A One-Semester Engineering Chemistry Course

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Abstract

The number of courses in engineering curricula has been reduced during the last decade. A typical response by programs is to reduce the number of core courses, and move the specialty courses into the earlier years. Many curricula now require only one (if any), semester of chemistry. Recognizing that engineers need material from both semesters of the traditional two semester sequence, a new one-semester course was developed. This course has been designed around the pedagogical theme that "The properties of larger particles are based upon the properties of their constituent particles and their interactions". As such, the students are introduced to "modern" physics. To deliver a course such as this effectively , we have found that we need to adopt innovative teaching techniques including: focusing on the recitation, frequent feedback, the use of the studio-format, closer integration of the laboratory experience with the course, self-directed laboratory exercises, context- based learning, and the use of the internet. The course structure and the use of these techniques will be discussed.

Introduction

The purpose of engineering education is well described by the words of Stephen van Rensselaer, the founder of the first civilian engineering college :"...instructing persons, who may choose to apply themselves, in the application of science to the common purposes of life"[1]. Chemistry is one of those scientific disciplines in which engineers must be competent if they are to address the common purposes of life. The impact of chemistry on modern society has been phenomenal including, advances in materials development, environmentally sound manufacturing, and biomedical advances which have increased the quality of life for many. However, whereas thirty years ago many engineering students would complete two semesters of basic chemistry, many engineering disciplines have reduced this experience to one semester or even eliminated it. Still, chemical processing concepts are taught throughout almost all engineering curricula.

This result may be partially explained by engineering faculty and students being unhappy with the introductory chemistry experience. Recent findings of the National Science Foundation which reported that students are not being served well by the "usual" methods of instruction[2].

Much of this dissatisfaction and disinterest in engineering was found to occur during the first two years of an engineer's education when they are exposed to the scientific concepts they will apply during their careers. Ninety percent of engineering majors who switched to a non-engineering major, and seventy five percent who persevered, described the quality of teaching as poor overall. Seniors about to graduate in engineering made it clear their experience in these introductory courses had given them a shaky foundation for higher level work.

The National Science Foundation, in a recent call for proposals (Action in Engineering), has identified several needed changes to address these findings. These include:

1) active project-based learning inside and outside of the classroom,
2) increased student-teacher dialog,
3) horizontal and vertical integration of subject matter,
4) introduction of mathematical and scientific concepts in the context of engineering, and
5) the broad use of information technology.

The causes of and proposed solutions to the dissatisfaction with the exposure to chemistry and other scientific disciplines for engineering students, without assigning blame, requires an examination of the differences between a scientist and an engineer. A scientist is one who discovers new principles of nature through a systematic system of observation, experimentation, and study. An engineer puts the knowledge discovered by the scientist to practical use[3].

To apply chemistry to practical applications engineers need to know if and how a chemical reaction will occur. This assessment requires understanding the behavior of groups of molecules. To understand how groups of molecules behave one must understand the properties of individual molecules, which requires understanding the properties and interactions among individual atoms. That in turn requires an understanding of sub-atomic particles and their interactions. Therefore, the one-semester chemistry course for engineers has been designed based on the following pedagogical statement.

To understand the properties and behavior of a material or chemical substance one must understand the properties of and interactions among its components.

The subject matter is therefore organized in the reverse order of a traditional chemistry course to address the interests of engineering students better . In the study of chemistry one can see that the scientist and engineer will approach things in a reverse order. The scientist looks at phenomena and "digs in", looking at molecules, atoms and sub-atomic particles. The engineer is a "builder", who looks at the pieces and tries to put them together to make something. The scientist looks at phenomena and is excited to discern fundamental influences, the engineer starts thinking of applications. Because of this difference, we feel that to teach chemistry effectively to engineering students, the typical introductory chemistry course meant to stimulate interest in chemistry for scientists, is not appropriate. The order in which topics are presented needs to be changed, i.e. points 3 and 4 of the Action Agenda need to be addressed.

It makes no sense to assume that a non-traditional course can be taught in the traditional manner. One typically thinks of the introductory science and mathematics course as consisting of a sequence of lectures combined with a series of assignments and examinations which require little more than rote memorization or repetition. This approach may be sufficient to excite scientists, some Nobel Laureates have mentioned that one aspect of a single lecture stimulated their career; but it is not engineering. The Chemistry faculty at Rensselaer had never taught the course in this manner. Expanding on their teaching style we were able to adopt the philosophy "Involve me and I'll not only learn but understand and remember", as we developed our course. Bloom, a noted educational specialist, identified a hierarchy of six educational levels, each higher level being more rewarding[4]. The typical course experience as described earlier focuses on the lower learning levels and is not appropriate for college students. We feel that college students should perform at the fourth level, Analysis (breaking down a problem into parts and solving it), and by the time they graduate at the fifth level, Synthesis (tying together distinct concepts). To apply this, we need to address points 1 and 2 of the Action Agenda. Information technology can be used to make this more effective.

The Course

A first-year course, “Chemistry of Materials”or “Materials Chemistry” specifically targeting engineering students, has been developed and refined over the last 10 years at Rensselaer Polytechnic Institute and Virginia Commonwealth University . The course design involves three aspects;

- Identifying appropriate subject matter[5],
- Presenting the subject matter in an order consistent with our pedagogical statement[6], and
- Increasing the involvement of students in their own learning[7,8,9].

Subject Matter

As stated earlier we felt that a survey course is inappropriate for engineering students. Therefore we divided the course sequence into the following three sections.

Properties and Behavior of Atoms
    Sub Atomic Particles, Nuclear Reactions, Basic Quantum Physics, Electron Configuration.
    Periodic Table of the Elements - Ionization Energy, Atomic and Ionic Size, Electron Affinity, and Electronegativity
Properties and Behavior of Molecules
    Ionic, Covalent, and Metallic Bonding, Lewis Structures, Resonance
    Hybridization and Molecular Geometry
    Intermolecular Forces.
Properties and Behavior of Groups of Molecules
    Stoichiometry

Kinetic Theory of Gases. and the Ideal Gas Law,
Equilibrium Constants, LeChatelier's Principle, Acids and Bases, Buffers.
Thermodynamics: Heat, Work and Energy, Calorimetry, Determining Enthalpy Changes, Entropy and the Second Law, Gibbs Free Energy, Equilibrium Constants, Vapor Pressure.
Kinetics: Reaction Rates, Orders of Reactions, Rate Constants, Reaction Mechanisms.

In Materials Chemistry several topics which are especially important to engineers which are typically found in the second semester of a general chemistry course are covered: nuclear reactions, metallic bonding, acid base behavior, complete thermodynamics, vapor pressure and kinetics. The subject matter also includes the following topics typically included in a modern physics course are covered: nuclear reactions, mass-energy equivalence and Planck's equation. However these topics are immediately applied to the structure of the atom. To cover this subject matter adequately some novel approaches have been developed.

Properties and Behavior of Atoms

At the beginning of the course, after reviewing basic stoichiometry, we introduce students to the concept that systems (or things) tend to the lowest possible energy state. This is used throughout the course to explain equilibrium states.

We then introduce the students to the "modern world" by explaining the four fundamental forces of nature. While exploring the nucleus we briefly mention the two flavors and three colors of quarks which make up protons and neutrons. This allows to explain radioactive decay, but more importantly introduces the students to the concept of a residual force before they need to apply it in the more important topic of intermolecular forces.

We introduce electron configuration by mentioning the Schrodinger Equation, stating that it describes the region of space where an electron is likely to be found, and then describing the results of the solution and the implications. The results and implications are the most important, that two and only two electrons can exist in a given orbital, that the number of orbital shapes increases, and that the number of different shape orbitals depends on the principal quantum number or row of the periodic table. Answering the question "so-what?" is extremely important to engineering students, and therefore an in-depth discussion of periodic properties follows the discussion of electron configuration.

Properties and Behavior of Molecules

Immediately following the discussion of the periodic table we introduce bonding. The electron dot structure is used to represent both ionic and covalent bonding.

Our description of covalent bonding first focuses on molecular orbitals (defined as regions of space where an electron is most likely to be). We tell the students that molecular orbitals exist, that electrons in bonding orbitals are in a lower energy state than those in atomic orbitals. We then teach bonding mentioning that the octet rule is a special case of a more general rule. This allows to describe all covalently bonded materials with the exception of those with resonance structures, and clears up many misconceptions. For example students are told that a triple bond is three distinct pairs of electrons and not six electrons sharing a common region of space as in a benzene ring, and the existence of noble gas compounds can be explained.

Using molecular orbitals as a starting point one can explain metallic bonding, hybridization and molecular geometry. We ignore the sea of electrons model, and focus on band theory - the existence of closely spaced energy levels, which enables small amounts of heat (low temperature) to unpair electrons and allow them to conduct electricity. Hybrid orbitals are used to explain why all carbon hydrogen bonds in methane are of equal energy. Finally the geometry of molecules can be explained by simply counting the number of electron pairs repelling each other (VSEPR).

Properties and Behavior of Groups of Molecules

We used the kinetic theory of gases to describe conditions under which the ideal gas law is valid. This allowed students to better understand non-ideal gas behavior.

We used weak acids as an example of chemical equilibrium and buffers as an example of LeChatelier's Principle as opposed to treating them as separate topics. While some instructors mentioned the Henderson-Hesselbach equation, others ignored it preferring the use of equilibrium tables. While we all recognize the importance of the Henderson-Hesselbach equation in biochemistry, we did not feel it should be the sole method to teach buffer behavior. Often students try to use the Henderson-Hesselbach equation to find the pH of a weak acid. An equlibiruim table can be constructed to determine both the pH of a weak acid and a buffer solution.

We showed the students the origin of Gibbs Free Energy as a means to satisfy both the First and Second Laws of Thermodynamics and thus convince them of its usefulness. Temperature dependent vapor pressure is presented to the students as an example of the relationship between Gibbs Free Energy and the equilibrium constant.

Course Format

From the time the course was initiated it was recognized that increased involvement of students was necessary if they were to master the subject matter. The recitation was seen as a, if not the, key learning experience of the course and only faculty, post-doctoral associates, or advanced graduate students were allowed to teach the recitation section. All instructors were expected to be involved with all aspects of the course, and directly involved with students. Between 1996 and 1998 at Rensselaer recognizing the need to involve students further, the course was completely converted to the studio format, where lecture-group discussion-problem solving and laboratory experiments are combined into a single learning experience[7]. Teaching assistants, sometimes undergraduates were used to assist the instructor in these class sessions. This approach had been deemed successful in other basic courses in mathematics[10,11] and physics[12].

At Virginia Commonwealth University it was seen that such increased student involvement was necessary, but that the common lecture was valuable and ought not be eliminated. Building on experience in a basic statics course where it was shown that in-class problem solving and self-directed laboratories enhanced learning[13], it was decided to develop a two-hour studio-based recitation as the key learning experience of the course and supplement this with self-directed laboratory experiences. For many years students had commented that the recitation was where they learned everything, and that lecture was a waste of time. We recognized the former and told the students that the purpose of lecture was to prepare them for recitation where they would apply what they have learned. Each recitation therefore consisted of 2-3 cycles of review of lecture material, in-class problems solved by the students and discussion.

In addition to the in-class problems the students had multiple opportunities to demonstrate their knowledge and receive feedback. In-class problems prepared the students for homework, which in turn prepared them for quizzes, subsequently tests and then the final examination. This constant feedback was important to the success of the students. Further, only multi-step problems which required the students to think and perform at the Analysis level of Bloom's Taxonomy were assigned as homework. To help the students solve these more difficult problems an internet tip was prepared for each problem [8]. These served as "after-hours office-hours" and asked the students questions similar to what we as faculty would in our office to help them through the steps of a problem. Another form of feedback was to develop a set of homework solutions that taught solution strategy. Simply demonstrating the correct solution to these problems, in the form of mathematical equations, on the board or in homework solutions will not work[14]. Photocopying the solutions provided to the instructor, and making them available to the student, is also not sufficient[15]. The student needs to learn the thought process as well as the method of solution. The laboratory experience was designed to eliminate the cook-book laboratory experiment and replace it with a series of activities structured so that they reinforce the material presented in class in a manner similar to the scientific learning cycle[16].

Laboratory Experience

Eight self directed laboratory experiments were piloted during the Fall 2000 Semester at VCU. A fraction of the students taking the course participated.

Photoelectric effect - The students were asked to assess the validity of Einstein's hypothesis. Is there evidence of a work function? Is there evidence that photons exist? Using a lamp, colored slides, and a photoelectric cell the students measured the photocurrent and retarding voltage. The intensity of the light was varied by changing the distance between the light source and the photocell. Students could see that photocurrent depended on distance and thus intensity and that the retarding voltage depended only on the "color" or frequency of light. This evidence was enough for to convince them of the particle nature of light and the photoelectric effect.

Atomic Orbitals and Molecular Shapes - Using a commercial package orbital viewer and a UK based website for VSEPR and molecular shapes the students were asked to compare two sets of orbitals with the same principal quantum number, two sets of orbitals with the same angular momentum quantum number. They were also asked to determine the molecular geometry of second period hydrides. Through this exercise the students were able to see the various shapes.

Intermolecular Forces - The students measured the boiling points of six simple organic compounds butanol, ethanol, hexane, methanol, pentane and propanol to determine how intermolecular forces affected the boiling point.

Ideal Gas Law - Using a pressure sensor and a syringe the students were asked to assess the validity of the ideal gas law. By varying the amount of gas in the syringe they were able to generate a series of plots where $P=k/V$ and k varied with the number of moles.

Equilibrium - The students determined the equilibrium concentration for the following reaction - $Fe^{+3} + SCN^{-} \dashrightarrow FeSCN^{2+}$. The concentration of $FeSCN^{2+}$ was measured through spectrometrically. The students had to determine if the equilibrium constant changed for a series of initial concentrations, and were asked to determine the amount of Fe^{+3} needed to produce a given concentration of $FeSCN^{2+}$, with a fixed amount of SCN^{-}. This approach allowed them to see that not all reactions go to completion.

Hess' Law - Using calorimetry the students were asked to predict the ΔH for the following reaction $NaOH(aq) + HCl(aq) \rightarrow NaCl(aq)$ after calculating the ΔH for the following reactions: $NaOH(s) \rightarrow NaOH(aq)$ and $NaOH(s) + HCl(aq) \rightarrow NaCl(aq)$.

Acid - Base Titration - Students determined the concentration dependence of pH for carbonic acid and then estimated the amount of base required to neutralize the acid. They repeated this for calculation HCl, and by comparison learn that the difference between a strong and weak acid.

Kinetics - The students determined the rate law of crystal violet (CV) + NaOH to determine if it is an elementary process.

In these experiments the students were not given specific experimental conditions to examine, and were required to write a brief lab memo (with an introduction, procedure, results and discussion) to explaining their findings. They were expected to state the hypothesis in their own words and interpret the results.

Discussion

Assessment of Course Effectiveness

A detailed assessment, based upon the handout describing the recent workshop at Rose-Hullman[17], as distributed at the 1998 ASEE conference was conducted.

- First, four to five broad goals were identified, based on the course description. the course description was rewritten to tell the students what they could expect to do as a result of taking the course.
- Based on these goals a list of 12 objectives was developed, which are similar to the material found in course descriptions in many college catalogs.
- Specific metrics, based on the activities listed in the course syllabus were identified to measure these objectives. This included graded performance records (histograms of individual test questions), student comments on course objectives and general survey responses.

- The information in the course portfolio was used to measure the success of these objectives and then the course goals, and identify appropriate action.
- Finally an evaluation of the course was prepared based on the measurements. This evaluation is similar to a reflective memo, which has been suggested as the second step of the assessment process[18].

This assessment was completed at VCU following the Fall 2000 term. The evaluations show that the course goals were met satisfactorily. Student comments show that this course is better received than the traditional chemistry course, and that the students feel the self-directed laboratory experiments enabled them to understand the course material better than students who had not performed them.

Incorporation of Active Learning

The course discussed in this paper requires that the students perform at a higher level than the traditional introductory science course. Active learning which leads to increased student involvement in the learning process is necessary for a course such as this to succeed. The increased emphasis on recitation as the key learning experience has been successful and well received by students. Many students stated that the in-class problem solving, where everyone was required to work on a problem was the best part of the course, and that it helped prepare them for the homework assignment(which was graded).

We believe that there need to be multiple opportunities for feedback (graded assignments). The students cannot be expected to master these topics instantly, but with quizzes, tests, as well as homework they can gradually learn the subject matter. We believe that experience and feedback are as important than reading and lecture in the learning process. However, we recognize that the reading and lecture is necessary to introduce the student to the experience and cannot be eliminated. Outside of class resources such as the internet tips, well graded homework assignments (as well as quizzes, and tests), and instructional homework solutions are also necessary to assist the students in their learning. The students liked the instructional homework solutions. There were no negative comments on well graded assignments, but in the past there had been comments such as “all the grader does is mark with a check or an x”.

Student comments regarding the tips were negative. Students wished that all the tips could be handed out at once, or that the tips actually said “try this or do that”. We feel this would defeat the purpose of the tip; it is supposed to be an aid not a crutch. Assistance is most effective when the student thinks about the problem. This is why when a confused student comes to our office, we ask the student to read us the problem, pick on simple stuff we know they understand and involve them in the problem solving process. Once we find out where they are confused we rarely say “Oh, here just plug this in and do this step”, we ask probing questions to make them think so they will remember. One renowned educator recently stated that his most effective instructor never answered his questions, but simply asked him questions until he found the solution[19]. The tips are meant to do just that.

Incorporation of Materials Science

Originally this course was developed as the first of a two-course sequence to fully integrate chemistry and materials science[5], and culminated with a discussion of cubic crystal structures and crystallography, which was intended to serve as an introduction and link to the materials science course. This has been eliminated. The students did not see how crystallography related to the rest of the course. By finishing with kinetics the students can determine how (after determining if) chemical reactions will occur and explain these findings.

Incorporation of Self-Directed Laboratories

A laboratory experience is essential for a chemistry course. We feel that by participating in a self-directed laboratory the subject matter is most effectively learned. The course assessment demonstrates that this is approach successful.

There are two other objectives to the traditional chemistry laboratory: 1) that the students learn how to work carefully, and 2) that they learn some basic laboratory techniques. Working carefully is a skill that all engineering students need, but the focus on basic laboratory techniques, while necessary for science majors, is unnecessary for most engineering students.

Including students in the discovery process was successful, however we have recommended some changes. First the computer-based labs (atomic orbitals and molecular geometry) should be incorporated into the lecture, recitation and possibly included in a homework assignment. Second, the lab experience should be fully integrated into the course and not graded separately. This would allow the lab material to be included on course assignments and remove any division between the course and the lab. Disconnected laboratory and course experiences are a common complaint of dissatisfied engineering students[2]. Finally, because it is extremely important that acid-base and buffer behavior is understood by engineers, it is proposed to replace the equilibrium experiment with a buffer experiment to reinforce LeChatelier's Principle, and decrease the emphasis on titration.

Conclusion

Over the last 10 years an effective one semester chemistry course for engineers has been developed. What began as a project to integrate materials science and chemistry more fully, recognizing that the traditional introduction to chemistry was not meeting the needs of engineering students, has evolved into an excellent engineering chemistry course. Without the commitment of and cooperation between chemistry and engineering faculty the course would have been a failure. The course is successful not only because it covers subject matter identified as important to engineering students, but because the course is structured to address many of the concerns raised about introductory engineering education. Increasing the level of student involvement in the learning process is key to the successful implementation of this course. This requires increased faculty involvement when compared to the traditional course. We feel the benefit to the students justifies this involvement and that were it possible, to evaluate a ratio of a student's educational experience to the faculty time and resources, that the ratio for this course would exceed that of the traditional exposure for engineering students by a factor of two or more.

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