been worked out so there is room for discovery and creativity, even on a small scale.

There were many examples of the cooperative learning aspects of the course that mirror what other cooperative learning approaches have experienced (*1–11*):

- community building
- increased motivation
- reduction in alienation and anonymity
- improvement in team skills
- active student participation in the learning process
- increased comprehension and accomplishment

These benefits are usually achieved in institutions with small class sizes and more interaction between students and faculty, but this course experiment makes it clear that they can be realized at large institutions as well. There are longer-range benefits to undergraduate education. It is recognized that successful curriculum reform requires more than improved lectures, course materials, churning of the curriculum, etc. It requires a change in the way that faculty and students view themselves (*4*). It is clear that this course model is an example of one that replaces the traditional model of passive learners and inspired lecturers by a model where the students take an active and responsible part in the learning process and faculty members facilitate learning by preparing a learning environment that will challenge and empower students. These changes are fundamental and represent new traditions that guide students and faculty into a new approach to education. It is important to extend such approaches to other upper-level courses in the chemistry curriculum.

Acknowledgment

This work was supported by the National Science Foundation under grant 94-50615.

Literature Cited

1. Moll, M. M.; Allen, R. D. *J. College Sci. Teach.* **1982,** *11,* 219–222.
2. Tobias, S. *Revitalizing Undergraduate Science: Why Some Things Work and Most Don't*; Research Corporation: Tucson, AZ, 1992.
3. Tobias, S. *They're Not Dumb, They're Different: Stalking the Second Tier*; Research Corporation: Tucson, AZ, 1990.
4. MacGregor, J. *New Directions for Teaching and Learning* **1990,** *42,* 19–30.
5. Bunce, D.M. *J. Chem. Educ.* **1993,** *70,* 179 and associated papers.
6. Newmann, F. M. *Phi Delta Kappan,* **1991,** *72,* 458–463.
7. Walters, J. P. *Anal. Chem.* **1991,** *63,* 977A–985A, 1077A–1087A, 1179A–1191A.
8. Ricci, R. W.; Ditzler, M. A. *J. Chem. Educ.* **1991,** *68,* 228–232.
9. Laws, P. W. *Physics Today,* Dec. 1991, pp 24–31.
10. Pickering, M. *J. Chem. Educ.* **1985,** *62,* 874–875.
11. Alty, L. T. *J. Chem. Educ.* **1993,** *70,* 663–665.
12. Yamazaki, H.; Sperline, R. P.; Freiser, H. *Anal. Chem.* **1992,** *64,* 2720–2725.
13. Kagan, S. *Cooperative Learning*; Resources for Teachers, Inc.: San Juan Capistrano, CA, 1992.
14. Johnson, D. W.; Johnson, R. T.; Smith, K. A. *Active Learning: Cooperatiion in the College Classroom*; Interaction Book Co.: Edina, MN, 1991.
15. Mazur, E. *Peer Instruction: A User's Manual* (Department of Physics, Harvard University, Cambridge, MA, 1993).

Active-Inductive-Cooperative Learning: An Instructional Model for Chemistry?

Richard M. Felder
Department of Chemical Engineering, North Carolina State University, Raleigh, North Carolina 27695-7905

Introduction and Overview

In the Fall 1990 semester, I taught the introductory chemical engineering course to a class of 123 students, most of them sophomores. This class became the experimental cohort in an ongoing longitudinal study. Those who remained in sequence in the chemical engineering curriculum took four more courses from me in successive semesters. I amassed demographic and precollege admission data on the students, administered instruments to assess personality type and learning and study skills, tracked their academic performance and retention in chemical engineering, and surveyed them repeatedly regarding their attitudes toward chemical engineering as a curriculum and career, their responses to various aspects of their educational experience, and their levels of confidence in their academic and problem-solving abilities. Published reports describe the performance of the experimental group in the introductory chemical engineering course (*1*), compare outcomes for students from rural and small town backgrounds with outcomes for students from urban and suburban backgrounds (*2*), and summarize gender differences in academic performance, attitudes, and self-concepts (*3*). Future reports will compare the performance of the experimental group to that of a comparison group of students proceeding through the traditionally taught curriculum.

The instructional approach in the five experimental courses was designed to accommodate a broad spectrum of student learning styles. 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 routinely used realistic process examples to illustrate basic principles, occasionally provided opportunities for laboratory and plant visits, and several times brought in practicing engineers to describe how they use the methods the students were learning in class. I stressed active learning experiences in class, cutting down on the amount of time spent on lecturing, and 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. I regularly assigned open-ended questions and problem formulation exercises along with traditional algorithmic substitution problems.

The philosophy and principles that formed the basis of the experimental course instruction have been articulated by Felder (*4, 5*) (different learning styles and teaching methods that address them, developing and enhancing creative problem-solving skills) and by Johnson et al. (*6*) and Felder and Brent (*7*) (cooperative learning). The point of the study was not to test novel instructional methods: the effectiveness of each of the methods used was already well supported by both theory and prior research (6–9). The goal was rather to show that repeated use of these methods in a curriculum would have significant positive effects on students' performance and retention, attitudes toward chemical engineering as a career choice, and levels of self-confidence. The sections that follow outline the course formats and instructional methods used in the study and summarize the students' responses to them.

Course Structure and Instructional Approach

Five semester-long courses constituted the experimental sequence:

1. *Chemical Process Principles* (Fall 1990—4 credits). Material and energy balances on chemical processes, applied physical chemistry.
2. *Chemical Process Systems* (Spring 1991—3 credits). Process variable measurement methods, computer simulation of processes, elementary statistical analysis.
3. *Transport Processes I* (Fall 1991—3 credits). Fluid dynamics and heat transfer.
4. *Transport Processes II* (Spring 1992—3 credits). Mass transfer operations.
5. *Chemical Reactor Design and Analysis* (Fall 1992—3 credits).

There was only one lecture section per course, with enrollments varying between 90 and 123. In each class session I used a mixture of lecturing, problem-solving, and a variety of small-group exercises that lasted anywhere from one minute to most of the period. I tried not to lecture for more than 20 minutes without giving the class either an exercise or (in 75-minute periods) a brief stretch break.

In all courses but the first one (for which I coauthored the course text), I gave the students large portions of my lecture notes as handouts or coursepaks, including most detailed derivations, explanatory paragraphs, and complex flow charts and figures. 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 work on their own, warning them that some would appear on tests (which they did). I also 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. Many students did not care for this policy, but they learned to live with it. The hours of chalkboard writing I saved by handing out the notes and not covering every word of them in class were more than enough to accommodate all the active learning exercises described in the next section.

In-Class Exercises

In-class exercises were done by students working in groups of two to four. At any time during a class period I might ask a question or pose a problem, give the groups anywhere from 30 seconds to five minutes to come up with responses, and call randomly on individuals or groups to share their responses. The objective might be to recall material from the previous class period, answer a question, outline a solution strategy for a given problem, guess what the solution might look like, take the next few steps in a solution procedure, find ways to check a solution, or list reasons why a calculated solution might disagree with an experimentally measured value of the same quantity.

I also occasionally gave groups problems that required analytical, evaluative, or creative thinking, calling on them to do such things as list stated and hidden assumptions in a problem solution and speculate on their validity, figure out what additional information might be required in an underspecified problem and where they might get that information, explain familiar phenomena in terms of course concepts (e.g., *explain in terms of concepts you learned this week why you feel comfortable in 65 °F air and freezing in 65 °F water)*, brainstorm reasons why a given design might fail or be unsafe or environmentally unsound, and think of practical applications for relatively abstract or theoretical results. 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.

Finally, in addition to asking "Do you have any questions?" and enduring the leaden silence that usually follows this query, I sometimes challenged the groups to do something like "*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 indication of the students' level of understanding of the material.

In addition to varying the objectives of the in-class exercises, I varied their structural format. Sometimes I would have students sitting in adjacent seats get directly into teams, choose a recorder to write down the team's response or problem solution, and go to work, with only the recorder being allowed to write. 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). 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 writing, 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 team's 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.

At the end of occasional periods, I would call on individuals or pairs of students to write "One-minute papers" *("List the main point in the material we covered today. Then list the muddiest point.")* and collect the responses. Their main points told me whether or not most of them were basically with me, and their muddiest points usually contained one or more ideas I had taken for granted and glossed over. The results collectively let me know where to begin the next class period.

Homework Assignments

Homework problem sets were due each class period in the first course 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 most of 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 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% involved a wide variety of problem types, including (i) 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"*); (ii) open-ended problems that usually involved either troubleshooting (*"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"*); (iii) 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 (*5*). 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. Some students showed an instant creative flair, others never quite got the point, and most started off with no idea of what I was looking for but got much better with repeated practice and feedback.

Cooperative Learning Format

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. (I now prefer to organize the teams myself, using data from a first-day questionnaire to group students with varied ability levels and common meeting times outside class.) On the first day of CHE 205 I assured the students that when they eventually went to work in industry they would have to work in teams so they might as well start learning how to do it now, 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. [Johnson et al. (*6*) provide all the necessary ammunition for this line of reasoning.]

For 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 assignment. The cover page of the assignment was to list all participating team members and their designated roles. 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 announced on the first day of each course that some students 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. As it happened, these last-resort options were rarely exercised: the teams usually managed to work their problems out by themselves. [See Felder and Brent (*7*) for a more complete discussion of student problems that tend to arise in cooperative learning and ways to deal with them.]

Tests

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 exam I handed out a study guide containing a wide variety of generic problem types and qualitative questions I might include, and I devoted pretest class sessions to answering questions and discussing selected items on the study guide. Sometimes the students worked together to guess problems that might be on the test and then formulated solutions. They usually came up with problem ideas that I actually included on the test, which raised their level of interest considerably in subsequent review sessions.

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 trying to find a two-hour block for each test. The average grades varied from the high 60's to the low 80's, 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.

Course Grading

A weighted average grade was determined for each student based on (i) grades on the three tests, with the lowest grade being assigned half the weight of each of the other two tests (45–55%), (ii) the grade on the final examination (35–45%), and (iii) the average homework grade (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 6–8 challenge problems (the specific number varied from one course to another). 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. The widths of the gray areas (which I never spelled out to the students) were 2–3 points for the A/B, B/C, and D/F borderlines and 5–6 points for the C/D borderline. 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 mandatory 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.

Student Ratings and Attitudes

After the first few weeks of CHE 205, the student ratings of the experimental courses were consistently and overwhelmingly positive, and 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. 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.

Every few weeks in the introductory course (CHE 205) I assessed the students' attitudes to group work. They were initially mixed, with a minority of students objecting vigorously to having to work in groups, but 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 some complaints, however, and six weeks into the course 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. Evaluations of group work remained heavily positive throughout the remaining courses.

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.

Discussion and Conclusions

I am convinced that this class performed at a higher level than any traditionally taught chemical engineering class I have ever observed and 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 points.

- The final grade distribution in CHE 205 (which generally serves as the filter for the curriculum) was dramatically different from any I had ever seen when I taught this course before. In the previous offerings, the distributions were roughly bell-shaped; 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 instructional approach had helped all but the least qualified and most poorly motivated students.
- I observed a remarkable sense of community among these students by the time they were juniors—they studied together, partied together, and complained with unusual unanimity when they were unhappy about something in the curriculum. 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."
- The students' proficiency at 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. Several faculty colleagues independently noted that this seemed to be an unusually good class.
- The nature of my office hours changed considerably as the study progressed, with fewer individual students coming in to ask about routine problem solutions and more groups coming in for help in resolving debates about open-ended problems. I inferred that the students had begun to rely on one another to resolve the former questions rather than looking to me as the source of all such information.
- 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."*
- Industrial recruiters showed an unusual level of interest in the students in the group, particularly noting their experience with teamwork. 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.
- 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 only 10% rated them not very important or unimportant.

- 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 extent that they wanted to prolong it), a higher level of confidence in their aptitude for advanced study, or both.

In short, my observations, the students' responses, and independent research 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 (10). At least in my view, however, the potential benefits—the deeper student learning and more positive student attitudes toward their subjects and toward themselves—more than justify the difficulties.

Could this approach be taken and applied verbatim in an undergraduate chemistry course? Perhaps not—any teaching approach must be adapted to fit the needs and objectives of different subjects and the idiosyncratic styles of different instructors. I truly believe, however, that the basic elements of the approach—active, cooperative learning, extensive use of practical, visual material to motivate and illustrate the presentation of abstract, verbal/mathematical concepts, routine inclusion on assignments and tests of a variety of problem types—should be just as effective in chemistry and any other science as they were in the experimental chemical engineering course sequence. I am writing this paper in the hope that some of my colleagues in chemistry will be sufficiently intrigued by the possibility to experiment with the approach in their courses and to write about the results. The ensuing dialogue can hardly fail to be productive.

Acknowledgment

This work was supported by National Science Foundation Undergraduate Curriculum Development Program Grants USE-9150407-01 and DUE-9354379, and by grants from the SUCCEED Coalition and the Hoechst Celanese Corporation.

Literature Cited

1. Felder, R.M.; Forrest, K.D.; Baker-Ward, L; Dietz, E.J.; Mohr, P.H. *J. Engr. Educ.* **1993**, *82(1)*, 15–21.
2. Felder, R.M.; Mohr, P.H.; Dietz, E.J.; Baker-Ward, L. *J. Engr. Educ.* **1994**, *83*, 209–217.
3. Felder, R.M.; Felder, G.N.; Mauney, M.; Hamrin, Jr., C.E.; Dietz, E.J. *J. Engr. Educ.* **1995**, *84*, 151–174.
4. Felder, R.M. *J. Coll. Sci. Teaching* **1993**, *23(5)*, 286–290.
5. Felder, R.M. *J. Engr. Educ.* **1987**, *77(4)*, 222–227.
6. Johnson, D.W.; Johnson, R.T.; Smith, K.A. *Cooperative Learning: Increasing College Faculty Instructional Productivity*. ASHE-ERIC Higher Education Report No. 4, George Washington University: Washington, DC, 1991.
7. Felder, R.M.; Brent, R. *Cooperative Learning in Technical Courses: Procedures, Pitfalls, and Payoffs*; ERIC Document Reproduction Service, ED 377038, October 1994.
8. McKeachie, W. *Teaching Tips*, 8th ed.; D.C. Heath: Lexington, MA, 1986.
9. Wankat, P.; Oreovicz, F.S. *Teaching Engineering*; McGraw-Hill: New York, 1993.
10. Felder, R.M.; Brent, R. *College Teaching* **1996**, *44*(2), 43–47.

Which would have advanced the most at the end of a month—the boy who had made his own jackknife from the ore which he had dug and smelted, reading as much as would be necessary for this,—or the boy who had attended the lectures on metallurgy at the Institute in the meanwhile, and had received a Rogers' penknife from his father: Which would be most likely to cut his fingers?

Henry Thoreau