AC 2007-139: A STUDENT-CENTERED APPROACH TO THE STOICHIOMETRY COURSE

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Abstract

For several years, the stoichiometry course at N.C. State University has incorporated a variety of student-centered teaching methods, including extensive active and cooperative learning. This paper describes the instructional approach used in the course, outlines student responses to it, and offers recommendations to instructors contemplating a similar approach.

Introduction

The introductory chemical engineering course in most programs—the "stoichiometry course"—is considered by many alumni the most important course in the curriculum. Their jobs may not call for them to remember anything from their transport or kinetics or control or calculus courses, but if they are still functioning as chemical engineers, they are probably still involved with material and energy balances on processes—formulating them, solving them, and trying to figure out why they don't close in practice the way they do on paper. Students taking the course have historically not had such a positive view of its utility, however. They are more likely to fear and/or despise it, describing it in terms that often include the term "weed-out," and it is not uncommon for that description to be accurate. Exam grades in the course are chronically low, failure rates are high, and student ratings are often lower than they are for any other course in the curriculum.

Beginning in the late 1970s, an active learning-based approach to the stoichiometry course was adopted at N.C. State, in which most lectures included activities that provided practice and feedback in the methods that would be required on homework and tests. A 1990 paper outlined the new instructional approach and described the turnaround in student performance and evaluations that resulted from its adoption.[1] The stoichiometry course has continued to evolve. Since the early 1990s, it has been taught using cooperative (team-based) learning, with measures being taken to hold all team members individually accountable for the entire content of team assignments. Instructional technology has played an increasingly important role in the course, with variety of software tools supplementing traditional instruction. Assignments include traditional closed-ended problems as well as open-ended problems that call for creative or critical thinking or both.

In the Fall 2005 semester, 110 students enrolled in two sections of the stoichiometry course. Although each of the authors was primarily responsible for one lecture section, we worked together closely to generate common course materials, assignments, and tests, and we periodically guest-lectured in each other's sections. This paper outlines the structure of the course and how it was taught, and offers suggestions to faculty who might wish to adapt the approach to their own teaching.

Course Structure and Policies

The stoichiometry course at N.C. State, designated CBE 205, is a four-credit 1-semester course, structured as three 50-minute or two 75-minute interactive lecture classes per week taught by a faculty member plus a two-hour weekly problem session (recitation) conducted by a graduate teaching assistant. The text is the 2005 addition of *Elementary Principles of Chemical*

Processes,[2] which comes bundled with a CD containing several instructional resources and a workbook that guides students through the solution of selected chapter-end problems. The course covers Chapters 1–9 of the text.

In the Fall 2005 offering of CBE 205, handouts and worksheets that guided students through problem solutions were used extensively in lectures, problem sessions, and homework assignments. In the problem sessions, the TAs provided a modest amount of formal instruction in Excel and E-Z Solve (a program on the text CD that solves algebraic and differential equations numerically); carried out active exercises that guided students through the solution of unassigned text problems and problems from old tests; and answered questions.

Some features of the course structure that departed from traditional practice were as follows:

- After the first four weeks of the course, most of the homework was done by instructor-assigned student teams, with measures taken to satisfy the five defining conditions for cooperative learning (individual accountability, positive interdependence, face-to-face interaction, development and appropriate use of teamwork skills, and regular self-assessment of team functioning). We will later say more about those measures.
- Homework problem solutions were not posted, although final answers were given so that students reworking problems would know when their solutions were correct. When solutions are posted, many students just copy them verbatim without trying to understand them; copies find their way into file cabinets in fraternity and sorority houses; and the frequency of perfect solutions achieved without understanding steadily rises from one semester to the next.
- The students could refer to their texts on the midterm and final exams, but not to their course notes or graded homework.
- Study guides and examples of past exams were posted on the course Web site one to two weeks before each of the three midterm tests and the final exam. The study guide for a test contained a comprehensive list of learning objectives for that test—statements of all the terms, phenomena, and concepts the students might be asked to define or explain and the kinds of problems they might be asked to solve, including but not limited to the problems they had solved in homework assignments.

The course syllabus, course policies (including the course grading system, which did not include curving), assignment schedule, handouts, study guides, sample tests, and other course materials may be viewed at <*www.ncsu.edu/felder-public/cbe205site/cbe205.html*>.

Instruction in the course closely followed Chapters 1–9 of *Elementary Principles of Chemical Processes.* The students were required to bring the text with them to every lecture class, among other reasons so that when working through problems in class they would get practice in finding the information (physical properties, conversion factors, graphical correlations, etc.) they would need to look up on the open-book tests to come.

A common student complaint in the stoichiometry course is that the examples presented in class tend to be much simpler than many of the chapter-end problems that show up on homework assignments. The 2005 edition of the course text comes with a workbook that guides students through the solutions of several of the more complex text problems. We asked the students to bring the workbooks to problem session each week, and the TA's chose relevant problems for the students to work through individually or in groups. We also included at least one workbook problem in each week's homework assignment to be completed and submitted individually, and we encouraged students to solve unassigned workbook problems when studying for exams. In their end-of-course evaluations, many students reacted positively to having the workbook as a resource.

Problem sets were assigned weekly. Most of the assigned problems were taken from the end of the textbook chapters, frequently with added open-ended parts calling for reflection on the meaning of calculated results or speculation about possible explanations for differences between the calculated results and results that might be measured. Most assignments included one problem from the text workbook to be completed individually. Every three or four assignments the teams were asked to assess their performance as a team. The assignments can be seen at <*www.ncsu.edu/felder-public/cbe205site/homework.html*>.

One assignment has to do with information literacy. Early in the course, librarians visit during a problem session to introduce students to important discipline-specific resources that chemical engineers typically use, including *Perry's Chemical Engineers Handbook,* the *Chemical Economics Handbook,* the *Kirk-Othmer Encyclopedia of Chemical Technology,* and the *Chemical Market Reporter*, as well as databases including *Compendex* and *SciFinder Scholar*. The presenters stress the importance of proper literature citation and give students brief practice citation exercises, and they discuss the idea that the credibility of information depends strongly on the source, with Perry's Handbook and a *MySpace* blog representing extremes of trustworthiness.[3]

The following assignment is given to students following the information literacy presentation. Typically they are given 2–3 weeks to complete it. By linking information competencies to assignments related to class material, we move beyond decoupled instruction that is quickly forgotten to "just-in-time" need-based instruction.

<u>Library Assignment</u>

1. Select a chemical substance from Table B.1 in your text that begins with the same letter as your first name or the nearest possible letter (for example Andy → Aniline). Find and report the information listed below for this substance in references other than the course text or CD, and properly cite the references. Organize your report neatly and show all units.

- **(a)** Specific gravity, molecular weight, normal melting and boiling points, Antoine constants, heats of fusion and vaporization at the normal melting and boiling points, and heat capacity as a function of temperature. If some of these properties are missing for your chosen species, choose a different species with complete physical properties.
- **(b)** Several examples of industrial uses of the species.
- **(c)** Toxicity data and environmental hazards associated with the species.
- **(d)** At least three companies that manufacture the species.
- **(e)** Worldwide demand and/or sales.
- **(f)** Unit pricing ($/kg, $/gal, etc.) Your figure should reflect bulk pricing, not pricing of small units from laboratory supply firms such as Fisher Scientific.

2. From the textbook index, select a topic that begins with the same letter as your last name or the nearest possible letter (for example Brent → Bubble point). Identify three published articles (not web sites) that deal with this topic and list their full bibliographic citations. Then find the articles and photocopy or print out their first pages and abstracts (if the abstracts are not included in the first pages).

Getting Started

On the first few days of class we did all the usual things—handing out materials, explaining course procedures, and talking about the importance of the course and the need to keep up with the work on a regular basis—and we advised the students to read "How to Survive Engineering School"[4] and "A Survival Guide to Chemical Engineering."[5]

On the first day, we asked the students to organize themselves into groups of three and four, presented them with a fairly extensive material and energy balance problem (Problem 8.74 of the course text), and gave them about five minutes to itemize the information they would need and the approach they would take to solve the problem. We told them that the exercise was intended to give them a preview of what the course was about and a taste of how we would be conducting the lectures and problem sessions, and we assured them that while we would collect their outlines, we would not grade them. At the end of five minutes they signed and turned in their papers. On the last day of class, we gave them the identical in-class exercise and then returned their first-day efforts to give them a tangible sense of how much they had learned in the course.

The students' first assignment was to submit a one-page autobiography, using autobiographies of the instructors as models. Our autobiographies included information about our families and personal interests as well as our academic interests, and we encouraged the students to do the same in theirs. We compiled a portrait of the class from the autobiographies and shared it as a memo to the students. Our goals in this exercise were to give the students a sense of their instructors as somewhat normal and approachable human beings and to help them start to develop a sense of community.

Handouts and Active Learning

We prepared a series of class handouts that supplemented the course text and contained a number of questions and problems, with blank spaces for answers and solutions. The complete set of handouts can be found at <*http://www.ncsu.edu/felder-public/cbe205site/handouts.html*>. In a typical lecture session, the class would work through part or all of a handout in a mixture of lecturing by the instructor, individual activities, and small-group activities focused on the questions and gaps in the handouts. The students would individually read a passage of text or part of a problem statement or solution and perhaps briefly discuss it in small groups to make sure they understood it. When they reached a gap, one of several different things might happen: (a) the instructor might go through the solution at the board in traditional lecture format; (b) the students might be given a short time (30 seconds–3 minutes) and asked to work individually or in small groups to try to fill in the gap; or (c) the instructor might skip the gap and tell the students to be sure they knew what went in it before they got to the next exam. The class was told and periodically reminded that some of the questions and problem segments in the handouts would show up on the exams, and they did.

When active learning (individual and group activities in class) was used, the instructor used a variety of formats. Sometimes students worked together in pairs or groups of three or four; sometimes they worked individually; and sometimes they worked individually first and then got into pairs, compared their solutions, and tried to reconcile any differences (*think-pair-share*). Occasionally they worked in pairs with one student doing the solving and explaining and the other asking questions and giving hints if necessary (*thinking-aloud pair problem solving*), with the roles reversing from one activity to the next. In all of these cases, when the instructor stopped an activity, he/she would call on several students for responses, ask for additional responses from volunteers, perhaps augment or elaborate on the responses, and proceed with the lesson.

Numerous research studies have demonstrated the effectiveness of relevant activities at promoting learning and skill development.[6] We believe that more genuine learning resulted from those brief activities in class and problem sessions than from everything else we did in class. (For more information on active learning, see Felder & Brent.[7])

Cooperative Learning

Most of the weekly homework assignments were completed by student teams, with the assignments being structured in a manner that met the five defining criteria for *cooperative learning*[8]:

1. *Positive interdependence*. The team members must rely on one another. If a team member fails to fulfill his or her responsibilities, the overall team performance evaluation suffers.

2. *Individual accountability*. Different team members may take primary responsibility for different parts of the assignment, but each team member is held individually accountable for the entire assignment content.
3. *Face-to-face interaction, at least part of the time.* Much of the learning in cooperative learning takes place as teams discuss and debate conflicting strategies and solutions. This criterion precludes the "divide-and-conquer" strategy in which different team members complete different parts of the assignment and simply staple the parts together, so that each student only knows about the part he or she did.
4. *Development and appropriate use of interpersonal skills*. Team members are helped to develop skills required for high-performance teamwork, including leadership, communication, time management, project management, and conflict resolution.
5. *Regular self-assessment of team performance.* The members periodically reflect on what they are doing well as a team, what they need to improve, and what if anything they will do differently in the future.

Detailed information about cooperative learning strategies and the research base that supports the effectiveness of this method is provided by Smith *et al.*,[8] Felder & Brent,[9,10] and Oakley *et al.*[11]

Primarily because some students normally drop CBE 205 in the first few weeks of the course, we made the first four assignments individual, which minimized the number of homework teams that had to be reformed due to drops. As is consistently recommended in the cooperative learning literature, we formed the teams rather than allowing student self-selection. All teams had either three or four members. Before we formed the teams, we collected information from all the students including their grades in prerequisite courses, the hours during the week when they were unavailable for working on group homework assignments, and their gender and ethnic background. (They had the option of declining to provide the latter two pieces of information.) We then formed the teams using three criteria:

1. *Ability heterogeneity*. When there is a spectrum of abilities among team members and the team is functioning effectively, the weaker students get the benefit of one-on-one tutoring from their stronger teammates and the stronger students get the greater depth of understanding that usually results from teaching others. Grades in prerequisite courses serve as our measure of ability.
2. *Common blocks of time to work on assignments outside class*. If teams are randomly formed, conflicting demands imposed by other classes, extracurricular activities, and jobs can make it impossible for the members to find a common meeting time at a reasonable hour of the day. We do our best to make sure that the teams we form have a few hours each week when none of the team members have conflicting obligations.
3. *No isolation of at-risk minorities in teams.* Studies have shown that students in minorities historically at risk for dropping out tend to be marginalized if they are isolated in student teams.[8] Women and African-American, Latino, and Native American men are at greater risk for dropping out of chemical engineering in the first two years of the curriculum than are men in other ethnic groups, and so we tried to make sure that no team had only one member in any of those categories.

To sort the students into teams, we used an on-line instrument called *Team Maker*® developed by Richard Layton at the Rose-Hulman Institute of Technology.[12] The students enter the requested information into a database, the instructor specifies the sorting criteria, and Team Maker does the sorting. We have found that the instrument sorting is more reliable than our manual efforts ever were and takes much less time to implement.

Early in the semester, the students were told that a month after the teams were formed, they would be dissolved and reformed unless every member of a team stated in writing that he or she wished to remain with the same team members, in which case the team could stay together. One team in each section chose not to remain together, and we distributed their members among existing teams of three. In the past, only the most dysfunctional teams have not elected to remain together, and we have never had to dissolve more than two of them. Some of the teams that remain together encounter interpersonal conflicts, but with or without our help they work through them, which is one of our primary course objectives.

We used several methods to achieve the five defining criteria of cooperative learning.

- The midterm and final examinations were all taken individually and covered all of the content and skills involved in the homework assignments. Students had to get an average individual test mark of 60 or better to pass the course, regardless of their homework scores.
- The students were advised to outline the solutions to every problem individually before working out all the details in the group sessions. On the first few assignments, we had the students sign and turn in their individual outlines with the final team solution. The outlines were logged in but not graded unless they were not done, in which case points were deducted.
- Peer evaluations of team citizenship were conducted using an on-line rubric called the *Comprehensive Assessment of Team Member Effectiveness (CATME)* developed by Matthew Ohland of Purdue University and colleagues at several other institutions.[13] The rubric was explained shortly after the students begin working in teams and completed three times during the semester. After the first administration, the ratings were released to the students so that they could see how their individual ratings compared to the team's average rating and discuss reasons for any low ratings that may have been given. (The students are not told how each teammate rated them.) The ratings from the second two administrations were used to adjust each student's average team homework grade for the period since the prior administration. The adjustment algorithm is outlined in Reference 13.
- On two of the midterm tests, we offered a bonus of three points to all members of teams with average test grades of 80 or higher. (The test averages were generally in the low 70s.) This offer encourages the best students in each group to try to get the highest grade possible and it also encourages tutoring, as the stronger students try to help their weaker teammates maximize their grades to help raise the average above the criterion level. We do not require all team members to get above 80, which would put unrealistic and sometimes impossible demands on the weakest members.
- Every three weeks the homework assignment included a question that asked the team to specify (a) what they were doing well as a team, (b) what areas needed improvement, and (c) what, if anything, would they try to do differently in future assignments.

- Several times during the semester we conducted 10-minute *mini-clinics* in class to help students figure out methods for dealing with common problematic situations.[10] We would describe a situation (e.g., the presence of a hitchhiker on the team) and ask the students to work in small groups and brainstorm possible team responses. We listed their suggestions on the board and added our own if we had ideas none of them thought of (which didn't usually happen). Then we had the groups try to reach consensus on the best initial team response to the problem teammate, the best next response if the first one didn't work, and the best last resort response. (Most groups suggested either firing the student or leaving his/her name off subsequent assignments). We listed those suggestions, and then went on with the lesson. The students left with excellent strategies for dealing with the situation under discussion, and the miscreants were put on notice that their irresponsibility would probably have unpleasant consequences in the future.
- Students who chronically missed team meetings and/or failed to do what they were supposed to do prior to the meetings could after several warnings be fired by unanimous consent of the rest of the team, and students who repeatedly received no cooperation from their teammates could quit after several warnings. Both students who were fired and students who quit had to find teams of three willing to accept them for the remainder of the course, otherwise they would get zeroes for the remaining assignments. In practice, both firing and quitting are relatively rare. In the fall of 2005, two students were fired and none quit.

Technology

The computer played a central role in the course. We used it to demonstrate instructional software tools, communicate with students, make up assignments and tests, maintain class records, archive student team peer ratings and use them to adjust team homework grades for individual performance, and post student handouts, assignments, study guides, the course syllabus and policies, and old exams. The TAs demonstrated software in the problem sessions and maintained spreadsheets with assignment and test grades and problem session attendance records. The students worked through the instructional tutorials and used other resources on the text CD, e-mailed questions to instructors and TA's, viewed and downloaded assignments and various resources posted on the course Web site, and used Excel and E-Z Solve on homework problems. The Department does not yet offer CBE 205 in a distance education format, but given the current extent of our use of instructional technology, the transition to a distance offering in the future should be straightforward.

Most computer instruction in CBE 205 took place in the weekly two-hour problem session. A brief introduction was given to E-Z Solve (which is user-friendly to an extent that almost precludes the need for instruction), and then half of each of the first four problem sessions was spent teaching Excel, using an instructional CD we developed with basic instructions for key operations and worked-out examples from the course text. The students worked individually and in pairs on their own laptops or on laptops checked out from a department cart. Starting in 2006, the university began requiring all N.C. State students to bring their own laptops, which will eliminate the need to maintain the cart.

Assessment and Evaluation

Study Guides and Tests

There were three midterm exams and a comprehensive final exam in the lecture section, and two computer quizzes (on E-Z Solve and Excel) in the problem session. (See <*www.ncsu.edu/felder-public/cbe205site/tests.html*> for sample exams.) The midterms and final exam were open-book but the students could not refer to their lecture notes or worked-out homework solutions, and the computer quizzes were closed-book. The students were strongly advised to use tabs or some other system to mark locations of important text material so they wouldn't waste a lot of time hunting for things during the open-book tests. They were also advised to read "Tips on Test-Taking"[14] before the first midterm exam.

One to two weeks before each exam, we posted study guides on the course Web site (see <*www.ncsu.edu/felder-public/cbe205site/guides.html*>) that listed the terms and concepts the students might be asked to explain and the types of things they might be asked to do (calculate, formulate, derive, troubleshoot, brainstorm…) on the exam—which is to say, we announced our learning objectives for the course. The class period before the exam was designated as a review session and the students were encouraged to come prepared with questions about the test, which they did. In some of these sessions, we described a system and had the students brainstorm questions and problems related to it that we might ask on the test. The tests were composed entirely of questions and problems of the types listed on the study guides.

Course grading

An absolute grading system was used to determine final course grades, using a weighted average of the midterm exam grades (40%, with the lowest of the three grades counting half as much as each of the other two), the final exam grade (30%), homework grades, with team grades adjusted for individual team citizenship (20%), and problem session quizzes and in-class exercises (10%). The grading criteria were as follows: ≥97=A+, 93–96.9=A, 90–92.9=A–, 87–89.9=B+,..., 63–66.9=D, 60–62.9=D–, <60=F. A grade of C– or better is required to move on to the next course in the departmental curriculum.

The course grade distribution was as follows, with "A" denoting grades of A+, A, and A–, and similarly for B, C, and D: A–18%, B–36%, C–27%, D–6%, F–9%, (S, U, IN)–4%. Grades of S and U (satisfactory and unsatisfactory) are given to students who choose to take the course on a pass-fail basis—which only non-majors are allowed to do—and IN denotes incomplete, a grade given only to students prevented from completing the course requirements by serious demonstrable extenuating circumstances.

Student Evaluations

We collected informal mid-semester student evaluations and formal course-end evaluations, the latter using the form prescribed for all courses by the CBE Department.

The mid-semester evaluations asked the students to list features of the course that were contributing to their learning and features that were hindering their learning. The features contributing to learning mentioned by more than two students were (in order of the number of students mentioning them) the homework, office hours, class handouts, problem session, group homework, instructors' availability and helpfulness, lectures, class activities, text, and text workbook. The features that they felt were hindering their learning were the earliness of the class (8 a.m. for one section, 8:30 for the other one), the rapid pace of the lectures, group homework, harsh grading of homework, length of the assignments, and lectures (too much theory, not enough examples, repeating material in handouts). In response to their comments, we increased the number of worked-out examples covered in lectures and problem sessions, and eliminated some material from the lectures so we could slow the pace down. In response to a complaint from one of the students, we also cautioned one of the TA's to avoid sarcastic remarks when grading homework

In the final course evaluations, the course and the instructors were ranked well above average for all departmental undergraduate courses. The only systematic complaints had to do with the heavy workload, the problem session (which some students did not find particularly helpful), and the earliness of the class.

Conclusions and Recommendations

The stoichiometry course described in this paper incorporates a variety of instructional methods designed to maximize learning and skill acquisition. The methods include writing learning objectives and using them to guide the design of both instruction and assessment; sharing the objectives with the students in study guides for exams; and using forms of active and cooperative. Although the course tests included more high-level thinking questions than CBE 205 exams normally contain, the students performed substantially better than they normally do when the course is taught traditionally.

We did not carry out a control study to confirm the last observation, mainly because there was no need to do so. Our objective was not to validate the methods we were using: the literatures of cognitive science and engineering and science education are filled with demonstrations of the effectiveness of those methods.[6,8,15–17] Moreover, Felder used many of the same pedagogical methods in a sequence of chemical engineering courses including the stoichiometry course and demonstrated that the performance and attitudes of the students in his classes were consistently superior to those of a traditionally-taught comparison group.[18,19]

This is not to say that every instructor of the stoichiometry course should immediately try to do everything we have described in the paper. We would never presume to suggest such a thing even if we believed it to be sound advice, which we don't. Different teachers have different teaching styles, personalities, teaching philosophies, levels of experience, competing demands on their time, and levels of comfort with different teaching methods. For an instructor to launch full scale into a pedagogical approach with which he or she is unfamiliar and/or uncomfortable is a prescription for likely disaster.

What we suggest is that instructors consider a gradual movement toward the style of teaching we have described. For example, if you are an instructor preparing to teach the stoichiometry course:

- Consider doing several things at the beginning of the course to help establish a sense of the class as a learning community, such as learning as many of the students' names as you can as quickly as you can and/or sharing something of yourself with them through an introduction or biography and getting them to do the same for you.
- If you have never written formal learning objectives, try writing them for one section of the course and posting them in a study guide for the test covering that section.[20]
- If you have relied exclusively on traditional lecturing in the past, consider introducing some short small-group activities that call on the students to do the same things they will be called upon to do in assignments and tests.[7]

- Instead of only assigning homework problems of the "Given this and this, calculate that" variety, add problems that call for students to improve their higher-level thinking skills, such as asking them to think about why measurements might differ from values they calculate, or to think of as many ways as they can to measure a physical property described in the course, or to interpret familiar phenomena making use of concepts taught in the course.
- Once you have gained a reasonable level of comfort with those methods, you might move toward balancing individual work with cooperative learning, assigning problem sets to student teams but taking care to hold individual team members accountable for all the knowledge and skills required to complete the assignments.[8–11]

As these methods become more familiar, you can continually increase their use, always seeking the optimal blend of pedagogical effectiveness and your own comfort level.

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