

This two-part series describes the structure of the stoichiometry course at North Carolina State University. The course has a variety of learning objectives, and several nontraditional pedagogies are used in the course delivery. The first paper outlined the course structure and policies, the preparation given to the teaching assistants (who play an integral part in the course delivery), and the course assignments. This one describes the methods used for classroom instruction and assessment.

A Student-Centered Approach to Teaching MATERIAL AND ENERGY BALANCES 2. Course Delivery and Assessment

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THE FIRST WEEK

On the first few days of class we did all the usual things—handing out materials, explaining course procedures (see Appendix 1A in Part 1), and talking about the importance of the course and the need to keep up with the work on a regular basis. We also did several things that are not routinely done in engineering classes.

On the first day, we took digital pictures of the students in groups of four holding name tent cards, and later we studied these “flash cards” in our offices and attempted to learn the students’ names. One of us knew all of the students in her section by the second class of the semester; the other is less gifted as a mentalist, and knew about 90% of his students by the end of the second week. The name tents, which the students also brought to their problem session, helped the graduate TAs learn the students’ names as well.

Also on the first day, we asked the students to organize themselves into groups of three and four. We then 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



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and the approach they would take to solve the problem. We told them 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 (see Appendix 2A). 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 the class start to develop a sense of community.

Something we didn't do, but plan to do in the future, is a variant of an activity our department head, Peter Kilpatrick, uses when he makes outreach visits to community high schools. Peter polls the students to get their nominations for the greatest challenges facing the world today, typically getting responses that include solving the energy crisis, reducing our dependence on nonrenewable resources, curing AIDS and other diseases, feeding the world's growing population, and reversing global warming. He then talks about how engineers in general and chemical engineers in particular will be essential in efforts to solve those problems. We can take the additional step of pointing out that whatever form the solutions to these problems eventually take, material and energy balances will inevitably play critical roles.

Finally, on the first day of class we advised the students to read "How to Survive Engineering School"^[1] and "A Survival Guide to Chemical Engineering."^[2]

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>. Appendix 2B shows an illustrative page from one of them.

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 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 then proceed with the lesson.

The approach of using handouts and active learning exercises has several purposes. Students can read straightforward material much more rapidly than instructors can present it. Having them read prose descriptions, definitions of terms, and simple algebraic and arithmetic calculations saves an enormous amount of class time—enough to cover the difficult material in lectures and activities and still get through the complete course syllabus. In addition, people learn difficult material and develop skills through practice and feedback, not by being lectured on what they are supposed to know. Numerous research studies have demonstrated the effectiveness of relevant activities at promoting learning and skill development.^[3] 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 and Brent.^[4])

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*^[5]:

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. In addition, team members who behave irresponsibly (e.g., “hitchhikers,” who fail to do what they are supposed to do and often don’t even show up) do not get the same grade as those who perform responsibly.

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.

Smith, *et al.*,^[5] Felder and Brent,^[6,7] and Oakley, *et al.*,^[8] provide detailed information about cooperative learning strategies and the research base that supports the effectiveness of this method, and Felder, *et al.*,^[9,10] describe and assess an implementation of cooperative learning in a sequence of chemical engineering courses, beginning with the stoichiometry course.

In the remainder of this section, we summarize the principal features of the Fall 2005 implementation of cooperative learning in CHE 205.

Team Formation

Primarily because some students normally drop CHE 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.

Not surprisingly, some students objected to having to work in instructor-formed teams, arguing that they preferred to work by themselves or at least to be allowed to choose their own teammates. We acknowledged their unhappiness and explained that our primary responsibility as teachers is to prepare them to be engineers, and engineers work in teams whether they like it or not, don’t get to choose their teammates, and are evaluated on their ability to work effectively with those teammates as much as (or more than) on their technical skills. That explanation may not have made all the protestors happy, but it went a long way toward calming them down.

All teams had either three or four members. In our experience, two is too few (not enough diversity of skills and problem-solving approaches, and no intrinsic mechanism for conflict resolution) and five is too many (someone in the group is likely to be left out). There were 14 teams in one section and 16 teams in the other section. Of the 30 teams, 23 had four members and seven had three members. Having four members provides more diversity of ideas and keeps groups from falling below critical mass if someone drops the course or is fired from the group (a possibility we discuss later); having some groups of three accommodates classes in which the number of students is not exactly divisible by four and enables us to add team members from groups that dissolve.

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.* We did not want some groups composed entirely of A students (which inevitably form when students are allowed to self-select) and other groups composed of C, D, and F students. Such groupings are intrinsically unfair, and teams of all good students are likely to use a divide-and-conquer strategy (parcel out the work and not even look at the parts of the assignment other than their own). 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 invariably 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 has 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.^[6] 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.

When we first began to use cooperative learning, we had the students fill out a one-page information sheet with the information needed to form teams using those criteria, and

then sorted the students into teams manually. For the last, two years we have used an online instrument called “Team Maker” developed by Richard Layton at the Rose-Hulman Institute of Technology.^[11] 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.

Individual Accountability

We used several methods to hold students individually accountable for all the assignment content (not just the parts they focused on) and for fulfilling their responsibilities on the team:

- ▶ *The midterm and final examinations were all taken individually and covered all of the content and skills involved in the homework assignments.* If students did not participate in solving the homework problems or if they participated but did not understand all of the solutions, their test grades would be likely to suffer and they would get low course grades. In addition, students had to get an average individual test mark of 60 or better to pass the course, regardless of their homework scores.
- ▶ *The 205 students were warned about the dangers of the divide-and-conquer strategy (discussed previously), of simply working out solutions together at group meetings, and were advised to outline the solutions to every problem individually before working out all the details in the group.* In divide-and-conquer, each student truly understands only the problem solution he or she obtained, and in group sessions, the strongest team members tend to outline and begin every problem solution, so that the weaker students may never get practice in either activity before the exams. On the first few assignments, we had the students sign and turn in 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 online rubric called the Comprehensive Assessment of Team Member Effectiveness (CATME), developed by Matthew Ohland of Purdue University and colleagues at several other institutions.^[16]* The students used the rubric to rate their teammates and themselves in the categories of contributing to work, interacting with teammates, keeping the team on track, and expecting quality. The rubric was explained shortly after the students began working in teams and was 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 were 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 12.

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 (optional).

- ▶ *Students who were hitchhikers (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. Students who repeatedly received no cooperation from their teammates could quit after several warnings.* 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 zeros for the remaining assignments. In practice, both firings and quittings are relatively rare. In fall 2005, two students were fired and none quit.

Positive Interdependence

Several features of the course implementation promoted mutual reliance of team members on one another:

- ▶ *We encouraged the students to distribute primary responsibility for working out different problems among the team members, balancing this advice with the measures listed in the preceding section to discourage the divide-and-conquer approach.*
- ▶ *We defined four team roles that rotated with each assignment—coordinator (to arrange meeting times and delegate responsibilities), monitor (to check each team member’s understanding of problem solutions), recorder (to produce the final version of the complete assignment), and checker (to check the final solution for errors and turn it in when it was due).* On teams of three, the coordinator also functioned as monitor. If a team member failed to fulfill his or her role, the assignment grade would likely suffer.
- ▶ *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 did not require all team members to get above 80, which would have put unrealistic and sometimes impossible demands on the weakest members.

Face-to-Face Interaction

The main thing we did to encourage face-to-face interaction was to make sure the members of the teams we formed

had common blocks of time to meet outside class. The steps described above to discourage divide-and-conquer also had the effect of promoting interaction.

Regular Self-Assessment of Team Functioning

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.

Development of Teamwork Skills

- ▶ *Shortly after the teams were formed, we had them complete a team expectations assignment in which they wrote and signed off on team rules and expectations, made copies for each member, and submitted a copy to the instructor.* When they completed peer ratings, we suggested that they refer back to the rules and base their evaluations in part on how well the team members were meeting the agreed-upon expectations.
- ▶ *Completing the CATME peer evaluation rubric was an important step in the students' acquisition of teamwork skills.* The rubric identifies well-established characteristics of members of highly effective teams and provides students with detailed feedback on how well or poorly they are displaying those characteristics. Having to complete the rubric for practice two weeks after the teams began to work together helped the students understand what was expected of them, and doing it twice more with the outcomes affecting individual homework grades reinforced their understanding.
- ▶ *Periodic self-assessment of team functioning provided further opportunities for students to reflect on the behaviors that were helping and hurting their performance as a team.*
- ▶ *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.^[7] 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.*
- ▶ *We used—and taught the students how to use—active listening^[7] for conflict resolution.* On several occasions, a conflicted team reached an impasse and required

intervention. The first of the two conflicting sides made its case, and someone on the opposite side repeated it verbatim without responding to it, with people on the first side making corrections until the second side got it right. Then the second side made its case, and the first side had to repeat it without attempting to refute it. After that, the two sides worked out a resolution. Doing so was relatively easy once each side understood the other side's case well enough to articulate it.

Team Dissolution and Reformation

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—one of our primary course objectives.

INQUIRY-BASED LEARNING

In the traditional deductive approach to teaching, basic facts and methods are taught and illustrated, and later—sometimes much later, if at all—the students are introduced to applications of the methods to real-world problems. The alternative is *inductive teaching*, in which students are first presented with a challenge of some sort (e.g., a question to be answered, an observation to be explained, or a problem to be solved), and the relevant principles and methods are presented in the context of addressing the challenge. Prince and Felder^[13,14] outline and compare various forms of inductive teaching—including inquiry-based learning, problem- and project-based learning, case-based teaching, and Just-in-Time Teaching—and summarize the research attesting to the effectiveness of these methods.

While we did not use a purely inductive approach in CHE 205, the instruction had a strong inquiry-based flavor in that questions and problems provided the context for much of the teaching. The students were told on the first day of classes that they could not count on being shown explicitly in lectures how to solve all their homework problems, but they were assured that extensive guidance would be provided in the text, the course handouts, and by the instructors and TAs during office hours. The first-day exercise, in which we had the students outline what they would do to solve a complex problem taken from the course text, is a classic inductive activity. Once we had begun discussing material balances early in Chapter 4, all new topics (recycle and bypass, reactive systems, gas laws, phase equilibrium relations, etc.) were introduced as logical

extensions of the type of analysis the students were already accustomed to.

TECHNOLOGY

The computer played a central role in the course. We used it to demonstrate instructional software tools, communicate with students, create 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 TAs, 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 CHE 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 CHE 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 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.

A technology-based resource that we do *not* use in CHE 205 is PowerPoint, since we believe that anything we might use it for can be done better with a combination of handouts, boardwork, and occasional access to Web-based resources. For the reasoning behind this decision, see Felder and Brent.^[15]

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. 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"^[16] before the first midterm exam.

One of the lecture sections met in three 50-minute periods per week and the other met in two 75-minute periods, which made it difficult to give the two sections equivalent in-class exams. Partly to avoid this difficulty and partly to minimize speed as a major factor in test performance, common midterms were given to the combined sections in two-hour blocks on

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Friday afternoons. The midterms were designed to be completed by the students in about an hour (which meant that the instructors could work through the solutions in less than 20 minutes). Each section took its own three-hour final exam.

One to two weeks before each exam, we posted study guides on the course Web site (<http://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.

Some instructors who hear about this approach for the first time are skeptical: it appears to them that we are spoon-feeding the students, eliminating the need for them to study anything beyond a narrowly restricted body of material. This is far from the case. The study guides are generic and comprehensive, and students who study hard enough to be able to do everything on them have learned what we wanted them to learn and deserve good test grades. Moreover, the study guides and the tests include problems that require thinking and conceptual understanding at levels considerably beyond those typically required in stoichiometry course tests. Based on our past experience in CHE 205, a significant percentage of the students would get low grades without the explicit understanding of our expectations that the study guides give them, and massive curving would be required to keep us from having to fail most of the class. With the study guides, they understand that they will have to go beyond rote memorization and formula substitution to succeed in the course, and all

but 10–15% of them routinely do so. (The grade distribution for Fall 2005 is given in the next section.) This is not spoon-feeding—it is teaching.

Course Grading

The absolute grading system outlined in Appendix 1A of Part 1 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 based on the peer ratings (20%), and problem session quizzes and in-class exercises (10%). A grade of C– or better in CHE 205 is required to move on to the next course in the departmental curriculum.

The grade distribution for Fall 2005 is shown in Table 1. 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.

This grade distribution is typical of course offerings since we began using the system described in this series of papers, although sometimes there are fewer C’s and more A’s and B’s. It is markedly different from distributions commonly seen in the time before 1990 when the course was taught traditionally. Then, A’s were rare, more students got C’s than any other grade, and as many as 40% got D’s or F’s or dropped the course, or if grades were curved, failing exam grades would be curved up to B’s and C’s. We are aware that some might suspect that our higher grade distributions reflect a lowering of standards. We invite any who have this concern to examine the study guides and exams on the course Web site and judge for themselves.

Academic Integrity

The following section is included in the course syllabus:

- ▶ *Academic integrity.* Students should refer to the university policy on academic integrity found in the Code of Student Conduct (found in Appendix L of the Handbook for Advising and Teaching). It is the instructor’s understanding and expectation that the student’s signature on any test or assignment means that the student contributed to the assignment in question (if a group assignment) and that they neither gave nor received unauthorized aid (if an individual assignment). Authorized aid on an individual assignment includes discussing the interpretation of the problem statement, sharing ideas or approaches for solving the problem, and explaining concepts involved in the problem. Any other aid is con-

sidered unauthorized and a violation of the academic integrity policy. All cases of academic misconduct will be submitted to the Office of Student Conduct. If you are found guilty of academic misconduct in the course, you will be on academic integrity probation for the remainder of your years at NCSU and may be required to report your violation on future professional school applications. It’s not worth it!

The language in the syllabus was carefully chosen to describe authorized aid as opposed to listing the behaviors that constitute cheating (we’d surely leave something out). This language has evolved due to painful personal experience and the fact that some of our engineering students must surely be contemplating a career in law, based on the excuses that we’ve heard from them. We spend at least 10 minutes on the first day of class discussing academic integrity and giving examples of appropriate and inappropriate behavior, and we also have someone from the Office of Student Conduct come to a problem session early in the semester to discuss university policies related to cheating. We prefer to spend this time making our expectations explicitly clear up front rather than spending it later in Judicial Board hearings. We still catch cheaters from time to time, but we believe our precautionary measures significantly reduce the number of attempts at it.

At the suggestion of the director of the NCSU Office of Student Conduct, we are in the process of shooting a video with students role-playing specific examples of what does and does not constitute cheating. In Fall 2006 we premiered a live version of the skit on the first day of class, which was well received by the students. Our hope is that the skit, and later the video, will make abundantly clear to students what the boundaries of acceptable behavior are when they work on individual and team homework and when they use the same computer for assignments involving E-Z Solve or Excel.

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 midsemester 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

Grade	A+, A, A–	B+, B, B–	C+, C, C–	D+, D, D–	F	S, U, IN
% of Class	18%	36%	27%	6%	9%	4%

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 TAs 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

This two-part series of articles outlines an approach to teaching the stoichiometry course that 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, cooperative, and inquiry-based learning. Although the course tests included more high-level thinking questions than CHE 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.^[3,5,13,17-19] Moreover, one of us 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.^[9,10]

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.

Instructors considering these approaches may be concerned about the time requirement. Teaching a course for the first

time will involve an enormous time commitment whether the course is taught traditionally or in the manner outlined in these papers. The most time-consuming activity in our implementation was preparation of the handouts, but this was done over a period of about five years. Now that the coursepack containing the handouts is in place, almost no time is required to prepare lectures. At steady state, the instructors and the six teaching assistants each spend approximately 10 hrs/week between lecturing, office hours, and grading.

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.^[4]*
- ▶ *Instead of always lecturing on principles, then illustrating problem solution methods in class, and then assigning similar problems, use some inquiry-based learning in which students are first given challenges (e.g., questions to answer, realistic problems to solve, or experimental observations to interpret) and the principles and methods to be taught are introduced in the context of addressing the challenges.^[13,14]*
- ▶ *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.^[5-8]*

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.

ACKNOWLEDGMENTS

We acknowledge with gratitude the numerous and significant contributions to CHE 205 of the TAs (especially Adam Melvin) and Paul Cousins, director of the N.C. State University Office of Student Conduct.

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APPENDIX 2A

COLLECTIVE CLASS AUTOBIOGRAPHY

Dear students,

Learning about you from your biographies has been an enjoyable, educational, and humbling experience. We wanted to share a little of what we learned so that you can get a sense of the impressive group of people that you are.

You're mostly Southerners, many from small towns and farms, but there are also quite a few Yankees and international students from all over the world. In the class are speakers of Spanish, French, Chinese, Hindi/Bengali, and a West African dialect that the writer didn't name. Most of you are single, some are engaged, a few are married, and one of the latter has a son "who is four and well on his way to becoming an evil genius."

Some of you were influenced to choose your current majors by charismatic family members or teachers, many chose them because they were good at chemistry and math in school, and some were motivated by a desire to help people (biomedicine) or protect the environment (environmental science). Some have worked in industry and have a feeling for what engineers do; most have not and are hoping they've made a good decision and afraid that their friends who question it may be on to something. ("What's your major?" "Chemical Engineering." "Wow, are you crazy?") They probably have made a good decision—there's almost nothing you can think of that skilled professionals do that you don't find engineers doing, and N.C. State is an outstanding place to learn to do it. Some people claim that engineering students are all narrow-minded geeks who have no interests outside of their classes, but you collectively make liars out of them. For one thing, you can write—and I'm not just talking about the one who got a degree in English literature before coming back to get an engineering degree. Many of your essays were stylishly and entertainingly written, including a beautifully crafted piece that talked about how much the author hated having to write. Your interests are all over the place, including working on and racing cars, reading, music (we have several pianists, violinists, and drummers, as well as a banjoist and a concert-level French hornist), debate, the outdoors, and sports. Among you is a commercial pilot and flight instructor, an army chemical operations specialist, an expert in outdoor power equipment technology (which apparently is a competitive field—one of you placed first in the state and 11th nationally in it), a personal fitness trainer, a paralegal, an actor, a firefighter, and a jewelry maker.

You are a very athletic crowd. Collectively you're into tennis, backpacking, biking, basketball, baseball/softball, football, running, golf, dance, rock climbing, kayaking/canoeing, volleyball, wrestling, cheerleading, competitive horseback riding, skiing/snowboarding, swimming (one of you does mini-triathlons), surfing, karate, discus/shot put/high jump, wakeboarding, skateboarding, fishing, hunting,

hockey, and lacrosse . . . and there are enough of you who play soccer at a very high level to put together a team that could probably wipe out every other department in the college. You also include a number of fanatic Wolfpack football followers, and one brave soul who admits to being a big Tarheel fan. (No, I won't reveal names.)

You are also well developed spiritually. Many of you spoke of the importance of your faith in your life, some mentioning being active in your church, campus faith-based organizations, and mission work. Among you are volunteers for Habitat for Humanity, the SPCA, the Durham Rescue Mission, the Appalachia Service Project, the Red Cross, the March of Dimes, and several local hospitals.

In short, you are a diverse, talented, and generally splendid group of people. We feel privileged to be your teachers this semester, and look forward to getting to know you better as the semester progresses.

Sincerely,

Lisa Bullard and Richard Felder

APPENDIX 2B

SAMPLE PAGE FROM A CLASS HANDOUT

• Internal energy table

(a) Choose a reference state (phase, T, P) for a species, at which \hat{U} is set equal to 0. (Example: Liquid water at the triple point, used in Tables B.5–B.7)

(b) Determine $\Delta\hat{U}$ for the change from the reference state to another. Call the result \hat{U} of the species at the second state relative to the reference state. Repeat for many states, and tabulate \hat{U} .

(c) Thereafter, calculate $\Delta\hat{U}$ for a specified change of state (to substitute into the energy balance equation) as $\hat{U}_{\text{final}} - \hat{U}_{\text{initial}}$, substituting values from the table for both internal energies.

If you chose a different reference state, the numbers in the table

would all be different but the difference between the values for any two states would always be the same. The two internal energy tables shown below for carbon dioxide at 1 atm illustrate this point.

Ref: CO ₂ (g, 1 atm, 0 °C)	
T(°C)	\hat{U} (kJ/mol)
0	0.00
100	3.82
200	8.00
300	12.50

Ref: CO ₂ (g, 1 atm, 100 °C)	
T(°C)	\hat{U} (kJ/mol)
0	-3.82
100	0.00
200	4.18
300	8.68

Exercise: A table of specific internal energies of nitrogen at P = 1 atm contains the following entries:

T(°C)	\hat{U} (kJ/mol)
0	-0.73
25	0.00
100	2.19
200	5.13

(a) What reference state was used to generate this table? _____

(b) Q: What is the physical significance of the value 2.19 kJ/mol?

A: It is for the process $\Delta\hat{U}$ N₂(__, __ atm, __ °C) → N₂(__, __ atm, __ °C)

(c) What is $\Delta\hat{U}$ for the process N₂(g, 1 atm, 200 °C) → N₂(g, 2 atm, 100 °C)? _____

(d) Calculate the heat required to cool 2.00 mol N₂ from 200 °C to 100 °C. □