Chapter 5

A Trajectory of Reform in General Chemistry for Engineering Students

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This chapter considers efforts to enhance learning within the general chemisty course taken by pre-engineering students. Because this course is inherently offered as a service course, often for students in a different college from the Chemistry Department at a university, there are both constraints and opportunities related to the manner in which reform can be enacted. Efforts spanning roughly 15 years are described and an emphasis on the nature of problem-solving within the course emerges as a common theme. The issue of student motivation is also considered with pre-engineering students serving as a prototype of a type of student who doesn't inherently see the value of learning chemistry.

In some respects, there is a love/hate relationship between chemistry faculty members and the large service courses in introductory chemistry that they often teach. Most are well aware that the large number of students in these courses represent a claim on university resources for their Department, but those same students can present challenges in terms of inspiring meaningful learning. One cohort that often fills this role is the entering freshman class of pre-engineering students. There is little question that these students take a rigorous set of classes and are often quite capable students, and yet the experience of many chemistry instructors is that they find motivating "the engineers" a singular challenge. In part this situation may be attributable to a learning culture that is, in measurable ways, different from that of the basic sciences (*1*). Nonetheless, it is possible to cast the learning objectives in terms that are more commonly appreciated by the pre-engineering students. This chapter describes one trajectory by which this type of adaptation within the "chemistry for engineering students" course has developed.

Emphasizing Problem-Solving: Gateway Exams

While it may be a stretch to suggest that engineering students are inclined to remember detailed chemistry facts, such as when precipitates will form, there are other broader constructs that are taught within the general chemistry course that are capable of providing meaningful and hopefully transferable learning for students. Other disciplines, particularly mathematics, have confronted this same premise by enacting "gateway examinations" in calculus classes (*2*, *3*).

Essentially, the idea behind gateway exams is that certain components of a service course provide specific skills needed in later courses. Once identified these skills are assessed separately on a competency basis. Students who demonstrate competency in calculus skills like differentiation and integration receive grades that allow them to continue to courses with a calculus pre-requisite, based on the expectation that the needed skills from the course are in hand. To adapt this concept to General Chemistry requires several things. First, skills that are particularly useful to engineers and might be separately assessed must be determined. Second, questions that will assess those skills must be devised. Finally, because competency based assessment allows for retaking gateways exams, the logistics of a system must be worked out.

Unlike calculus, where specific skills needed in engineering mathematics are readily enumerated, problem-solving in chemistry tends to be more closely tied to content specifics. Nonetheless, there are problem-solving skills that are likely to be transferable to engineering contexts and these skills include (1) recognizing knowns and variables in a problem; (2) being able to determine what information is missing and needs to be looked up; (3) being able to recognize relationships between variables in a problem; (4) recognizing multiple levels of complex problems and (5) being able to represent problems with diagrams. A gateway examination system based on these identified skills was implemented in a General Chemistry course for engineering students and important insights into the nature of assessing problem-solving were derived from this study.

From a cognitive theory perspective, there are several reasons to suggest that questions that are designed to elucidate student understanding of their own problem-solving skills will have useful learning outcomes. Prior research suggests that enhanced metacognitive skills are associated with higher order learning (*4–6*), and most college courses include such learning as important goals. The gateway exam approach within general chemistry therefore was designed to explicitly assess whether or not students can identify their own problem-solving strategies for various chemistry problems. Such explicit questions tend to force metacognition.

The gateway exam scheme in general chemistry for engineering students focuses on the assessment of student problem-solving. Studies associated with conceptual understanding in chemistry (*7–9*) and physics (*10*, *11*) have demonstrated that the ability of a student to get a correct numerical answer does not necessarily demonstrate that they know the science incorporated in the problem. In part because of these studies, the gateway testing regime was designed to have students to describe how they solve problems, often ones that include incomplete information, rather than simply providing numerical answers for specific chemical queries. Thus the premise is that students who cannot elucidate their problem-solving strategies are not as likely to generalize those strategies outside of chemistry.

When it was implemented, the gateway exam concept was used in the first semester of a two-semester general chemistry course taken exclusively by pre-engineering students. This course was subsequently abandoned by the College of Engineering for a one-semester alternative, as will be noted later, but the essential premise of the gateway project is not altered by that curricular modification. To maximize the opportunity to emphasize problem-solving, two gateway exams were required during this course. The first exam is given roughly 2 weeks after the first regular exam – and after both stoichiometry and introductory energy concepts have been covered in the course. The driver for student behavior was only positive, that is, there was a grade benefit for passing two exams, but there was no sanction associated with not passing both tests. The exam consists of nine questions, all of which were free response format. To provide some insight into the way such questions are worded and graded, an example of one question from the Gateway Exam are provided in Figure 1.

This type of question can cause difficulty in grading because of the use of free responses. The precise rubric is seldom given as a student response. This type of ambiguity, however, is not particularly unique – and is encountered in any free response question. Other questions require fewer components for a correct response – but this example is representative of the type of question that is in the gateway exams. All gateway exams were graded by a team of only two graders to minimize grading errors associated with interpretations of student responses.

It is important to realize that the expected responses to questions such as these are quite different from what students have been expected to produce in their previous courses. Some students noted their discomfort with questions that did not ask for a specific answer, but rather how to proceed to get an answer.

Because the gateway exam concept includes competency based examinations (*12*, *13*), it also requires the scheduling of retake exams. Students are allowed to take similar exams until they demonstrate that they are competent in the material being assessed, in this case problem-solving skills. This requirement did impose some logistical concerns that were handled via a scheduling system similar to those currently available in many course management systems. Further details about the logistics of implementation of competency based exams will not be included because they tend to be platform dependent.

For the implementation of gateway exams, students were expected to pass two separate exams (after roughly four weeks of class and again after eight weeks), so with a cohort of 93 students, a total of 393 exams were collected and graded. Unfortunately, the grading burden associated with such a large number of exams was not evenly distributed, as students clumped together when they took retake exams – mostly at times near the deadline. In addition, establishing the cutoff point for competency based testing is not without controversy (*14*). For gateway exams in general chemistry two cutoffs were established. For the first instance of the exam, taken during class time, a passing grade is 78% (70/90) while for retakes the cutoff was increased slightly to 83% (75/90). The separate levels were instituted to provide some impetus for students to try to pass on the first attempt. Even with the lower cutoff, few students (less than 5%) passed the exams on the first try. Despite the fact that few students passed the Gateway Exam on the first try – most students who made an effort to take retake exams did eventually demonstrate competency. Patterns of student retake behavior reveal some interesting trends.

"*Copper oxide, CuO is responsible for the green color sometimes observed on copper fixtures used on houses or other buildings. CuO can be converted back into copper by a reaction with hydrogen at high temperatures,* $CuO(s) + H_2(g) \rightarrow Cu(s) + H_2O(g)$. *Suppose you have a piece of a façade from a famous building and you wish to remove the oxide coating by this reaction. If the surface area of the piece is 480* cm^2 *and the oxide coating is 1.5 mm thick, how would you determine the minimum amount of hydrogen gas you would need to carry out this particular reaction? Would you need to look anything up to solve this problem?*"

Rubric of expectations for a correct response components for the example question
1. Determine the volume of CuO from the given dimensions (conversion of mm to cm)
2. Look up the density of CuO
3. Determine the mass of CuO by multiplying density by volume
4. Look up or calculate the molar mass of CuO
5. Convert mass of CuO to moles of CuO
6. Use chemical equation to note that moles of CuO and H_2 are the same
7. From the moles of H_2 determine the mass of H_2 using the molar mass.

Figure 1. An example question and scoring rubric from the first Gateway Exam.

The most interesting pattern associated with gateway exams is the difference in the recollection of students who passed both exams versus those who did not. In an end of course survey students were asked, among other things, to identify how many times they retook gateway exams in order to demonstrate competency. These self-report results can be compared to actual student retake numbers and this data is summarized for students who did not pass two exams in Figure 2.

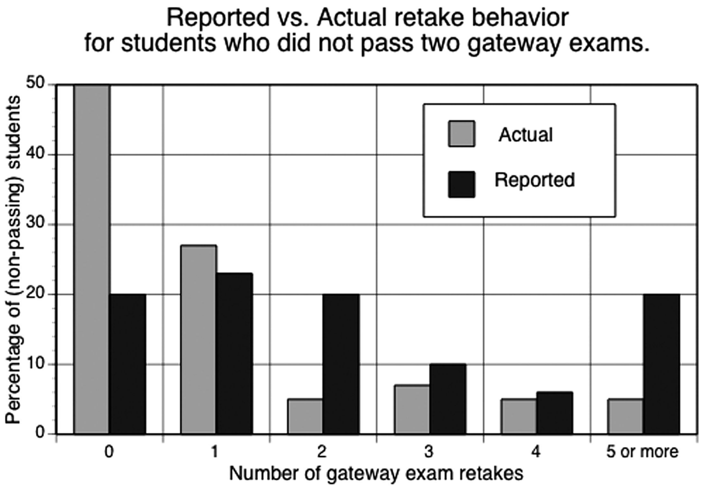

Figure 2. Actual student retake behavior compared with reported retake behavior for students who did not pass both gateway exams.

Looking at this information, which shows only students who did not pass both gateway exams, half of them did not avail themselves of retaking either exam (50% actual retakes are zero). Only 20% of these students reported that they took no gateway exams. At the other end of the spectrum, only ~5% of the studented who didn't pass both exams took 5 or more gateway exams, and yet 20% report having done so. Perhaps it is not surprising that students who struggle with the gateway exams mis-remember their efforts. Nonetheless, this evidence suggests that followup communications with students who have not yet passed gateway exams may be an important component of promoting student success.

Externally Imposed Curricular Changes

At roughly the same time that the gateway exam project was implemented, faculty and adminstrators in many colleges of engineering were confronting a realization that they had to respond to an overcrowded curriculum. Basic science courses were investigated relative to the overall credit load and in many schools, for many engineering majors, the chemistry requirement was reduced from two semesters to one. In principle, chemistry departments could respond by having students take the first semester of the two-semester sequence, and it's apparent that this response has occurred in a number of schools. From the perspective of

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course content, however, this choice is less than ideal because some of the topics in the second semester, such as corrosion and electrochemistry, would appear to be useful for future engineers.

At the same time, attempting to simply squeeze all the content of a full year course into a single semester is also an unattractive option. Thus, efforts to establish a sensible one-semester alternative were undertaken and implemented. Initial activities involved working with faculty from the engineering departments to identify chemistry content they viewed as particularly important. Next, general chemistry instructors were queried to identify fundamentals that could not be abandoned if the more applied topics often mentioned by the engineers were to be adequately treated. Then, for a series of four semesters, the new one-semester course was offered and measures of learning included the use of a full-year ACS general chemistry exam (*15*) to make comparisons between local students in the one-semester course and national samples of students in full-year courses. During these four semesters, course average grades on the ACS "brief" exam (selected because it only used half of the final exam testing period) were within half of a standard deviation of the national average, three times slightly below and one time slightly above. Thus, even though the one-semester course necessarily abbreviates the coverage of topics, students in the course show reasonable content knowledge when compared to a national sample of students who have taken a full, two-semester version of general chemistry.

The course thus designed includes coverage of most of the topics of the full year general chemistry course. In many cases, however, the depth of the coverage is sacrificed. Thus, topics covered include:

- Introductory concepts
- Molecules, reactions and chemical equations
- Stoichiometry
- Gases and gas laws
- Atomic structure and the periodic table
- Chemical bonding
- Materials
- Thermochemistry
- Thermodynamics
- Kinetics
- Equilibrium
- Electrochemistry

In addtion to the fundamental chemistry, however, specific efforts to cover engineering applications were also incorporated. Thus, for example, as noted earlier, the coverage of electrochemistry was explicitly tied to understanding of corrosion. Coverage of corrosion includes galvanic and crevice corrosion, in addition to uniform corrosion that is more commonly found (often briefly) in general chemistry courses. Similarly, the treatment of stoichiometry focuses significant time on the use of fuels, not excluding other important reactions, but providing an emphasis on chemistry that a significant number of engineering students might find relevant to their future studies.

A major drawback for staging this course was the lack of a textbook that utilized this approach. A number of educators recognized this problem in designing a one-semester course, and as a result several textbooks were developed (*16–18*). The idea that the chemistry content should look essentially like any general chemistry course, but that the content be couched within applications that might be more easily seen as relevant to engineering students was the core concept of the text developed by Brown and Holme (*16*), and this book is now being revised into a third edition. The chapter coverage looks similar to the bulleted list above, with the exception of an additional chapter on nuclear chemistry. Engineering contexts that have emerged for the course include a diverse set of topics including, air pollution, biomass and biofuels, concrete fabrication and aging, nanotechnology, and trace analysis of materials. An additional emphasis on materials related chemistry results in the incorporation of ideas about polymers, for example, throughout the text as well.

Another feature of this book is that it incorporates a feature that uses many of the problems devised in the gateway exam project. When the course was moved to the one-semester format, the curricular crowding in terms of topic coverage became such that the time devoted to the gateway exam problem-solving testing was no longer feasible. In a formal sense the gateway exam project was shut down. Nonetheless, the idea of explicitly teaching the value of problem-solving and working to help students transfer problem-solving skills remains in the course and in this textbook. At the end of each chapter, there is a section referred to as "Focus on Problem-solving" and the questions there are similar (indeed in many cases identical) to those used in the gateway exam project. Thus, the lessons learned in that project continue forward even though the competency based testing concept itself is no longer in use.

Further Investigations of Problem-Solving

Regardless of the time contraints and curricular demands of the one-semester course, the premise remains that a key developmental component of the chemistry course for pre-engineering students lies in the enhancing of problem-solving skills. An important question then becomes, what is problem-solving in this context, and how do chemistry exercises help students learn problem-solving skills? Thus, having initially implemented gateway exams, then having to forego them as a result of curricular compression, a key question still required research. Specifically, how do chemistry problems become more than just exercises (*19*) for engineering students? This question was investigated in two ways; using an online problem-solving system called IMMEX (*20–24*) and via interview-based qualitative research with pre-engineering students.

One means used to determine student problem-solving behaviors used the IMMEX system. The IMMEX system was an on-line tool that required students to solve ill-defined problems that related chemical concepts to real-life contexts. Each problem set in IMMEX was designed to have a general description of the situation, and have links to all the data and background information a student might need to solve the problem. Each problem set has different examples, or

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clones, with different values for variables, or different compounds to identify, and the exact example given to each student was randomized. Students solve several clones for each assignment, and this repetition results in them stabilizing into a measurable problem-solving strategy (*21*). A computer system tracked data behind-the-scenes about what links the students access within a problem set and collected that information into a database. The information in that database is then analyzed using artificial neural networks, Hidden Markov Models and sorting of student learning trajectories (*20*) into quadrants that measure both effectiveness and efficiency of problem-solving.

For the purposes explored here, the key feature of these quadrants scores is that they categorize students based on the solutions they achieve and the pathways they take to get there. Those students who fall in quadrant 1 are neither efficient nor effective at that given problem; students in quadrant 2 are efficient but not effective in their problem-solving; quadrant 3 has students who are effective at finding a correct answer but not efficiently and quadrant 4 has those students who are both efficient and effective at solving the complex problem. This ordering of quadrants represents a ranking where students would ideally progress from lower values (1 & 2) towards higher values, with a score of 4 being the goal.

In the one-semester chemistry for engineering course, during a particular semester, students were assigned five different IMMEX problems covering the topics of (1) identifying elements or compounds, and states of matter (Model Madness); (2) stoichiometry (How Much to Order); (3) gas laws (Gas Laws on Planet Ardanda); (4) thermochemistry (RXN) and (5) the qualitative identification of an unknown (Hazmat). Again, it is important to place these assignments in terms of content coverage in the course, problem 1 is based on prior knowledge of basic chemical facts. Problems 2-4 are based on material that is directly covered in class. Problem 5 requires students to identify an unknown based on the results of chemical tests, a task that was not specifically covered in the course, but requires logical application of test results that utilize familiar topics. For example, the Hazmat problem uses flame tests to allow students to identify elements present, and this concept is incorporated in the instruction of atomic structure in the course. The idea of atomic spectra being useful in this way in the laboratory, however, was not explicitly covered.

The percentage of students whose problem-solving strategies stabilize into each of the four quadrants on each of these problems is shown in Figure 3.

Looking at this graph it is possible to identify important trends that suggest the pathway pre-engineering students take related to problems versus exercises in chemistry homework. First, the percentage of students in either quadrants 1 and 2 (where effectiveness in problem-solving is less) is roughly the same through the 1st three problems, drops slightly in problem 4 and rises notably for the final problem. To the extent that obtaining a correct answer is the goal of the homework assignment that uses the IMMEX system, students in these quadrants are struggling. The number of struggling students does drop in the last "familiar" topic assigment, but rises sharply when the content is less familiar. While the details are different, the importance of content familiarity is also evident with students who do succeed in solving the problems (quadrants 3 and 4). In this case, the problem-solving goal is towards higher efficiency. Looking at problems 2

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through 4, the efficiency is increasing, to the point where 83% of the students are effective at obtaining the correct answer, and with half of them doing so efficiently (quadrant 4). When the last, less familiar unknown analysis, problem is assigned the efficiency of this group of (successful) students drops precipitously. Thus, for this cohort of students at least, this data suggests that a majority of pre-engineering students progress towards more efficient problem-solving strategies throughout the course as long as the problems involve chemistry content on which they have received explicit instruction. Perhaps they are able to progress to the point where what starts as a chemistry problem becomes a chemistry exercise. That progression is strongly hindered (efficiency drops significantly) when they must utilize chemical information in less familiar ways to solve the problem.

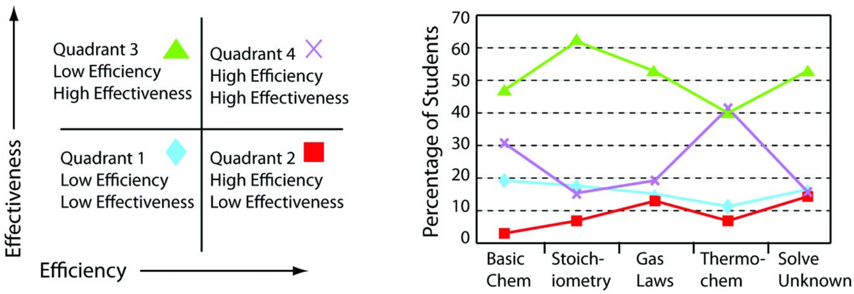

Figure 3. (left) Definitions of learning trajectory quadrants. (right) Percentage of students in each learning trajectory quadrant (number of students in sample = 650).

The second study that probed the difference between exercises and problems in general chemistry for engineering students used qualitative methods in an interview format. Twenty volunteers were solicited from a large-lecture pre-engineering general chemistry class to take part in a one and a half hour to two-hour interview at a time of mutual convenience for the interviewer and interviewee. The students were offered free food for taking part in the interview and informed consent was obtained. In order to ascertain the students' thoughts while they were working through a set of chemistry problems, a talk-aloud protocol was used during the interviews (*25*). This protocol asks students to verbalize what they are thinking about doing or why they are using a particular idea or method while they are doing it. During the interview, students had access to their textbooks, to a calculator and to the internet to be able to look up unfamiliar terms or ideas. The interviews were video and audio recorded for data collection purposes and they were transcribed as part of the data analysis process. Of the twenty volunteers, 11 students completed the two tasks analyzed here as well as having participated in a readiness diagnostic test for the course that was used to establish that similar background knowledge was present in the students whose work was analyzed. The chemistry content of the interview consisted of three questions each on stoichiometry and thermochemistry. For the purpose of the discussion here, results from the student interviews during two of the stoichiometry questions will be presented. These two questions were patterned after end-of-chapter questions in general chemistry textbooks and are presented in Table 1.

Table 1. Interview questions for stoichiometry problems

Familiar Question (exercise)	*Unfamiliar Question (problem)*
What mass of oxygen is needed to completely combust 1.00 g of ethanol to produce carbon dioxide and water?	Octane (C_8H_{18}) is a component of gasoline. Complete combustion of octane yields H_2O and CO_2. Incomplete combustion produces H_2O and CO. If 1.000 gallon of octane is burned in an engine and the total mass of CO, CO_2 and H_2O produced is 11.53 kg, what is the efficiency of the process, in other words, what fraction of the octane is converted to CO_2? The density of octane is 2.650 kg/gal.

The initial analysis of problem-solving behavior utilizes a categorization scheme proposed by Calimsiz (*26*), that identifies seven traits of problem-solving:

(1) gaining basic familiarity with the problem
(2) restating the problem
(3) searching for a starting point
(4) working from the starting point towards the final goal
(5) consulting sources
(6) modifying or abandoning a step or route
(7) evaluating the work done

While any of these behaviors can be found in a students' attempt to solve a problem, the percentage of time spent in each behavior points to the strategies being used. There is no single correct path to solving problems of this nature, but for students to reach the level of efficiency that is associated with quadrant four in the previously noted IMMEX study, an increased amount of time in productive work towards the goal (behavior 4) is probably the most likely to lead to efficient solution of the problem. A graph showing showing percentage of time spent in each of the seven problem-solving behaviors for both tasks is shown in Figure 4.

These two graphs show distinct differences that establish that students who encounter familiar style stoichiometry problems (Figure 4 - top) spend a majority of their time productively moving towards an answer (behavior 4) and looking up resources needed to achieve that goal (behavior 5). By contrast, for the unfamiliar problem that includes both complete and incomplete combustion, more exploratory behaviors are notably more common. A greater percentage of time is spent gaining familiarity with the problem and restating it (behaviors 1 and 2). While still a small percentage, more time is spent looking for a starting point (behavior 3). Relatively little time is spent looking up resources (behavior 5), though the same resources were available in both cases – including internet access. Finally, a significantly greater percentage of time is spent by students trying to evaluate their progress (behavior 7). It is certainly true that students still spend much of their time trying to "work the problem" (behavior 4), but it is also apparent that the unfamiliar problem type induces more general problem-solving behaviors. Given the challenge of this problem for most of the students, they are ultimately utilizing general strategies that are likely to be important to learn if they are to improve their overall problem-solving ability.

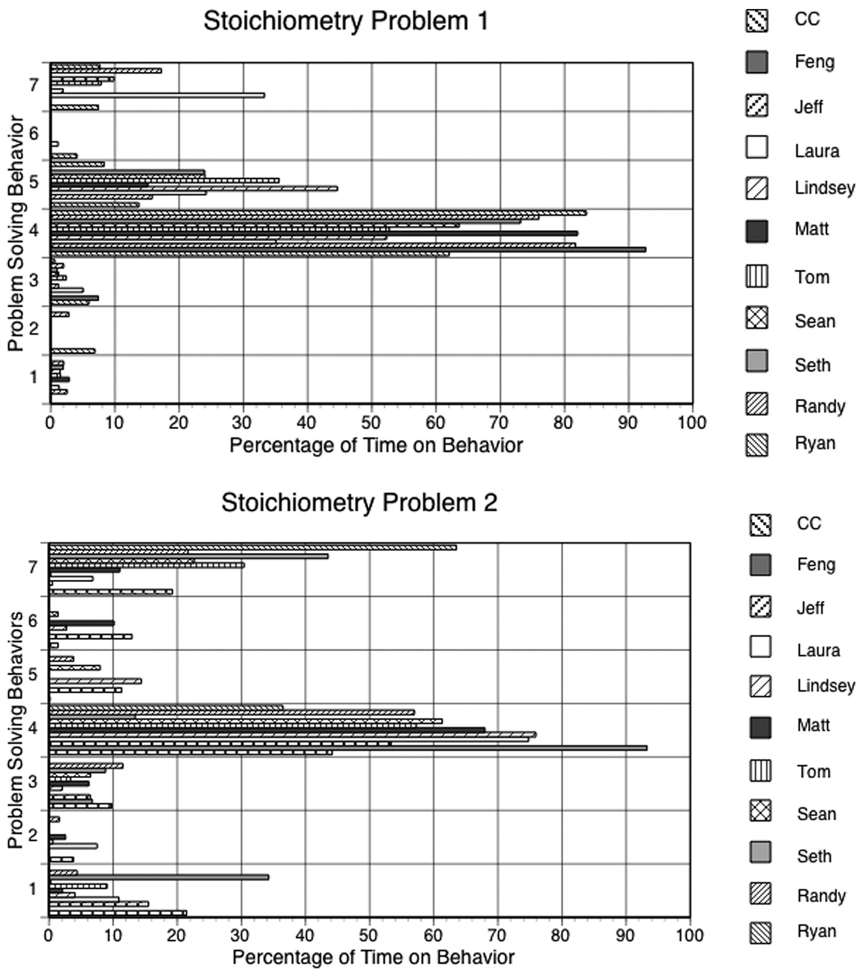

Figure 4. Problem-solving behaviors for a familiar task (top panel) and for an unfamiliar task (bottom panel).

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This final observation, that it is possible to induce more problem-solving exploration with a fairly modest contextual change to a traditional stoichiometry problem is a key result. To the extent that an important learning objective for pre-engineering students in general chemistry is the development of problem-solving skills, it is noteworthy that practice of such skills can be induced with arguably modest increases in the complexity of the type of problems students are expected to do. Anectdotal supporting evidence in support of this premise arises from classwide discussions of a kinetics problem as part of homework in the course. The problem was a unimolecular dissociation into two product molecules, and the only information given was the total pressure as a function of time. In this problem, a student must be aware that the total pressure change essentially provides a second numerical relationship that allows the problem to be solved. A similar level of reasoning is needed in the octane problem used in this study.

Thus, there appear to be two ways that remove students from a problem-solving behaviors that are algorithm driven and more akin to answering exercises. As noted in the IMMEX study, changing the chemistry context appears to challenge students into using more general (and at least early on less efficient) problem-solving strategies. The second method that accomplishes this goal is to incorporate the need for students to recognize a second quantitative relationship within the problem, beyond those relationships in more "exercise" style problems.

This combination of observations has implications for how to incorporate problem-solving strategy development within the one-semester general chemistry course for engineers. The homework assignment strategies for this course have been changed to explicitly incorporate the findings presented here. Students are presented with "suggested" problems from the end-of-chapter selections that are more commonly in the exercise category so they can have the practice they may need with this level of question. These suggested problems are not handed in. Rather, a small number of the more challenging problems that are more likely to move them past exercise-level algorithmic approaches are what must be turned in for grading. Grading burdens on teaching assistants are minimized by limiting the number of these problems that are assigned. The problems occasionally include the "Focus on Problem-solving" style questions where the answers students must provide are strategies, rather than numerical answers. Students in the course are told explicitly that these assigned problems are expected to be more complex and likely more time consuming for them – and because of the time they take such problems could not be included on timed-tests, for example. Shifting such problem-solving activity to the homework side of the course is accompanied, however, by explicit discussion of strategies for approaching complex problems during lecture. Thus, while the accountability students have (points in the course) is paired with homework, the message of problem-solving strategy development is consistent in all aspects of the course.

Summary

This chapter has focused on the teaching of general chemistry for pre-engineering students. Because this course is fundamentally a service course for other majors, the premise has been taken that ways to connect to the needs of those engineering majors must be advanced. In this case, the primary transferable need that has remained the focus of attention throughout many changes in the course has been problem-solving.

Nearly any chemistry instructor would be delighted if engineering students remember a sizable portion of the chemical details of such a course, but realistic appraisal of the prospects for this outcome is not likely to be optimistic. Using problem-solving improvement as an explicit goal for engineering students, within the context of essentially traditional concepts of chemical science represents a meaningful compromise. Students appear to have a greater buy-in for the course because the benefits towards their own goals for their studies are made explicit. At the same time, it is possible to convince students that problem-solving in any domain requires fundamental knowledge of the content – in this case chemistry.

The trajectory by which this problem-solving emphasis has emerged for this course has been presented here. To be sure, a significant amount of research remains to establish that the goals of transferring problem-solving skills are achieved with this approach. Such research is expected to be initiated in the future.

Acknowledgments

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