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# Techniques for Teaching Scientific Reasoning and Problem Solving

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Several years ago, the frustrations in teaching freshman chemistry courses had tested the limits of chemistry faculty. Like most introductory science courses, the freshman chemistry courses promised to introduce students to scientific methods of investigation and claimed to stress scientific reasoning and problem-solving. Like most (we suspect) introductory science courses, ours were not making good on these promises.

To be sure, students who completed freshman chemistry knew and could recall important information. Most of them could perform calculations and solve problems using the material they'd studied . . . so long as the problem explicitly stated or strongly implied which concepts, theories, and formulae were to be used. However, if we posed more complex problems—problems which required application of two or three concepts or problems which were not "set up" for solving— very few students knew where to begin, much less how to work through these problems. In the laboratory, students seemed lost if they were not given step-by-step directions for experiments and paralyzed if asked, for example, "to design and conduct a series of experiments for the determination of phosphate in various detergents."

Of course, none of this should have surprised us, since the teaching methods and examinations in freshman chemistry emphasized precisely those competencies which students developed—the ability to recall information and to use it as directed in solving problems. Faculty assigned readings, gave lectures, performed experiments . . . and students memorized. To be sure, the questions posed in class, at the end of each chapter of the text, and on exams asked students to apply their knowledge in solving problems. However, these questions typically asked students to apply only a single concept and the problems were usually highly structured. Students were getting little practice in wrestling with problems which required the application of several concepts or which asked them to decide what information was needed in order to solve the problems.

In 1979, we began revising the section of introductory chemistry offered to chemistry majors and chemical engineers in order to make it more consistent with its claims to stress scientific reasoning, problem-solving, and investigating. Yes, the course continues to include readings, lectures, and demonstrations that introduce and explain course material. However, because students need to practice their thinking skills, the course now includes many small group discussion exercises and a group research project.

## SMALL GROUP DISCUSSION EXERCISES

Students in this course now spend at least half of each 75-minute class meeting in small groups (5-6 students) discussing problems. Sometimes, the problems are presented in written form. Other times, students watch a demonstration or perform an experiment in their groups and record their observations. They are then asked to use what they've learned to explain their observations or formulate hypotheses or propose additional experiments to test alternative hypotheses.

In one class, for example, students are divided into groups and given the following task:

> Dissolve the ammonium chloride in the beaker that is given to your group with water. Place a few drops of water on the damp sponge and set the beaker on it. Discuss and explain your observations using thermodynamic and chemical reaction theories.

As students perform the experiment and discuss their observations, the instructor moves from group to group, noting each group's progress and offering hints when students need them. After 20 minutes or so, class reconvenes and the groups are asked to report. The remaining time is used to compare, contrast, and discuss the strategies and explanations which different groups considered.

A session on redox reactions illustrates a variation of the same instructional technique. Students watch a series of experiments in which various combinations of three unknown solutions are mixed. After each experiment, students' observations of color changes and elapsed time for the reactions are recorded on the board. After four or five of these experiments, students break into small groups and try to formulate hypotheses to explain these experimental data. Quickly, students begin to speculate, "I wonder what happens if you leave out reagent A or reagent B?" After 10 or 15 minutes, most groups ask for additional experiments. Then, it's back to the small groups for more discussion. Eventually, at least one group comes up with something resembling an hypothesis, and the class is asked to propose additional experiments to test the hypothesis. By now, students are eager to see their hypotheses verified, pay rapt attention as these experiments are performed, and let out cheers when their hypotheses are confirmed. While such activities were introduced primarily in order to give students practice in scientific reasoning, they also bring some of the drama and spirit of scientific investigation into class.

## GROUP RESEARCH PROJECTS

Although the small group discussion activities provide practice for particular scientific reasoning skills, they do not typically require students to practice the combinations of skills involved in scientific research. Thus, participation in a group research project is required in the course. Early in the semester, students are assigned to groups of five or six members. A student leader is appointed to organize the group, direct its activities, and report its progress. Each group must define a chemical problem or question, design an experimental procedure, conduct the experiment(s), and prepare both a written and an oral presentation of the group's research.

For most freshmen, this project represents their first attempt to conduct a scientific study from start to finish. Initially, students find the assignment ambiguous, unstructured, and generally unsettling; they need considerable guidance and frequent reassurances. In order to provide some initial direction, they are given a list of 35-40 suggestions which include analytical methods such as "determination of phosphate in detergent," "assay of aspirin in various medical preparations," "ion-exchange capacity of water softeners," "comparison of volumetric analysis versus gravimetric analysis."

In the sixth week of the course, each group must submit a written definition of the question or problem it intends to investigate. The following samples of "proposals" were submitted by students in 1983 and illustrate the types of problems students define:

> Determine the phosphate distribution down the Pawcatuck River. We will attempt to generate hypotheses to explain any differences in the distribution.

> Is there a loss of calcium when using skim milk as opposed to whole milk? If so, what is that loss?

> What amount of protein is available for consumption in one week at the dining hall? How does this compare to the suggested level of protein intake?

Is spring water worth paying for? Are there really benefits to drinking spring water or mineral water over tap water? Ions to be determined are: F, Cl, Br, I, Na, K, Mg, Ca.

These problem definitions are reviewed and returned to students with questions, suggestions, and—usually—requests for revisions. Once the groups have written acceptable definitions of their research problems, each group is asked to submit an outline of the experimental procedure to be used. Again, their proposals are reviewed and returned with questions, suggestions, and requests for revisions. Thus, by the time students begin work in the laboratory, they've already been assured that their topics and experimental procedures are acceptable, that their projects are significant, and that they are manageable in the time available.

The last six scheduled laboratory meetings are reserved for working on the group research projects. This required dropping some of the standard laboratory experiments conventionally required in freshman chemistry, but we were not convinced that those experiments were teaching students much that was worthwhile anyway. Still, students spend many additional hours in the lab; most of these projects require 30-40 hours from each student. They complain, of course, but not with much fervor.

## RESULTS

Although evidence of the impacts of these instructional techniques on student learning remains largely impressionistic, initial attempts to determine their effects have been encouraging (Fasching and Erickson, in press). Most students are able to handle the simple and the moderately difficult application problems included on course exams. Although not many students completely solve the most complex problems, about half show signs that they know how to approach these problems and are able to provide at least partially correct solutions. Before revising the course, very few freshman chemistry students demonstrated the ability to tackle such problems. The group research projects have been consistently excellent. Although these projects are intended to provide an "introduction" to scientific research, we think some freshman projects have been comparable in quality to research performed by first-year graduate students in chemistry.

Student evaluations of the course have been easier to monitor systematically and show dramatic improvements on almost every item. In 1979, only 40% of the students rated the course better than satisfactory, and 21% rated it below average. In 1984, 77% of the students rated the course "excellent" or "good," and no students rated the course less than satisfactory. Student responses to more specific questions followed similar patterns.

These results have been encouraging. Yet, five years is a long time to work on improving a course. Thus, the number of students (20-25% each semester) who rate the course "satisfactory" has been frustrating, especially when one consults their explanations of why they rated the course as they did. The following sample of comments from students' evaluations reveals some recurring ambiguities and tensions:

> I know that the instructor's intent is there and I realize that he is trying to teach us to think critically about the problems we are asked, but. . .it doesn't seem to tie in with what we should be learning as prescribed by the book. . .

> The course makes each student think and reason out solutions which can be compared with classmates'. This is necessary. But more lectures would help. There aren't many straight lectures.

> I like the concept of group learning. I also like chemistry. I like the labs, although they are too demanding. I don't feel I have the background to do some of the things I am asked. There are not enough notes. I do not know what is expected. I find it difficult to prepare for our tests. I think we should go over homework in class. . .

> The facts in sciences are extremely important and should be learned with diligence. Basic equations and formulas used in solving them are essential tools for a bright future in a more detailed science. CHEM 192, however, was

> instructed in a more relaxed style than I liked because I ended up not retaining knowledge which is important and necessary for the future. CHEM 192 should be instructed using many sound examples and stressing the basic facts and solid ways of finding the correct answers. . .keep precise and basic sciences more in line with a straightforward factual approach and try to give concrete examples and questions on the material.

> The teacher is good in his field. He encourages us. But he doesn't define things. Thinking is fine, but learning is what I'm here for.

"Thinking is fine, but learning is what I'm here for." Indeed. Often, students sound as if they define teaching and learning along the following lines: teaching is lecturing and assigning textbook chapters; learning is memorizing what the teacher and the text have said. Thinking is an extra—sometimes interesting, but not the main business. Clearly, this course is based on different assumptions about what constitutes teaching and learning, and students' comments acknowledge those differences. Yet, students seem to hold onto their definitions of teaching and learning—and use them to guide their studying—with surprising tenacity. Why?

We suspect that Perry's (1970) findings about intellectual development among college students offer some clues. According to Perry, students' views of knowledge, their expectations of instructors, and their perceptions of their responsibilities as students change dramatically during the college years. Students in the earliest developmental positions, Dualism, view knowledge as an accumulation of facts, right answers, and truths; all else belongs in a domain with wrong answers, falsehood, and "mere opinion or theory." Professors are viewed as Authorities, and their job is to present the facts to students . . . as many as possible in the time available. Students are the eager recipients of this information, which they diligently record in their notes, doggedly commit to memory, and dutifully write down as answers to examination questions.

If one looks at students' comments about this course in light of these characteristics, several phrases stand out in their evaluations: "It doesn't seem to tie in with what we should be learning as prescribed by the book"; "More lectures would help. There aren't many straight lectures"; "There are not enough notes"; "CHEM 192 should be instructed using many sound examples and stressing the basic facts and solid ways of finding the correct answers . . ." Their evaluations are filled with recommendations one might make if one viewed knowledge as right and wrong answers, if one regarded instructors and textbooks as Authorities, if one viewed learning as memorizing the right answers which Authorities present in lectures and readings . . . , if one were in Dualistic positions.

If it turns out that the 20% or so who rate the course only "satisfactory" are in positions of Dualism, then the assumptions which have guided our efforts to strengthen the course are probably not sufficient. We have assumed that students would develop their scientific reasoning and problem-solving skills if we provided enough opportunities for them to practice those skills. Each year we have increased the number and variety of practice exercises, and we're currently working on a program of computer-assisted practice. We're convinced these activities have benefitted many students. However, students who long for "basic facts" and "solid ways of finding the correct answers" are likely to find this course frustrating, no matter how many practice exercises are available. If we are to reach these students, then we'll need to find ways to support them so that they will risk a transformation in the way they view science and learning.

In other words, there's more to be done in this course.

## REFERENCES

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