Authentic Learning Environment in Analytical Chemistry Using Cooperative Methods and Open-Ended Laboratories in Large Lecture Courses

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It is recognized that a need exists to move from the passive learning styles that have characterized chemistry courses to an active style in which students participate and assume responsibility for their learning (*1–5*). In addition, it is argued that course reform should be linked to authentic student achievement, so that students can actively experience the feelings of practicing professionals (*6*). Course experiments where such changes have been introduced have proven successful but the number of examples of such changes is limited in the higher level courses or courses with large enrollments (*7–11*).

In this paper, a one-semester introductory analytical chemistry course is described that accomplishes this goal by the use of open-ended laboratories, cooperative learning, and spreadsheet programs. The course uses many of the ideas described by Walters (*7*). It is offered at the upperclass level to nonmajors and at the freshman level to students with solid chemistry backgrounds from high school. Typically there are 90 students, who are divided into 5 sections. A teaching assistant is assigned to each section. The course has two 4-hour laboratories and two or three lectures each week (depending on whether it is the upperclass or freshman course).

The heart of the course changes is the use of open-ended laboratory experiments in the last half of the course. A sample group project is to have the students develop a mixture of acid–base indicators that can serve as a spectroscopic pH meter. These projects are enhanced by dividing the students into teams of four who take charge of all aspects of accomplishing the projects' goals. Since there are many skills required to make these projects work, the first half of the course is spent developing the individual conceptual, computational, laboratory, problem solving, and group skills so students are prepared for the last half. These changes have markedly improved the student attitudes towards each other and towards learning chemistry, in addition to increasing the depth of coverage of the material and the students' comprehension levels. Although these benefits are usually expected from small colleges, it has become clear that they can also be achieved in large-enrollment universities.

Course Elements

The important elements in the open-ended projects are identified during the planning of the course and are brought into the course from its beginning in order to establish a central theme that continues throughout the course. Eight changes have been made in the course where these themes are emphasized:

- an absolute grading scale is announced at the beginning of the course
- a student board of directors is appointed to oversee all aspects of the course
- students read and analyze research papers
- interactive techniques are introduced in the lecture
- spreadsheet programs are used for homework and laboratory problems
- cooperative examinations complement traditional examinations
- open-ended laboratory projects replace many standard laboratory experiments

Grading

The absolute grading scale is recognized as an essential element to a course where students work cooperatively, because the competition in a course graded on the curve discourages cooperation (*4*). Grades are determined by a mixture of traditional examinations and quizzes, cooperative examinations, problem sets, laboratory grades based on quantitative unknowns, and group and individual grades on open-ended projects. Several methods have been used to arrive at individual grades for group projects, but the most effective has been a peer grade assigned by the team members. For a four-member team, each individual will receive grades from the other three members and the results are averaged. The individuals consider a person's effort, team skills, and contributions. The individual grades are then normalized to the team grade.

Student Formative Assessment

A student board of directors is appointed from volunteers using student diversity and representation from all course sections as selection criteria. The board members provide rapid feedback and formative assessment about course operation, make decisions about course issues, and bring up issues that are important for the class. They have power over all aspects of the course including grading, but the instructor retains a veto privilege (thus far unused).

Research Papers

Students are assigned to groups at the beginning of the first laboratory and given a professional paper to read. In order to help them understand the paper and to give each individual an important part in the group, the four teaching assistants in the course hold discussion sections on the important aspects of the paper. Representatives from each group attend each of the discussions and then return to their teams. Together, the group members pool their understanding and address the specific questions that test and deepen their understanding of the paper. The answers are written up and the team meets with the course instructors to discuss their insights. This group exercise builds group skills and introduces key concepts that will become important in the group projects. Later, research paper analysis is used to give more realistic problems for assimilating the course material.

As an example, a paper by Yamazaki et al. on "Spectroscopic Determination of pH and Its Application to the Determination of Thermodynamic Equilibrium Constants" (*12*) was chosen to begin the course. This paper would complement a project introduced later, where students develop a mixture of indicators to determine pH. The paper measured the absorption spectrum of two acid–base indicators in a carefully prepared buffer having an accurately known acid dissociation constant. After making appropriate activity corrections, the authors showed that the indicator could be used to measure pH in other solutions with an accuracy that exceeded pH meter measurements. For this example, the four students in a group would divide up to meet as representatives with each of the four teaching-assistant discussion sections, to learn about spectroscopic measurements, statistics and error analysis, thermodynamic and equilibrium concepts, and team management. This introduction empowered individuals in a specific area so they would have a defined place on the team during the initial meeting. The team addressed 10 questions such as calculating the ratio of the acid and conjugate base species of the indicator from data in a figure; determining why the data were weighted differently at different wavelengths and why there was no weight at an isobestic point; predicting the change in the absorbances if the temperature, ionic strength, or pH changed; and evaluating whether the temperature-induced changes in absorption could form the basis of a spectroscopic thermometer.

Lecture Activities

Group activities were introduced into the lecture in the form of think-pair-share exercises, collaborative problem solving, concept tests, and list generation (*13–15*). For think-pair-share, a simple numerical or conceptual problem is stated and after briefly thinking about its answer, students discuss their ideas for answers. Representative groups share their answers with the class or a class vote is taken on the correct answer from a list of nominations. An example of collaborative problem solving is calculating points in a chelation titration for different pH values and auxiliary complexing agent concentrations. The answers are pooled on overhead graphs corresponding to the different conditions. The class then discusses the effects of changing the competing equilibria conditions on the titration curves. The answers are duplicated and distributed so each student has a complete set of solved examples under varying experimental conditions. An example of a list generation exercise is to have students identify all factors that lead to chromatographic peak broadening.

Cooperative Examinations

The traditional examination format has been augmented in this course by cooperative take-home examinations. Students can discuss problems but their answers must be their own. This format allows more realistic and complex questions, although there are limits to the sophistication level that is achievable. Typical questions might include simulating the spectra that result for different pH and reagent concentrations when Cd^{2+}, a chelating agent, and a complexation indicator are mixed. The question uses concepts that appeared in the first research paper exercise, but it requires reformulating it in a different context. Students report that the examinations are a reliable indicator of their comprehension and problem-solving skills. Correlation plots of cooperative vs. traditional examination results show no significant differences.

Spreadsheets

Spreadsheet programs have become recognized as very powerful devices for teaching in analytical chemistry because they provide the power required to tackle complex equilibria. At the same time, they are accessible to the unsophisticated student and they are important tools for a student to master. The spreadsheet programs are used in both lecture and laboratory contexts. Exercises are assigned that increase student proficiency gradually. Starting from a simple successive approximation exercise, students advance to creating species distribution functions (α-plots) for weak acids and then to modeling a titration curve including nonideality corrections. They also use computers for data acquisition in conjunction with a scanning spectrophotometer and data analysis of the overlapping spectra in a two-component mixture.

Open-Ended Laboratory Projects

The open-ended projects are the heart of the course. They have well-defined goals, but students are free to use their own creativity in reaching the goals. A listing of projects that have been used in the course is given in Table 1.

The measurement of the pK_a of an indicator and the development of a spectroscopic pH meter were projects used in the semester when the first research paper was the Yamazaki et al. "Spectroscopic Determination of pH and Its Application to Determination of Thermodynamic Equilibrium Constants". The project on measuring the pK_a of an indicator was a reproduction of the work in the paper with a different indicator. A buffer with a well-known acid dissociation constant was prepared by accurate mixing of appropriate acids and conjugate bases so that pH could be calculated to four significant figures. Accurate absorbance measurements of the acid/conjugate base forms of the indicator then gave accurate values of pK_a of the indicator. Different groups in the class measured different indicators and the results were pooled so that students had access to all the information on all the indicators.

The development of a spectroscopic pH meter used the database to select a mixture of indicators that would give spectroscopic selectivity for pH over a wide pH range. Example student results are shown in Figures 1 and 2. Figure 1 shows the absorbance spectra of a mixture of thymol blue, methyl orange, phenol red,

Table 1. Open-Ended Laboratory Projects

Determination of carbonate in sodium hydroxide titrant
Creation of an assay for *p*-hydroxybenzoic acid
Measurement of α fractions for an acid-base indicator
Measurement of the pK_a of an indicator
Development of a spectroscopic pH meter
Development of a spectroscopic voltmeter
Development of a universal buffer
Analysis of chelating agent mixtures with potentiometric or spectroscopic methods
Analysis of titration error
Statistical evaluation of homogeneous vs. heterogeneous gravimetric methods
Construction and analysis of an electrochemical cell
Study of HPLC secondary equilibria

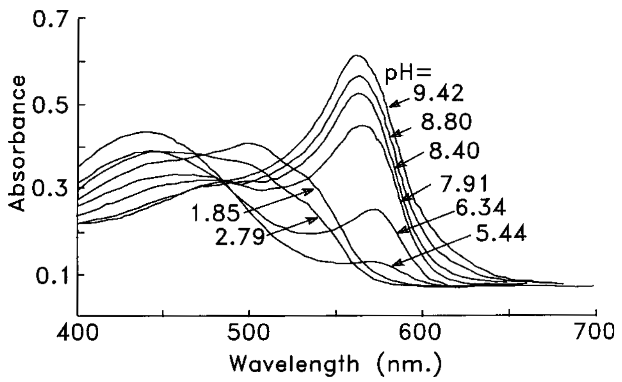

Figure 1. Spectra of a methyl orange, phenol red, chlorophenol red, thymol blue mixture for a series of pH values.

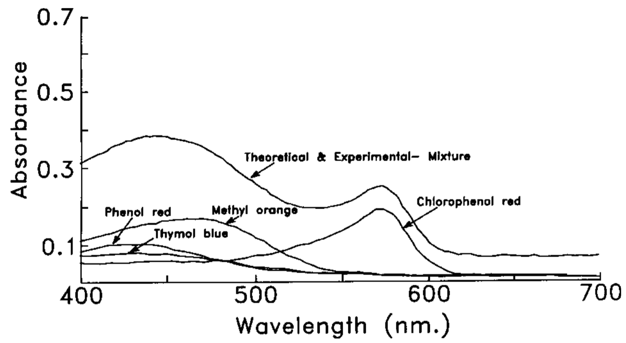

Figure 2. Comparison of the theoretical and experimental absorption spectrum for the pH = 6.34 sample in Figure 1 and the contributions to the theoretical spectrum from each of the individual indicators.

and chlorophenol red for 8 pH values from 1.5 to 9.4. Figure 2 shows a typical fit that was obtained for a pH = 6.3404, along with the contributions from each of the four indicators. Table 2 is a compilation of the results for each of the pH values showing the results of a pH meter measurement, a calculated pH based on knowing the buffer mixture, and the pH that resulted from the spectroscopic fitting procedure. There are obvious differences in the three measurements that need further work, but the results also show clearly that the procedure is feasible and good-quality results can be obtained.

Many of the projects come from traditional laboratory experiments. For example, the carbonate determination in a NaOH titrant project was adapted from an existing experiment where students determine the concentration of H_3PO_4 with a pH titration. The two equivalence points require equal volumes of NaOH titrant if there was no CO_3^{2-} absorbed from CO_2 in the air. If there is CO_3^{2-}, the equivalence points require different amounts of titrant because the CO_3^{2-} reacts with more H^+ at the more acidic equivalence point. Consequently, the NaOH solutions are made by diluting saturated solutions and the added water is sparged or boiled to eliminate CO_2 for the traditional experiment.

For the project, students are asked to design an assay procedure that can determine the amount of CO_3^{2-} in the NaOH using the H_3PO_4 titration. They must first establish a relationship between the volumes measured in the titration and the concentrations. Typically, they will choose either to standardize the procedure using standard NaOH and Na_2CO_3 solutions or to simulate the titration using the known values of the acid dissociation constants. They must then design and implement a procedure that uses appropriate concentrations and volumes. Often, students find that their results are not reproducible or that the simulations don't fit their data. An example of experimental data and a simulation are shown in Figure 3 for solutions containing no CO_3^{2-} (Fig. 3a) and 20% CO_3^{2-} (Fig. 3b). This problem is caused by the loss of CO_2 at the acidic pH values when the CO_3^{2-} is in the H_2CO_3 form. Creative students transcend the problem by reversing the usual roles of the NaOH and H_3PO_4. When H_3PO_4 is used as the titrant, the pH is not acidic enough to cause CO_2 loss until the

Table 2. pH Values[a]

pH Meter	Calculated pH	Spectroscopic pH
1.46	1.326	1.855
2.25	2.312	2.792
5.28	5.079	5.441
6.26	6.112	6.34
7.65	7.641	7.91
8.38	8.203	8.395
8.92	8.762	8.795
9.40	9.165	9.421

[a]Alternative measurements of buffer solutions using pH meter reading, calculated pH based on known pK_a values of buffer and known concentrations of buffer species, and pH determined by fitting absorption spectra of indicator mixture.

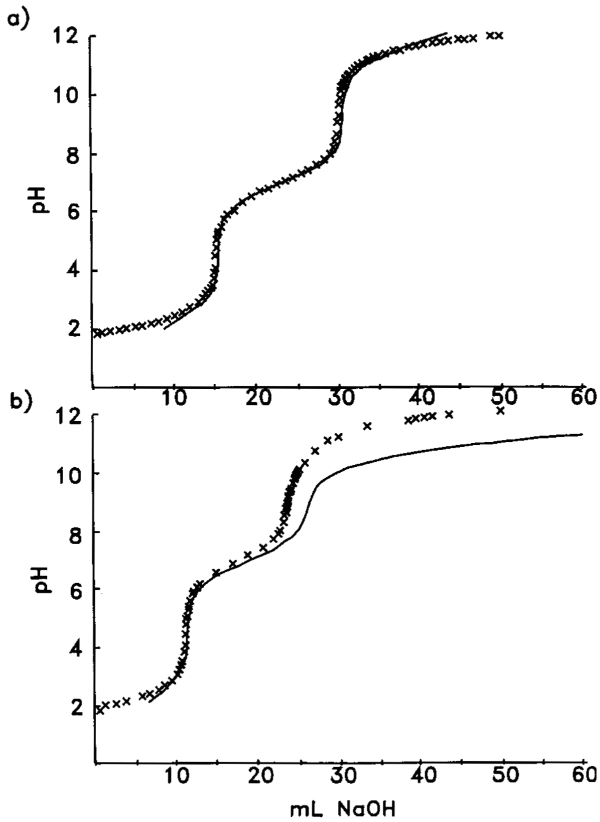

Figure 3. Titration of two solutions with NaOH where (a) the solution is H_3PO_4 and (b) the solution is 80% H_3PO_4 and 20% Na_2CO_3.

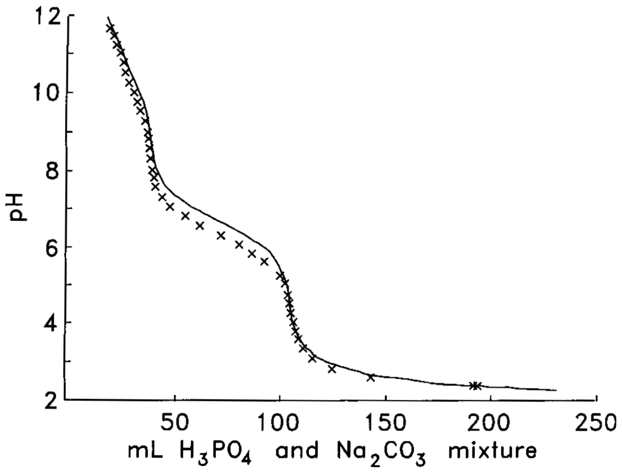

Figure 4. Titration of an NaOH solution with an H_3PO_4/ Na_2CO_3 mixture.

end of the titration. An example of this approach is shown in Figure 4.

The open-ended projects are conceptually simple; but there are enough details and enough unanticipated problems arise during the projects to provide students with many opportunities for creativity and practice in problem solving. In addition, the students struggle with course concepts in the context of a realistic problem, and this opportunity provides much greater insight into the course material. It also gives better insights into the way that science is actually practiced. Students should be made aware that experiments almost never work the first time because it is difficult to anticipate all the details and complications in a real system. It is an important lesson that all scientists learn from experience. They should recognize that an experiment does not fail if it doesn't work as anticipated, as long as it provides further insight for the next try.

The group project final report is done by the team. It includes description of the experimental plan, results, and discussion. The team members meet with the teaching assistant and faculty member to discuss the details of the project. The discussions have a professional character, the science in the projects being discussed without simplifications. It is an opportunity to reflect on the unsolved problems and the future directions that could be pursued. It is also an opportunity to reflect on the relationship between their experiences and the experiences that professionals have. The typical student group has invested a large amount of time and effort in the project and is proud of its accomplishments. Above all else, it is important that the discussion with the course instructors recognize the accomplishments and affirm the pride that is shown by the students.

Evaluation

The student response to these course changes was evaluated by questionnaires, free-written responses, and informal discussions with individual students. Table 3 gives the questionnaire statements and the mean student response in the freshman and upperclass courses, based on a scale from 1 to 5 (strongly disagree to strongly agree). The student response was favorable for each of the major course elements and for the overall course. The free-written responses took two forms. In the first, students were asked to write a critical evaluation of the team approach; in the second, they were asked to identify the greatest strengths and weaknesses of the group approach. Table 4 summarizes the student responses to the latter question by grouping them into 9 major categories along with the fraction of the comments that fell into each category. On average, each student made 2.1 comments. The greatest strengths were divided between the increased understanding of the course material, the enjoyment of working with problems that were more representative of real life, the thinking that was demanded by the course structure, the experience with working together in groups, and the opportunity to exercise creativity in the problem solving. Less frequently mentioned were comments about the increased depth of coverage, the challenge and sense of accomplishment, the opportunity to learn spreadsheet programs, and the development of problem solving

Table 3. Student Responses to Questionnaire Statements[a]

Statement	Freshman	Upperclass
The group work increased my understanding of the course material	4.2	4.0
I enjoyed the group projects more than regular lab experiments	4.2	—
The group projects took an extensive amount of time	4.5	—
The learning that occurred because of the group projects was worth the extensive time	3.8	3.2
The cooperative examination format was more effective than the traditional format	4.5	3.5
The assignment of individual grades by group members should be continued	3.7	3.7
The board of directors was a valuable addition and should be continued	4.0	3.9
The ideas tried in this course were valuable and should be expanded to other courses	4.4	3.8
I liked the format of this course	4.4	3.5

[a]The means for the scores are shown with a grading scale of 1 to 5 representing strongly disagree to strongly agree.

Table 4. Categorization of Comments to the Question: State the Greatest Strengths and Weaknesses of Group Approach

Strengths	%[a]	Weaknesses	%[a]
Increases understanding	14	Extensive time commitment	13
Better mirror of "real life"	11	Problems with group members	8
Requires deep thinking	10	Not enough preparation	7
Teaches group skills and builds community	8	Technical difficulties with equipment	4
Requires creativity	7	Inadequate time for project completion	4
Other	9	Other	5

[a]The percentages given represent the fraction of all comments made by all students that fall into each category.

skills. The greatest weaknesses were divided between the amount of time required in the course, problems in working together as a group, inadequate preparation for understanding the projects, technical difficulties associated with equipment and computer operation, and inadequate time to finish the project in a satisfying way. Less frequently mentioned were comments that the depth was too great to handle, the expectation level for the course was too high to sustain motivation, the projects became tedious during the data collection, and students got lost in the material. All of these evaluation exercises were consistent with each other. Ninety percent of the students in both the freshman and upper-level courses felt that the group work increased their understanding of the course material and 93% felt that the course required a great deal of time (average estimate was 18 hours of outside work).

There were differences between the freshman and the upper-level courses in whether the increased learning was worth the additional time. Table 3 shows that freshman students were much more receptive to spending time if it resulted in increased learning. Student discussions make it clear that upperclassmen feel much more comfortable with a traditional course structure and are skeptical about changing it. One upperclassman made it particularly clear when he stated that he appreciated the effort being expended on changing the course and that he could see why it was valuable. Nevertheless, he and his associates were close to graduation and they were most interested in getting out with the minimum amount of hassle.

The same general themes pervade the free-written responses but these contain more insight into the student feelings. In fact, there is a richness in the responses that cannot be easily categorized or condensed but will be the subject of a future paper. Table 5 gives example comments that best represent the student's perceptions and feelings about the course. They reflect the complex interplay between the three major themes of a course involving cooperative learning. The students are enthusiastic about the opportunity to work on problems that have elements of authenticity, the realization that their skill and mastery are improved by experiencing the course material in a specific context, and the cooperative interactions with fellow students. They also realize and accept that these accomplishments have been at the cost of increased work load.

A number of other important questions have not been addressed by the evaluation data given above. In particular, it is important to determine whether the course structure has improved the students' learning. This question is currently the focus of an extensive parallel study with a control class and the results will be published separately.

Conclusions

One of the most effective ways to accomplish effective learning is to involve students in original research. There are many constraints that prevent this approach from being applied to nonchemistry students, particularly at institutions with large enrollments. The open-ended laboratory approximates the research experience that can be implemented in large-enrollment courses. The open-ended projects need not be sophisticated to engage the imagination and excitement of students. As is clear from the evaluations, students welcome an opportunity to think about and work hard on problems that haven't

Table 5. Representative Comments from Free–Written Responses on the Desirability of Continuing a Group Approach to the Course

The greatest (obstacle) was communication and there was also a tendency for some members to slack on their responsibility and let others do the work for them. Both obstacles were greatly lessened at the end. Communication skills ... were greatly improved. This ability ... to communicate better especially regarding scientific ideas and solutions to small problems should allow us to be a better team member in the future. Individual responsibility also improved, though not nearly as much as communication. The greatest improvement was in each team member's education. By education, I mean in terms of knowledge and ... new ways of thinking. Both are gained in part from other members of the team and in part from oneself. One can learn from others and one can, through one's creativity, learn by one's self. By learning through creativity, I mean that for each original problem that is solved with creativity, that person gains a new way of thinking ... for the future. When I registered for analytical chemistry, I thought I was in for 5 credits of pure boredom. Not so. It turned out to be my most interesting class, due partly to the group work. Keep it. BUT, group work is very time consuming, especially outside of class. Overall, I would highly recommend that you continue to teach using team approaches.
At first I was not keen on the idea because I predicted a lot of unfair responsibility shifting, a general disorganization, no agreements, ..., basically ....too many cooks in the kitchen"...However, our team found answers in each other that we could not find in ourselves, support in getting things done instead of shifting responsibility, and often a fairly organized way of doing things... We also found that it was important for everyone in the group to understand everything about the lab, so everyone can add in when writing up the results together... One person's mistake becomes a team mistake. In the team approach, these rivalries between individuals cease and a team spirit of accomplishment dominates. More ideas and different opinions are absorbed. Time is efficiently used. Research is spread out and someone always knows something someone else doesn't.
Did the approach benefit each group member? I'll answer this with a qualified yes. The diversity of the problems kept us interested, and the difficulty kept us challenged. The material studied was related to our other assignments and the deeper understanding we gained by hearing others' ideas and explanations could be applied to other aspects of our work. The project work was not without its conflicts but debating and questioning proved necessary to handling the difficulty of the assignment. In addition, working in a group gave us a chance to fine tune our group skills, and these skills are an asset in many daily interactions. My reservations about the group work come in looking at the "big picture". The students were assigned to work together without regard to schedules... The idea of matching people in an effort to keep people from working with their closest friends is a good one. The combination of personalities kept the work fun and effective, but ... I would take schedules into account. My only other concern is time related. The projects took a significantly greater amount of time than we normally a lot .... Overall, the assignments were extremely challenging and the group approach made them tolerable. We all learned from one another while accomplishing our goal and I would continue the group approach.

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.

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