of a regularly scheduled lab was a serious shortcoming. Students felt the course material was too theoretical and not relevant to real life. The occasional lab or demonstration in the old course was always mentioned by students as being the high point of the course. Incorporating chemistry into the new course (including some chemistry labs) presented an opportunity to create materials science labs.

The labs are essential for those who are hands-on learners. We believe this has improved retention of a certain set of students who were previously drifting away from engineering, long before the engineering lab experiences of the junior and senior years. The labs illustrate and expand on concepts covered in lecture. In fact, student evaluations specifically mentioned that certain concepts only made sense after the lab.

The labs provide an opportunity to include non-traditional materials in the course. For example, although the course does not have room to cover concrete during lectures, this would obviously engage the prospective civil concentration students. Therefore, in the lab students make concrete batches and subsequently test the strength, studying the effect of different mix compositions.

Lastly, the labs are integrative whenever possible. For instance, one week the students synthesize polymers in a chemistry lab. The next week in the engineering lab, they test the mechanical properties of polymers. One week they study crystal structure in the chemistry lab, another week they test mechanical properties of metals.

6 Team Teaching

Having a regular course jointly taught by faculty from two departments was a novel model for Calvin College that presents advantages and challenges. We chose to arrange a firm lecture schedule, assigning each day to an instructor. Then, even if one person gets behind, the other person will return on the appointed day. This was essential for planning.

Administratively, each instructor gets half the credit for teaching the course. However, the instructor is teaching the full course worth of lecture (up to three sections), plus labs (up to four sections), in some weeks. Other duties tend to get behind in the overloaded weeks, but on the positive side, the split teaching provides "rest periods" where one instructor can step back, refresh, and reorganize. Alternating lectures and labs between instructors each week, as much as possible, relieves some of this burden of unbalanced workloads.

7 Evaluation of Course to Date

The course has been taught twice, with a total of six lecture and eight lab sections, as of the writing of this paper. Student course evaluations definitely indicate that students enjoy the course, overall, and are starting to appreciate the need for chemistry in their engineering careers. Evaluations also show that student perception of integration of disciplines improved significantly between the first and second years. Labs continue to be the most popular element of the course, overall.

After the first year, as we learned the pitfalls we made many minor adjustments. Students were generally content to have two instructors. They quickly adapt to varying expectations of different faculty, and have commented that they actually enjoy the variety. There were some administrative challenges to work out. For instance, it was necessary to designate a central location for handing in all papers, since students were continually confused about which instructor to give assignments to, and papers were sometimes lost. We scheduled the course so that students were working on homework with about a one-week delay to the lectures, which meant that the instructor in the classroom was usually not the one who assigned the homework currently being worked on (see Table 1). This caused the unforeseen benefit of starting to train first-year students about professionalism in work habits. The burden was on them to be organized, keep track of office hours, and plan ahead for help.

Students initially saw the course as two distinct courses. As units have been more closely linked, this problem is fading. We have experimented with joint test questions, and more closely linking the materials studied in the chemistry and materials science labs.

Initial trends in first-year student retention data provide strong support for the new course. Previously, first-year students took Introduction to Engineering and the first course in general chemistry (which was typically quite unpopular) first semester, followed by an Engineering Design and Communications course, which did not challenge most students, in the second semester. In the old curriculum, the engineering department's first-year-to-sophomore retention rate was relatively low and declining, sinking to approximately 72% in the last few years before our curriculum change. The new integrated chemistry course, which replaced Engineering Design and Communications in the second semester of the first year, has been taught twice and retention rates have increased to about 92%. This course is apparently a significant factor in the improved retention, although we cannot prove it directly. However, we have been unable to identify any other relevant changes during that time period. Faculty had already observed that the lack of challenging content in the previous (now eliminated) course was a problem, which helped to initiate the change to this new course. Combined with the assessment data which indicates students are very satisfied with the new course, we are inclined to attribute most of this improved retention to this curriculum change.

Qualitatively, faculty have found the new course to be a success. Students engage the materials science content more enthusiastically and deeply when it is clearly explained by the underlying chemistry. Students find chemistry less mystifying and frustrating when it is linked to practical applications.

In conclusion, a novel course format met multiple needs simultaneously. Additional chemistry was added to the engineering curriculum to better address its increased importance to the challenges today's engineers face in the workplace. Providing a better chemical foundation for the principles being presented enhanced the materials science content. Lab experiences were added and greatly enriched the course. Team teaching by two departments allows the content to be covered in appropriate technical depth while keeping the focus and emphasis of the course such that it is interesting and engaging to engineering students.

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