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General Chemistry for Engineers in the 21st Century: A Materials Science Approach

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ABSTRACT

In the case of General Chemistry, many engineering students only take a one semester class with important topics such as kinetics and equilibrium being given limited coverage. Considerable time is spent covering materials already covered in other courses such as General Physics and Introduction to Engineering. Moreover, most GChem courses are oriented toward health science majors and lack a materials focus relevant to engineering. Taking an atoms first approach, we developed and now run a one-semester course in general chemistry for engineers emphasizing relevant materials topics. Laboratory exercises integrate practical examples of materials science enriching the course for engineering students. First-semester calculus and a calculus-based introduction to engineering course are prerequisites, which enables teaching almost all the topics from a traditional two semester GChem course in this new course with advance topics as well. To support this course, an open access textbook in LibreText, formerly ChemWiki was developed entitled *General Chemistry for Engineering*. Many of the topics were supported using Chemical Excelets and Materials Science Excelets, which are interactive Excel/Calc spreadsheets. The laboratory includes data analysis and interpretation, calibration, error analysis, reactions, kinetics, electrochemistry, and spectrophotometry. To acquaint the students with online collaboration typical of today's technical workplace Google Drive was used for data analysis and report preparation in the laboratory.

INTRODUCTION

A read through Miodownik's *Stuff Matters* [1] would convince everyone that materials science is crucial to almost everything in engineering, both large and small. If one peruses textbooks or even the syllabii of courses on the Internet labeled "General Chemistry for Engineers," many will be nothing more than typical general chemistry with very little orientation towards engineering. Our approach was to design the course around modern materials science with an atoms-first approach that would allow us to get most of first-year general chemistry into a one-semester course for engineers with the addition of topics useful for engineering majors. The course is off and running on the first day since the course has much higher course prerequisites (see Table I) compared to typical first-year chemistry. This allows us to immediately dive into subjects such as atomic structure, a topic perhaps a bit too abstract for our regular students to start with. The textbook in LibreTexts [2] (open source) is designed to group topics to facilitate easy flow between atomic and molecular structure, reactions, states of matter, kinetics, and then into chemical equilibrium and thermodynamics.

Data-driven classroom activities and projects are integrated into a variety of topics such as bonding and real gas behavior. The laboratory incorporates a mix of topics from both first and second semester general chemistry and extends topics with simulations and error analysis. Incorporating online collaboration in assignments using Google Drive was also a goal [3, 4].

Table I. General Chemistry for Engineers vs. General Chemistry Courses at PGCC

	General Chemistry (full year)	General Chemistry for Engineers
Prerequisites	College Algebra	Calculus I and Intro.to Engineering
Student served	Pre-med, pre-pharm, biology	Engineering and materials science students
Topics start with	Basic measurement, dimensional analysis	Atomic structure, calibration of temperature devices
Laboratory	Guided-inquiry, very structured	Guided-inquiry, more open ended and with experimental design

COURSE CONTENT

The major goal was to integrate the typical content of general chemistry I and II into a one-semester four-credit class with laboratory (7 contact hours/week, 3.5 hrs/session). The content of the course is illustrated in Table II (highlighting first and second semester general chemistry topics) and the details can be found on the course website [5]. The course is designed around an atoms-first approach: atoms > molecules > states of matter, then to moles > reactions > kinetics > equilibria, and finally electrochemistry, thermodynamics, and nuclear chemistry. These three topic areas are blocks A, B, and C in Table II. More time was allocated for second semester topics. How are the topics enhanced for engineers?

In block A, metals, especially the transition metals, are given more emphasis in periodic trends, metallic bonding is given equal time with ionic and covalent bonding, including band theory for conductors, semiconductors, and insulators. Solid state, including 2D structures such as graphene and MoS_2, are discussed. Matsci excelets are used to enhance visualization of 3D structures by using 2D slices [6]. A thorough discussion of the cubic crystal system is done including binary metal alloys. Bonding, structure, and material type is integrated together using the bonding tetrahedron from the Chemogenesis web book [7].

In block B, reactions and their behavior as systems (kinetics and equilibrium) are introduced from both a macroscopic and microscopic approach. A number of chemical excelets [8] are used to bring kinetics and equilibrium alive as dynamic topics. This section is concluded by examining the Haber process for the production of ammonia. Here a variety of engineering topics can be discussed looking at an industrial process including steel alloys for reaction vessels, catalysts, reaction mechanism, and environmental and energy issues using three Nobel Prize in chemistry lectures [9]. Students examine online simulations to consider the economics of ammonia production. Students were asked and succeeded at solving a Haber process equilibrium problem (They had to solve a quartic equation!).

In block C, electrochemistry including corrosion and its cost and chlorine manufacturing and its environmental impact, thermodynamics, and finally nuclear chemistry round out the course. Here students were introduced to exponential behavior via the flipping of M&M's and then doing a detailed activity using an interactive Excel/Calc spreadsheet [10]. This activity covers background radiation, counting error, half-life behavior, and the decay of an unstable daughter. Nuclear reactors, radiation interaction with matter [6], and radiation safety are discussed.

Table II. Lecture Topics and Laboratories

<table>
<tr><th>Week*</th><th>Tuesday</th><th>Thursday</th><th>Block</th></tr>
<tr><td>1</td><td>Intro/Thermometers
Calibration Lab*/Spreadsheets</td><td>Data Analysis via Spreadsheets
Atomic Structure</td><td rowspan="5">A</td></tr>
<tr><td>2</td><td>Atomic Structure</td><td>Interactive Periodic Trends
Periodic Trends - the story with data</td></tr>
<tr><td>3</td><td>Electronegativity
Bonding - ionic & covalent</td><td>Bonding - metallic
Bonding Triangle & Tetrahedra</td></tr>
<tr><td>4</td><td>Discovering Molecular Geometries
Molecular Structure</td><td>Molecular Structure and Polarity</td></tr>
<tr><td>5</td><td>States of Matter - gases & fluids
Phase Changes</td><td>States of Matter - solids
Graphite Circuits</td></tr>
<tr><td>6</td><td>Reactions - Macroscopic
Investigating Chemical Reactions</td><td>Reactions - Microscopic
Bond Energies</td><td rowspan="5">B</td></tr>
<tr><td>7</td><td>Stoichiometry – moles & reactions</td><td>Stoichiometry – moles & reactions
Growing Materials - CVD
(Howard NanoExpress)</td></tr>
<tr><td>8</td><td>Kinetics
Burning Candle Kinetics Lab</td><td>Kinetics</td></tr>
<tr><td>9</td><td>Kinetics</td><td>Chemical Equilibrium</td></tr>
<tr><td>10</td><td>Chemical Equilibrium
Equilibrium Constant Lab - Spec 20</td><td>Chemical Equilibrium
Haber Process and Simulation</td></tr>
<tr><td>11</td><td>Electrochemistry</td><td>Electrochemistry</td><td rowspan="4">C</td></tr>
<tr><td>12</td><td>Electrochemistry</td><td>Thermodynamics</td></tr>
<tr><td>13</td><td>Thermodynamics</td><td>Nuclear Chemistry
M&M's Half-life Lab</td></tr>
<tr><td>14</td><td>Nuclear Chemistry
Decay and Distance (iLabCentral)</td><td>Nuclear Chemistry</td></tr>
</table>

*Weeks 1-7 from GenChem I, weeks 8-14 from GenChem II, and labs

The discovery-based laboratory portion of the course tried to enhance chemical concepts and where possible bring in engineering concepts such as graphite circuits. This is an aspect that will be strengthened in the future, such as using Howard's NanoExpress [11] to perform a chemical vapor deposition experiment and iLabCentral's remote radioactivity experiment [12, 13].

STUDENT FEEDBACK

For our inaugural run of the course, the course had four students (final grades: 2A's, B, C). Three of the students agreed that the amount of material covered and the pace were just right. They all agreed that level of lecture, laboratory, activities, and homework were just right. Results shown in Figure 1 show students want more hands-on activities including labs in lieu of lecture.

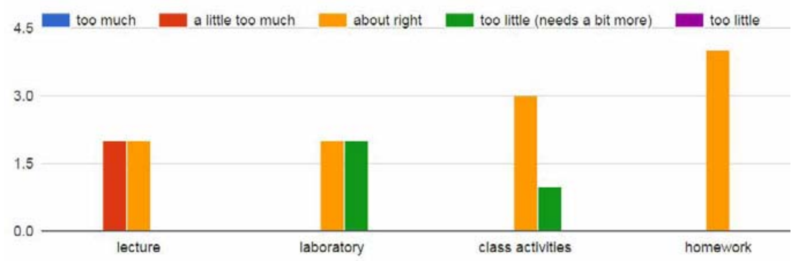

Figure 1. What about the amount of each item? (vertical axis is number of students)

Student comments were positive and constructive.

- More time for activities. Good opportunity to use all the lecture material in beginning of class and reinforce through practice. Keeps both students and professor engaged.
- The instructor is very knowledgeable so if expanded info was desired-just ask. Good practice for upper level engineering classes where much material is covered and exams are straightforward.
- Hard to beat a huge chemistry textbook with handwritten notes and post-it flags everywhere. Using in conjunction with online seems to be best.

OPEN SOURCE TEXTBOOK

Halpern [14] outlined the advantages of ChemWiki, now LibreTexts, for development of a open source textbook. Our present textbook [2], which was designed with the topic order as given in Table II, is enhanced with a variety of YouTube videos, PhET simulations [15], and excelets [6, 8]. From our student survey, more practice problems would be appreciated in the book and they loved the cost (Figure 2). The use of the interactive features of the book seems to have received limited attention; however, many of the items were used directly in class in activities or discussion and are posted on the course website. The textbook is still a collaborative work in progress. Contributions from others are welcome.

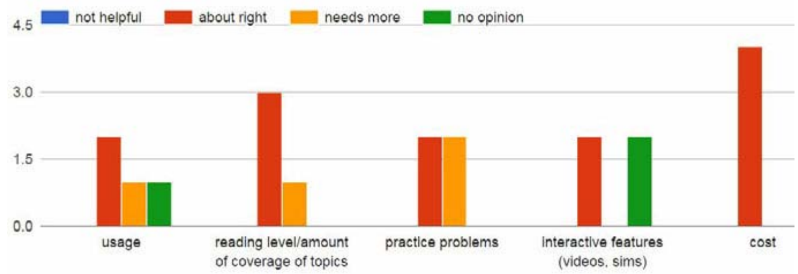

Figure 2. How did you find the ChemWiki textbook? (vertical axis is number of students)

SOME FINAL THOUGHTS AND NEXT STEPS

All-in-all this was a good first run of the course. For an instructor, timing the topics to stay on schedule is crucial. Having students that were better prepared mathematically helped with the course pace. More aspects of sustainability will be integrated into the course [16]. Strengthening the laboratory is a goal for the next pass, especially finding more engineering-related lab activities. Splitting the three hour lab period into two one and half hours sessions is being considered as this allows lab on both days. A new binary alloy density collaborative spreadsheet activity is ready to be tested [4]. This course has students preparing for our sophomore-level engineering materials science class, as well as, for organic chemistry. Learning outcome assessment will also be initiated in the future as well (course outcomes are on the syllabus at the course webpage [5]).

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