
A Longitudinal Study of Engineering Student Performance and Retention.

IV. Instructional Methods

RICHARD M. FELDER

*Department of Chemical Engineering
North Carolina State University*

ABSTRACT

As part of an ongoing longitudinal study, the author taught five chemical engineering courses in consecutive semesters to a cohort of students, using cooperative learning and other instructional methods designed to address a broad spectrum of learning styles. This paper outlines the policies and procedures, assignments, and classroom activities in the experimental course sequence and describes the students' performance and attitudes as they progressed through the sequence. The results suggest that active and cooperative learning methods facilitate both learning and a variety of interpersonal and thinking skills, and that while these methods may initially provoke student resistance, the resistance can be overcome if the methods are implemented with care.

I. INTRODUCTION AND OVERVIEW

In the Fall 1990 semester, I taught the introductory chemical engineering course (Chemical Process Principles) to a class of 123 students, most of them sophomores in chemical engineering. Those students became the experimental cohort in a continuing longitudinal study of engineering education. The ones who remained in sequence in the chemical engineering curriculum took four more courses from me in successive semesters. I used an instructional approach in the five experimental courses designed to accommodate a broad spectrum of student learning styles.¹ I presented course material inductively, moving from facts and familiar phenomena to theories and mathematical models as opposed to the usual "fundamentals, then applications" approach. I always used realistic examples of engineering processes to illustrate basic principles, occasionally provided opportunities for laboratory and plant visits, and several times brought in practicing chemical engineers to describe how they used the methods the students were learning in class. I stressed active learning experiences in class, cutting down on the amount of time I spent lecturing. In homework assignments I routinely augmented traditional formula substitution problems with open-ended questions and problem formulation exercises. I used extensive cooperative (team-based) learning, both in and out of class, trying to get the students to teach one another rather than relying entirely on me as the source of all knowledge.

The point of the study was not to test novel instructional techniques; the effectiveness of each of the methods I used in the courses was already well supported by both theory and prior experimental

research.²⁻⁴ The problem was that relatively few studies of the methods had been reported for engineering classes and essentially all of them were one-shot trials: a method was used, the student response was observed, and regardless of the outcome, the students never saw the method again. My objective was to demonstrate that repeated use of these proven instructional techniques in engineering courses would have significant positive effects on students' performance and retention, attitudes toward engineering as a curriculum and career, and levels of self-confidence.

Three articles about the study precede this one. The first reviewed the performance of the experimental cohort in the introductory chemical engineering course and summarized factors that correlated with success and failure in the course.⁵ The second and third examined performance and attitude differences between students from rural and urban backgrounds⁶ and between men and women.⁷ In the previous papers, the instructional methods that constituted the basis of the experimental course sequence were only briefly mentioned. This paper outlines those methods in detail and summarizes how the students responded to them. A future paper will compare the performance of the experimental cohort with that of a comparison group currently proceeding through the traditionally-taught chemical engineering curriculum.

II. INSTRUCTION IN THE EXPERIMENTAL COURSE SEQUENCE

Five semester-long courses constituted the experimental sequence:

1. *CHE 205—Chemical Process Principles* (Fall 1990—4 credits). Material and energy balances on chemical processes, basic concepts and calculations.
2. *CHE 225—Chemical Process Systems* (Spring 1991—3 credits). Process variable measurement methods, computer simulation of processes, applied statistical analysis.
3. *CHE 311—Transport Processes I* (Fall 1991—3 credits). Fluid dynamics and heat transfer.
4. *CHE 312—Transport Processes II* (Spring 1992—3 credits). Mass transfer and separation processes.
5. *CHE 446—Chemical Reactor Design and Analysis* (Fall 1992—3 credits).

The philosophy and principles that formed the basis of the experimental course design have been articulated by Felder^{1,8} (different learning styles and teaching methods that address them, developing creative problem-solving skills) and by Johnson, Johnson, and Smith⁹ and Felder and Brent⁹ (cooperative learning). The sections that follow outline the course formats and instructional methods used in the study and summarize the students' responses to them.

A. Course Structure and Organization

Each course was presented in a single lecture section that met for either three 50-minute periods or two 75-minute periods per week. CHE 205 had in addition a weekly two-hour problem session taught by graduate teaching assistants in sections containing 30-40 students each. Each class session involved a mixture of lecturing, problem-solving, and a variety of small-group exercises that lasted anywhere from one minute to (rarely) the greater part of the period. I never went through course notes verbatim and seldom worked through problem solutions in detail, but spent most of the time establishing contexts and applications of course material, outlining and explaining problem solution strategies and procedures, and answering questions. I tried not to go more than 15 minutes without giving the class an exercise of some sort, and in 75-minute periods I always included a brief stretch break. Occasionally I would end a period with a “one-minute paper” in which the students—sometimes individually, sometimes in pairs—would write the most important point made during that period and the muddiest point or most pressing unanswered question. I collected the responses and used them to plan how I would begin the next period.

B. In-Class Exercises

Almost every class period in the experimental course sequence included exercises done by students working in groups of two to four. Students in adjacent seats constituted the groups, so that minimal time was spent on group formation; occasionally I would begin a class by asking the students to sit somewhere else so they would work with different partners. The exercises had a variety of structures and objectives.

1. Recalling Prior Material: At the beginning of a period, I might give groups one minute to come up with three important points from the previous class or an assigned section of the text.

2. Responding to Questions: I might take any question I would normally ask in the course of a lecture and give it to groups to answer.

- *What procedure (formula, technique) could I use here?*
- *Is what I just said correct? Why or why not?*
- *What action might I take in this situation?*
- *What would I expect to happen if I did?*

I would typically give the students a minute or less to come up with answers and then call on one or two groups or individuals or ask for volunteers to tell what they came up with. I used the same response-gathering procedure in most of the exercises that follow.

3. Problem-solving: I would frequently give the groups one or more exercises in the course of working through a problem solution. For example,

- *Turn to page 138 in your textbook. Take a minute to read Problem 27, then outline a solution strategy.*
- *Without doing any calculations, guess what the solution of the problem might be (or what it might look like) and justify your guess.*
- *Get started on the solution of the problem and see how far you can get with it in five minutes.*
- *Lets all agree that this is the correct approach. Proceed from here.*
- *...and this is the solution we get. Find at least two ways to check it.*
- *Suppose we build and run the reactor we just designed and the product yield is 15% higher than we predicted? Is this necessarily good news? Think of as many possible reasons for the discrepancy as you can.*

I would give the groups enough time to think about the exercises

and begin to work—usually between one and five minutes—but not necessarily enough to finish complex tasks.

4. Working Through Derivations or Text Material: Several times each semester, I would identify an example or derivation that I felt was important enough to take up an entire class period. I would then give the following variation of the “Thinking-aloud pair problem solving” (TAPPS) method of Whimbey and Lochhead:¹⁰

Working in pairs, go through the example (or derivation) on page 237 of the text and explain each step. One member of each pair should do the explaining; the other should listen carefully, ask questions if anything is not clear, give hints if necessary, and make sure the explainer keeps talking. Raise your hands if you get stuck.

I would let the pairs work in this way for five to ten minutes, then call on one or more listeners to explain the solution or derivation up to a specified point, then have the students reverse roles within their pairs and continue the exercise.

5. Analytical, evaluative, and creative thinking: I would sometimes pose problems of the following sorts:

- *List all the stated and hidden assumptions you can find in this problem solution and say how good you think they are for the given system conditions.*
- *Explain in terms of concepts you learned this week why you feel comfortable in 65°F air and freezing in 65°F water.*
- *Think of as many reasons as you can why this design might (fail, be unsafe, be environmentally unsound).*
- *Think of as many practical applications as you can for what we just learned.*

I also occasionally gave incompletely defined problems that required estimation of unspecified quantities. In CHE 225, for example, I asked the groups to estimate the rate of heat input to a teakettle on a stove burner turned to its maximum setting. To get the solution, they had to apply standard engineering calculations but they also had to estimate the volume of a typical kettle and the time it takes to bring it to a boil, values that were not included in the problem statement. Working on such problems in class accustomed the students to exercising higher-level thinking skills and prepared them to engage in similar thinking on homework assignments and tests.

6. Generating Questions: In addition to asking “Do you have any questions?” and enduring the leaden silence that usually follows this query, I sometimes used the following exercise:

- *Think of three good questions about what we just covered.*

I never had any trouble getting as many questions as I wanted, and the questions generally provided a good assessment of the students’ level of understanding of the material I had just finished covering.

7. Formats of In-class Exercises: In addition to varying the types of in-class exercises, I varied their formats. I sometimes had the students get directly into teams and go right to work, and at other times I would ask them to work individually and then pair up to combine their solutions and synthesize better ones (“think-pair-share” in cooperative learning terminology). For longer exercises I might use a random process to designate a team recorder (e.g. the student whose home town was farthest away from campus, or the student to the right of that one) or let the team select one and allow only the recorder to write anything, thereby countering introverted students’ tendencies to work by themselves. In exercises of five minutes or longer, I would wander around and look over the shoulders of some of the groups, making comments or suggestions, reminding recorders who were losing themselves in the discussion to keep writ-

ing, and answering questions.

I would stop the teams at the designated time (or possibly give them more time if most of them seemed to be doing productive work) and either call randomly on students to present their teams' responses or call on teams and let them designate their own spokespersons. After collecting several answers and reaching agreement with the class on the correct ones, I would proceed with my lecture or give another exercise.

8. Covering the Syllabus: When I describe my instructional approach in workshops and seminars, I am invariably asked if I have to cut down the course syllabus to find the necessary time for all those exercises. The answer is a qualified no. Doing anything new and nontrivial is always awkward at first, and when I began to use active learning methods about ten years ago it slowed me down somewhat. However, by the time I got to the experimental courses my syllabi were no shorter than anyone else's in my department, and in all but CHE 312 (which I was teaching for the first time) I covered *more* material than I used to when I taught with straight lectures. I achieved this added coverage by using two strategies:

A. Extensive use of handouts.

I took large portions of my notes, including detailed derivations, explanatory paragraphs, and complex flow charts and figures, and gave them to the students in handouts or coursepaks. The handouts were sprinkled throughout with gaps, self-tests, and requests like "Verify" and "Prove." I went over some of these exercises in class and left others for the students to do on their own (with the warning that some would appear on tests). The hours of board writing I saved by handing out these notes were more than enough to accommodate all the active learning exercises I chose to do in class.

B. Not explicitly covering every point in class.

I told the students on the first day of each course that they were responsible for everything in the assigned readings—especially the handouts—and that they could not count on my telling them everything they needed to know to complete the homework assignments. Some of them—in fact, most of them—didn't care for this policy, but they learned to live with it. I was then free to devote most of the class sessions to critical conceptual and methodological points, providing the active learning experiences that would reinforce the students' understanding of these points, and I still got through the syllabus.

C. Homework

Homework problem sets were due each class period in CHE 205 and once a week in the other courses, and I also provided about a dozen additional "challenge problems" in each course that were either more difficult or required more creativity than most of the regular problems. The students completed the required homework sets in fixed 3- or 4-person teams, with one solution handed in per team. Solutions could be turned in up to two weeks late for a maximum grade of 50%, but teams that repeatedly handed in late assignments would have the privilege withdrawn. (This penalty never had to be imposed.) Challenge problems could be completed by individuals or pairs and would not be accepted past their due date.

The problem sets each contained between two and five problems, most with multiple parts. About 80% of the content of each assignment involved quantitative applications of the solution procedures presented in readings and lectures. The remaining 20% in-

cluded a wide variety of problem types, including: (1) problems calling for clear and jargon-free explanations of course concepts and explanations of familiar physical phenomena in terms of course concepts ("*Explain why it takes much longer to cook chili at a ski resort than at the beach.*" "*Explain why you can hold your finger extremely close to a hot pot with no problem but if you touch the pot you'll burn yourself.*"); (2) open-ended problems that usually involved either trouble-shooting ("*List up to 25 reasons for an unexplained drop in yield in the reactor, prioritized in order of their likelihood.*" "*State five potential environmental hazards in this process and indicate how you might safeguard against them.*") or brainstorming ("*Think of up to 40 ways to measure the viscosity of a fluid. You get one point for every four independent methods and double credit for a method that involves the use of a hamburger.*"); (3) problem formulation exercises, in which the students had to make up and solve problems involving material from the current course and sometimes also from other courses they were taking concurrently (see reference 8). In the latter exercises, the students were advised that straightforward "plug-and-chug" problems that were solved perfectly would earn C's, and that to earn top points the problems would have to show some combination of creativity and deep understanding of the course material.

The challenge problems were either unusually long or difficult quantitative problems, problems that required extensive computer programming as part of their solution, or problem formulation exercises. Performance on these problems was used in making course grading decisions for students on the borderline between two letter grades; also, satisfactory performance on about seven challenge problems was required to earn an A in a course (the precise number varied from one course to another).

D. Homework team formation and team-building

In establishing a format for group homework, I tried to follow the cooperative learning principles articulated by Johnson, Johnson, and Smith and reinforced by several of Karl Smith's presentations that I was fortunate enough to attend. In what follows I will simply state what I did; for more details about the theoretical and empirical justification of the procedures, see Johnson *et al.*² or Felder and Brent.⁹

I used a qualified self-selection process to form homework teams. On the first day of each course I instructed the students to organize themselves into teams of three or four, stipulating that no more than one member of a team could have received A's in specified courses. In the first course of the sequence I used prerequisite calculus and physics courses for this purpose, and thereafter I used the prior course in the sequence.*

On each assignment the teams designated a *coordinator*, whose job was to make sure that all team members knew their responsibilities and understood all problem solutions, a *recorder* to write out the final solution set, and one or two *checkers* to check the solutions for accuracy before they were handed in. The roles rotated for each

* This system of forming teams is the only aspect of the experimental instructional approach that I no longer use. I now use a questionnaire on the first day to determine each student's grades in selected courses, outside interests, sex, race, and times available for group work outside class, and form the groups myself to achieve ability heterogeneity, commonality of interests, and common meeting times. Heeding suggestions in the literature and my own research results, I also try to avoid groups in which men outnumber women and in which white students outnumber minority students in at-risk populations. I have found that the benefits resulting from this process justify the time required to implement it.

assignment. The cover page of the assignment was to list all *participating* team members and their designated roles.

On the first day of CHE 205 I tried to set the stage for cooperative learning. I told the students that my job is to prepare them for engineering practice and working in teams is standard operating procedure for most engineers, and I cited research studies demonstrating that cooperatively taught students tend to get better grades and enjoy courses more than students working individually and competitively. I noted that some of them would inevitably run into problems working together, usually involving group members doing more or less than their fair share of the work, and that part of their responsibility was to discuss these problems and figure out how to solve them. If the problems persisted, the groups were to meet with me and I would try to help them work things out. If and when all else failed, students who kept refusing to pull their weight could be fired by unanimous consent of the rest of their team, and students who consistently had to do most of the work could quit. A student who either quit or was fired had to find a team of three willing to let him or her join—generally an easy task for those who quit and a nearly impossible one for those who were fired. These last-resort options were rarely exercised: the teams usually managed to work their problems out by themselves.

Homework assignments periodically included questions calling on the groups to assess themselves, stating what they were doing well as a team, what they thought they could do better, and what (if anything) they planned to do differently on the next assignment. I viewed these questions as primarily for the students' benefit and did little more than glance over the responses to check for signs of serious team dysfunctionality.

I sometimes took a few minutes in class to discuss problems that students in several teams had raised. The most common complaint concerned freeloaders—team members coming to work sessions unprepared or not showing up at all. I reminded the class that only participants' names should go on the cover sheet, adding that it made no sense to complain about chronic freeloaders while continuing to give them full credit for the work, and at least once a semester I restated the last resort option of firing nonparticipating team members. Another frequent complaint—especially in CHE 205—was that the better students in a team would work out all the problems themselves without making much effort to explain what they were doing, leaving their weaker teammates with only fragmentary understanding. In one case, the complaining student blamed this situation for his failure on the first test. I announced in class that all team members and especially the assignment coordinator needed to be sure that everyone understood every problem solution, and that they could seriously hurt team members if they failed in this responsibility. I have no illusions that these pronouncements cleared up all the problems, but I had indications from students that they helped.

Several times each semester I reminded the students to try and set up each problem individually and then complete the solutions together. The first time I made this suggestion I noted that someone in every group is likely to be faster than the others, and in team sessions those students will figure out how to start every problem solution. I then reminded the students that they would be taking their tests individually, and if they never set up homework problem solutions themselves they would very likely run into trouble on the tests when their faster teammates would not be there to help them. Most students indicated in questionnaires that they were following this recommendation, especially after some of them learned the lesson the hard way on the first test.

Beyond the steps outlined above, I did relatively little to provide formal training in group functioning. I believe that such training can enhance the effectiveness of cooperative learning significantly; my failure to provide it was due mostly to my reluctance to add to the considerable time I was already spending on course planning and teaching, student performance and attitude assessment, data analysis, and project evaluation.

E. Testing and Grading

Three tests and a comprehensive final examination were given in each course, all taken individually. The tests and final exam were open-book and usually consisted of two to four multipart problems. The test content mirrored the homework problems: 80–85% mathematical analysis and quantitative problem solving, the remainder qualitative questions intended to test understanding of course concepts.

About a week before each test I handed out a study guide containing a wide variety of generic problem types and qualitative questions I might include, and I devoted pre-test class sessions to answering questions and discussing selected items on the study guide. Sometimes I would have the students work in teams to guess questions and problems that might be on the test and then formulate answers and outline solutions to several of the better ones. The students came up with some excellent problem ideas that I actually included, which raised their level of interest considerably in subsequent review sessions.

Beginning in the first course I had included questions of the "Briefly explain in terms a high school senior could understand" type in homework assignments, with assurances that problems of that sort would appear on examinations, which they did. I started getting questions about course concepts both in and out of class, which was unheard of before I started routinely putting such questions in homework and on tests. In one memorable review session before the second test of the third course, the students filled the period with questions about fluid dynamics concepts, with almost nothing about the quantitative problems that had constituted the bulk of the homework. It was a scene that many professors dream about but few experience—a classroom full of students asking deep conceptual questions about the course material as opposed to "How do you do Problem 3?"

I tried to minimize speed as a factor in test performance, designing the tests so that I could complete them in less than 17 minutes (for 50-minute class periods) or 25 minutes (for 75-minute periods). I then provided the students with even more time by finding a two-hour block for each test. The average grades varied from the high 60s to the low 80s, with very few extremely low test grades after the first course. On the rare occasions when there were no perfect papers, I added the necessary number of points to everyone's grade to make the top grade 100.

A weighted average grade was determined for each student based on: (1) grades on the three tests, with the lowest grade being assigned half the weight of each of the other two tests (45–55%); (2) the grade on the final examination (35–45%); (3) the required homework grades (10–15%). The weights varied from one course to another within the specified ranges. Students were guaranteed an A in the course if their weighted average grade was 90 or higher and if they did satisfactory work on a specified number of challenge problems. They were guaranteed a B with a weighted average grade of 80–89, C with 70–79, and D with 60–69.

The students were also told that a "gray area" existed below each of the specified cutoff grades, and that if their numerical grade fell into one of these areas, whether they got the higher or lower letter grade would be determined by how many challenge problems they made a reasonable attempt to solve and whether their test grades throughout the semester were generally improving or getting worse. This grading system was put in writing and handed out on the first day of each class. I never specified the widths of the gray areas, which were 2-3 points for the A/B, B/C, and D/F borderlines and 5-6 points for the C/D borderline. (A grade of C or better in most chemical engineering courses is required to advance in the chemical engineering curriculum.) There were many complaints about the challenge problem requirement for an A, but no other routine complaints about the fairness of this system.

A criterion-referenced course grading system like this one as opposed to a norm-referenced (curved) system is a requirement for cooperative learning. Students graded on a curve have little incentive to cooperate: if they help other students too much, they might bump themselves down to a lower grade. On the other hand, if absolute criteria are used so that in principle everyone can earn an A, then the students have every incentive to help one another and cooperative learning becomes feasible.

III. STUDENT RESPONSES

The initial response of the students in CHE 205 to having to do their homework in teams was mixed. Many liked the idea or were intrigued by it, but some objected strongly. The first problem sets were turned in by most students working in groups as instructed, but also by several individuals and one "group" consisting of a student, Elvis Presley, and Richard M. Nixon. I applauded that student for creativity but informed all who had not yet joined groups that the fun was over and I would accept no further assignments from individuals. By the due date of the second assignment, all students were in homework teams.

Every few weeks in CHE 205 I assessed the students' attitudes to group work. They steadily became more positive, as even the staunchest individualists began to discover the benefits of cooperation on the frequent and increasingly challenging homework assignments. I continued to get complaints from some of them, however, and six weeks into the course—partly as an experiment and partly out of impatience—I announced that students who wished to do so could now do homework individually. Out of roughly 115 students, only three elected to do so, two of whom were off-campus students who were finding it difficult to attend group work sessions. In courses I taught subsequently, I occasionally assigned individual homework but never again let the students opt out of assigned group work.

The final grade distribution in CHE 205 was dramatically different from any I had ever seen when I taught this course before. In the previous offerings, the distributions were reasonably bell-shaped, with more students earning C's than any other grade. When the course was taught cooperatively, the number of failures was comparable to the number in previous offerings but the overall distribution was markedly skewed toward higher grades: 26 A's, 40 B's, 15 C's, 11 D's, and 26 F's. Many of those who failed had quit before the end of the course. My conclusion was that the experimental instructional approach helped all but the least qualified and most poorly motivated students.

The student ratings of the experimental courses were consistently and overwhelmingly positive, although there were always several persistent detractors. The semester-end course and instructor evaluations for all five courses were either the highest or second-highest of all departmental ratings in their respective semesters, and midsemester evaluations were also extremely strong. The only experimental instructional feature that always received a heavy volume of student complaints was the challenge problems: some students felt that they were an unnecessary overburden in an already demanding curriculum, and many felt that it was unfair to require satisfactory performance on them as a condition for an A.

In the semester following the experimental course sequence, the students were asked to evaluate the sequence retrospectively. Of 67 seniors responding, 92% rated the experimental courses more instructive than their other chemical engineering courses, 8% rated them equally instructive, and none rated them less instructive. Ninety-eight percent rated group homework helpful and 2% rated it not helpful, and 78% rated in-class group work helpful and 22% rated it not helpful.

Several results suggest that the experimental courses may have had a significant impact on the students' retention in chemical engineering. After four years of college, 79% of the students who planned to major in chemical engineering when they enrolled in CHE 205 had either graduated or were still in chemical engineering, a retention substantially higher than normal. Sixty-one percent of the seniors responding to a survey in the capstone design course considered the experimental courses very important factors in their decision to remain in chemical engineering, 29% considered them important, and 10% rated them not very important or unimportant. A more complete evaluation of the effects of the experimental courses will be possible after May 1996, at which time the comparison group will have progressed through the entire curriculum.

IV. DISCUSSION AND CONCLUSIONS— A PERSONAL PERSPECTIVE

The instructional approach used in the experimental course sequence had the following principal features:

1. *Minimizing the instructor's role as the source of all knowledge and putting more and more of the burden of learning on the students.* I assigned homework without always providing in lectures all the information needed for its completion. I put the students to work during class periods instead of holding the stage myself for the entire time. I required them to work in teams, giving them the responsibility of teaching one another some of the material they would normally have looked to me to teach.

2. *Varying the types of questions posed in assignments and on tests.* I posed the usual quantitative problems, but also occasionally assigned brainstorming, troubleshooting, and problem formulation exercises and routinely asked questions requiring explanations of course concepts and interpretations of physical phenomena in terms of those concepts.

3. *Balancing concrete information (experimental results, familiar phenomena, practical applications, real-world problems and complications) and abstract information (theory, mathematical models) in all courses, with the presentation flowing inductively from the concrete to the abstract.*

An intractable problem associated with this study (and with all other educational studies in natural classroom settings) is that posi-

tive effects of experimental instructional methods may be due in part to the methods themselves, in part to personal attributes of the instructor, and in part to the Hawthorne effect (wherein doing *anything* differently may affect people positively). Even when the results for the comparison group are available, they will not establish definitively whether any observed between-group differences were due to the experimental instructional methods, and if so, which methods. In principle, I could have implemented an experimental design that involved my teaching the comparison group using traditional instructional methods, a procedure that was in fact impossible for various logistical reasons. Even if I had done so, however, the argument could be raised that I am biased against the traditional methods (which I am) and so could not teach with them as effectively as I can with the methods I believe in.

Nevertheless, I am convinced that this class performed at a higher level than any traditionally-taught class I have ever observed, and moreover, that the experimental instructional methods had substantial effects on both the quality of learning and the intellectual growth of the students. I base this statement on several arguments. First, why do I think this class was different?

- *Several faculty colleagues independently noted that the class seemed to be unusually good.*
- *The students' proficiency in formulating problems and answering questions that called for a measure of creativity was greater by the time they were juniors than I had ever observed in any other group of students at any level.*
- *The nature of my office hours changed considerably as the study progressed, with fewer individual students coming in to ask "How do you do Problem 3" and more groups coming in for help in resolving debates about open-ended problems. I inferred with considerable satisfaction that the students had begun to count on one another to resolve straightforward questions instead of looking to me for all the answers.*
- *I observed a greater sense of community in this cohort of students by the time they were juniors than I had seen in any other chemical engineering class. The student lounge began to resemble an ant colony the day before an assignment was due, with small groups clustered everywhere, occasionally sending out emissaries to other groups to compare notes and exchange hints (which I permitted as long as entire solutions were not exchanged). One student commented, "This class is different from any I've been in before. Usually you just end up knowing a couple of people—here I know everyone in the class. Working in groups does this."*
- *Industrial recruiters showed an unusual level of interest in the students in the group, particularly noting their familiarity with team project work. Although the chemical engineering job market was worse in the springs of 1993 and 1994 than it had been for the prior decade or more and many schools around the country were reporting placements of lower than 50%, only about 5% of the graduates in the experimental group failed to either find employment as chemical engineers or gain admission to graduate school.*
- *An unusually high percentage of the students went to graduate school, and of those, a number expressed an interest in pursuing academic careers—far more than in any other class in my recollection. This result suggests that compared to traditionally-taught students, the students in the experimental cohort had a more positive view of their academic experience (to an ex-*

tent that they wanted to prolong it) and/or a higher level of confidence in their aptitude for advanced study.

The question remains, how many of those results were consequences of the instructional methods I used and so would be observed by any other instructor using the same methods, and how many were due to either my ability as an instructor or the Hawthorne effect? I have several reasons to believe that the methods were at least partly responsible for the effects.

- *I used only methods whose effectiveness has been previously established.* Several thousand studies have confirmed the effectiveness of cooperative learning in every conceivable educational setting.² The learning benefits of other features of the course instruction, like balancing concrete and abstract content, varying the mode of instruction, including both conceptual and algorithmic exercises in homework and on tests, and learning the students' names in large classes, have also been well established.^{3,4}
- *In education, as in every other activity, practice and feedback inevitably lead to improvement.* It does not take a carefully controlled research study to prove that if students are repeatedly exercised in a skill—be it solving material balance problems, making up creative interdisciplinary problems, or resolving interpersonal conflicts in homework teams—and are given constructive feedback on their initial attempts, their level of mastery will increase. The improved problem-solving, creative thinking, and teamwork skills I observed in the experimental group are not particularly surprising; it would have been surprising if they had failed to appear.
- *The students themselves repeatedly credited the experimental instructional methods—particularly cooperative learning—with helping them learn.* In survey after survey during the study, they overwhelmingly reported that group work was effective for them. Their open-ended responses to questions about cooperative learning collectively sounded like a list taken from the literature on the subject: "When I get stuck I give up, but when I'm working with others I keep going." "It helps me understand better when I explain things to others." "I might sometimes blow off assignments working by myself, but I don't want to let my team down so I do them."

One episode in particular led me to believe that group work was having the desired effect on the quality of the students' learning. In the third semester of the study, the class was taking fluid dynamics and heat transfer with me and thermodynamics with a colleague. My colleague is a traditional instructor, relying entirely on lecturing to impart the course material, and he is known for his long and difficult tests, with averages in the 50's or even less not unheard of. The average on his first test that semester was 72, and that on the second test was 78, and he ended by concluding that it was perhaps the strongest class he had ever taught. Meanwhile, I casually asked the students how things were going, mentioning that I heard they were doing well in thermo. Several of them independently told me that they had become so used to working in groups, meeting before my tests, speculating on what I might be likely to ask, and figuring out how they would respond, that they just kept doing it in their other classes—and it worked!

In short, the combination of my observations, the students' responses, and independent studies supporting the instructional approach I used, convince me that the approach is indeed more effective than the traditional individual/competitive approach to

education. Obstacles to the widespread implementation of the methods tested are not insignificant, however. The approach requires faculty members to move away from the safe, teacher-centered methods that keep them in full control of their classes to methods that deliberately turn some control over to students. The professors must accept that while they are learning to implement active and cooperative methods they will make mistakes and may for a time be less effective than they were using the old methods. They may also have to confront and overcome substantial student opposition and resistance, which can be a most unpleasant experience, especially for teachers who are good lecturers and may have been popular with students for many years.

The message of this paper, if there is a single message, is that the benefits of the approach more than compensate for the difficulties that must be overcome to implement it. Instructors who pay attention to sound pedagogical principles when designing their courses, who are prepared for initially negative student reactions, and who have the patience and the confidence to wait out these reactions, will reap their rewards in more and deeper student learning and more positive student attitudes toward their subjects and about themselves. It may take an effort to get there, but it is an effort well worth making.

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