Critical Thinking in General Chemistry

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Although critical thinking has been defined and addressed periodically over the past 20 years, strategies to promote critical thinking in general chemistry have not gained widespread attention. Several authors have spent considerable effort designing critical thinking exercises and integrating these skills into the curriculum in introductory college biology and physics. Arons has outlined a specific set of processes for promoting an increase in critical thinking that he utilized during the 1970's in an introductory physics course (*1*). He observed that use of these procedures seemed to promote growth in intellectual development in Piagetian terms.

Moll and Allen in 1980 conducted a study in introductory biology by incorporating critical thinking teaching strategies (class discussion, video segments, specially designed home assignments) into the course (*2*). Based on pre- and post-test comparisons they argue that memory/recall alone lead to serious deficiencies in student understanding and conclude that students can make significant improvements in their critical thinking ability based on procedures outlined in this study.

Statkiewicz and Allen also employed critical thinking practice problems and evaluated the effectiveness of these exercises in developing critical thinking in biology in a class of 112 students in general biology and reached a similar conclusion (*3*). They also reported that such student analytical skills are transferrable to other different problems.

Zoller, during the early 1980's, fostered critical thinking in chemistry by using the strategy of having students pose test questions (and answer them) as part of the major course examinations (*4*). In his three-year study he noted that 98 subject students preferred the question asking category over traditional exam questions asked of them (on the final exam). Van Orden addressed the role of critical thinking writing assignments in general chemistry and studied the use of these in learning chemical concepts (*5, 6*). Using the second semester of a general chemistry course (N=42) he used homework, quiz, and midterm exam scores to ascertain the impact of critical thinking writing assignments (test group versus control group) and determined that average students can be taught higher order learning skills. He also found that critical thinking writing assignments are more effective than traditional methods in learning chemical concepts.

In this paper I report strategies I have used in general chemistry for science and engineering majors (Chem 12), a similar course for less-prepared science and engineering students (Chem 17), and Chemistry and Society (Chem 001), a course for nonscience students. These strategies are linked to both the intellectual developmental model of William Perry and the constructivist view of knowledge, especially as related to chemical misconceptions. Bodner and Nakleh, for example, have addressed the latter (*7, 8*). Finster has applied some of Perry's concepts to chemistry (*9, 10*).

Briefly stated, Perry's view is that college students, although they gradually change the way they view knowledge and values, generally begin at a level he labels "dualism" (*11*). The dualistic student generally accepts authority and wants that authority to provide an immediate source of decisions in a right/wrong dichotomy. Thus, students accept the word of the instructor or the textbook in this simplistic way. In subsequent stages of development the student discounts authority (any answer is good) and then may advance to acceptance of diversity and uncertainty. The student might finally advance ultimately to being able to analyze diverse points of view and recognize that knowledge is "relativistic".

Because of their placement at the level of "dualism" in Perry's scheme and the lack of successful training in critical thinking they have encountered in previous science courses, many first-year chemistry students are unskilled at critical thinking. "Covering the syllabus" and lecturing do not provide a supportive framework to encourage critical thinking skills. Chemistry courses I have taken (and taught) generally leave little time for reflection, tangential thinking, evaluation of data, and challenges to the belief system of the student. At the level of "dualism" students want to accept authority and prefer yes/no answers to problems. They want to accept the validity of laws, theories, and equations as absolute. They often fail to recognize assumptions or the possibility of alternate explanations or solutions.

The constructivist view of knowledge is that students create knowledge internally and are capable of building incorrect connections to previous learning that are invalid or the foundations of which are faulty. Promoting critical thinking skills can uncover such misconceptions in chemistry although these might be difficult to correct (*12*). In this paper, I take the approach that both the state of a student's intellectual development and the extent of conceptual knowledge are important factors in developing critical thinking strategies, and that practice at selected assignments provides feedback to both instructor and student which can be beneficial.

Assessing Students

Below are two exercises I introduce early during the semester that I ask students to do as take-home assignments or in small groups during class. I usually am taken aback by the results. Exercise 1, below, is a textbook problem (*13*). In a class during the Fall semester 1993, only 20 of 46 general chemistry students present that day could make a valid hypothesis from data given in this problem. This five-credit course, comprised science, engineering, and agriculture majors who were in need of remediation in chemistry.

Exercise 1

For the noble gases (the Group 8A elements):

He Ne Ar Kr Xe

(a) determine the number of protons and neutrons in the nucleus of each atom and (b) determine the ratio of neutrons to protons in the nucleus of each atom. Describe any general trend you discover in the way this ratio changes with increasing atomic number.

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Summary of Student Data for Courses Involved in Critical Thinking Exercises

Course	Credits	Semester	Male	Female	SAT Ave Verbal	SAT Ave Math	SAT Ave Total
Chem 012	3	Fall 92	59	10	471	575	1046
Chem 012	3	Fall 93	43	8	481	587	1068
Chem 017	5	Fall 93	34	12	403	471	880
Chem 001	3	Fall 92	23	16	370	489	859

See the table for class composition by gender and ability (SAT). The most common error was the belief that the proton to neutron ratio increased with increasing atomic mass. What prompted me to use Exercise 1 as a quiz question later in that same semester was my observation that over 50% of the students submitting this problem solution as part of a collected homework unit had failed to answer the second part of the question. I surmised they avoided it because this kind of evaluation was apparently difficult for them.

Exercise 2

Suppose the following data was collected by an experimenter who was observing the distance travelled by various gases in a set amount of time through a horizontal glass tube at room temperature and pressure.

Gas	Distance (to nearest centimeter)
SO_2	50 centimeters
HCl	66 centimeters
CH_4	100 centimeters
SO_3	44 centimeters

1. State your observation as briefly and to the point as possible.
2. Design a hypothesis to explain your observation.
3. Suggest an experiment to test your hypothesis.

Exercise 2 similarly asks students to examine data, state an observation, and design a hypothesis. This was administered as a group exercise during the second class of a three-credit chemistry course for students majoring outside science or engineering, Chem 001. See the table for descriptive data for this class. Most students were unable to suggest any connection between the chemical formula and distance travelled or to relate distance with any other factors, such as, the presence of oxygen or hydrogen, or perhaps the number of atoms in the formula. Most of the students had taken a high school chemistry course.

Recently, I also have administered this exercise to a class attended by 45 students who were science or engineering majors enrolled in the "normal" three-credit lecture section, Chemistry 12, Fall 1993. See the table for descriptive data. The students completed the assignment at the beginning of a class during which the kinetic molecular theory was to be discussed. All of these students had taken one year of high school chemistry and had completed approximately 25% of the general chemistry course.

Only 20 of these 45 students connected formula weight with the data in forming their hypotheses. Fifteen of the students linked the presence of H with longer distance and the presence of O or S with shorter distance. Seven students were unable to state their observation or make a hypothesis. It was interesting that the majority of students made their hypotheses in the observation step of the exercise. Apparently, students have had little training in observing and critically analyzing data.

I attempted to compare the experiments suggested by students with the hypothesis made by each to determine if the experiment would in fact test the individual hypothesis in a logical, straightforward manner. Only 21 of the 45 students were able to do this.

I also have used the multiple-choice format suggested by Statkiewicz and Allen and designed questions to assess the ability of students to explain answers (*13*). This format presents a problem or observation and gives several plausible choices for evaluation as true or false. Points are awarded for the rationale as well as the answer.

Exercise 3

Answer each of the five statements (a–e) as True or False. *Give an explanation for each of your answers.* You will be graded on the basis of your choice (True or False) *and* on the correctness or appropriateness of your explanations. You may use calculation, common sense, examples, analogies etc. for your explanation.

Three grams of gas are placed in a sealed, 10-L flask maintained at 0 °C. The molecular weight of the gas is 20. Which of the following would most likely occur if the valve to the flask is opened?

a. The gas and oxygen in the air will mix and react.
b. The gas will rush out of the bottle.
c. At 0 °C, the three grams of gas will still occupy 10 L.
d. Air will rush into the bottle.
e. The gas and air will remain separate and will *not* mix.

Exercise 3, designed by Stakiewicz and Allen, is typical of these questions that are assigned for out-of-class completion. Two classes of science-engineering majors (Chem 012, Fall 1992 and Chem 012, Fall 1993) recently completed this exercise and the following are observations I made during grading. These observations are typical of all classes that have completed this exercise. See the table for class composition and SAT scores.

1. Many students are unable to justify their answer. Only 21 of the 102 participating students calculated the internal pressure.
2. Many students cannot differentiate between fact and assumption. They *assume* the gas is lighter than air. They *assume* the pressure inside and out are the same.
3. Half of the students make assertions without proof: "The gases will definitely mix;" "The gases will definitely react;" "I never heard of finding pockets of gas."
4. Some interesting conceptual errors are uncovered: "Gases do not mix"; "Since the gas will sit on the bottom of the flask."; "Atmospheric pressure weighs less than the gas"; "Air will lie on top of the gas."

I have designed other questions of this type not only to probe the skill of students to apply principles to problems but also to ask students to identify the assumptions in a problem. Often students are unable to recognize what to the instructor is "a given." For example, during a gas law discussion ask your students to calculate the density of water at STP. Examination of student work reveals other interesting conceptual errors. On a recent exercise, 15 students in a group of 65 (Chem 012, Fall 1992) indicated that gases cannot diffuse in a vacuum, and, as indicated above, almost an entire class will fail to envision H_2O as a liquid at STP.

Strategies to Improve Critical Thinking

I often have heard teaching colleagues bemoan the "fact" that students do not know how to think. I assume this relates to the perceived inability of students to relate concepts to practice, be creative, and to solve complex problems with alacrity. Some of these observations are undoubtedly true. But my response to these colleagues is to ask the question, "How have you demonstrated critical thinking skills or instructed students in critical thinking in your discipline? Have you created assignments to encourage analysis and evaluation?" Do you ask probing questions? Do you insist that students use scientific terms correctly?"

I have used the following strategies to encourage critical thinking skills:

(1) *Ask questions frequently and direct them to individual students.* I use index cards with student names for random selection to call on several students each class. Design questions that are process-oriented, seek explanations, or ask for evaluations. "Yes" or "no" answers are not solicited nor accepted. Emphasis is placed on "why" or "how" and on relationships to previous information. Why hypochlorous acid is more acidic than hypoiodous acid is a more important target than *which* is more acidic.

(2) *Use examples and illustrations that challenge dualistic thinking and reinforce the notion that science does not have many absolutely correct answers.* In this regard it is useful to discuss such topics as Dalton's Atomic Theory, the ideal gas equation, and bonding theory to point out how these "laws" and theories have changed since their inception. The recent history of chlorofluorocarbons can illustrate how the "inertness" of these compounds is no longer accepted.

(3) *Promote discussion among students by using in-class group assignments and encouraging out-of-class study groups.* These assignments typically are problems or questions in which students share information and must come to consensus. Four to six students are assigned to groups in a random manner. These exercises are sometimes graded and usually are given on the day a homework assignment is collected in order that students do not come to class unprepared. These assignments can be awkward at first, but by a few weeks into the semester the classroom is noisy with discussion and argument. What seems to work best here is for the instructor to stay out of the loop (promotes better discussion, discourages dependence on an authority figure, encourages alternate approaches to problem solving, and evaluation of possible answers and alternatives.) Such group discussion and problem solving also facilitate formation of study groups that meet outside of class. In this way a supportive environment for critical thinking is established. McKeachie has reported that such discussions increase content learning as well as application skills (*14*).

(4) *Effective use of feedback encourages critical thinking.* Critical thinking skills are learned incrementally according to Perry. It is important, then, to ask students to clarify their questions in order that a "dialogue" be established in which the instructor can model how he or she supports opinions. Asking a student to resubmit assignments or portions of an assignment requires them to think through and reform previous assertions and more logically state or support answers. For example, numerical answers not clearly produced must be justified. Another benefit of this sort of feedback is the promotion of "process" as well as correct statement of fact (content). How a student gets an answer is at least as important as the answer itself.

(5) *Exemplification is critical to fostering critical thinking.* Hanna and McGill report that one of the qualities that distinguishes excellent instructors is that good instructors model the thinking processes critical to the particular discipline (*15*). They call this "exemplification".

Students must be shown examples of data analysis, alternate interpretations, and other skills that characterize critical thinking. Only if instructors state explicitly the assumptions being made will students begin to see this as an important task. If acknowledging the uncertainty in science is critical to instructors, they must demonstrate this with examples and behavior. One way to promote a healthy dose of skepticism is to ask students to read articles on controversies such as cold fusion or such value-laden topics as whether good teaching and good research go hand in hand. I encourage students who want "extra credit" to report on such articles in a weekly journal. These journals must be begun early in the semester and are graded. Instructor comments provide direction for future reading.

Advantage and Disadvantages

I have experienced several advantages or improvements in my general chemistry courses since the Spring of 1992 when I began to incorporate critical thinking strategies into my teaching, some of which were delightful surprises.

1. Students become active, responsible learners who grow in enthusiasm during the semester. Student evaluation instruments elicited many favorable comments.
2. Students are challenged to redefine and reorient their conceptual knowledge base as they develop an increasingly more evaluative, skeptical approach to science. Many do move, although gradually, to operating occasionally beyond dualism.
3. Responses to exercises and discussions allow elucidation of conceptual errors that students carry. "Gases cannot diffuse in a vacuum", "How many moles N_2 in N_2H_4", and other misconceptions are stated explicitly.
4. Students do more independent, active learning as responsibility for learning is shifted to them. In my Fall 1993 General Chemistry (Chem 17) there were four study groups of four to six students meeting weekly outside of class. Group exercise during class precipitated this increased student involvement.

There also are disadvantages to incorporation of critical thinking into courses.

1. Preparation of exercises and planning requires instructor time.
2. There often is initial resistance and frustration on the part of students to the class exercises early in the semester. Students want facts and answers to be concrete, and they are quite uncomfortable with a process where some ambiguity is encountered.
3. Grading requires more time because of the need to collect and respond to more assignments, including homework.
4. Critical thinking growth is difficult to evaluate. Student responses to questions, facility in recognizing assumptions, acknowledgment and acceptance of uncertainty, and the skill with which student solve problems do give qualitative indications of improvement.

Conclusion

Students entering college chemistry courses typically have received little instruction or encouragement to practice critical thinking skills. In the rush to "cover the syllabus" many college instructors allow students little time to develop skills other than fairly rudimentary problem-solving or multiple-choice answer selection. I have observed that student skills in critical thinking will improve if an environment is created that provides practice and encouragement. This environment is one in which some lecture time is sacrificed to group discussions. Process (how and why this answer is obtained is important) is emphasized over content (answers, covering the syllabus), focus is placed on active-learning over passive, and emphasis is placed on learning in-class as well as out-of-class.

Exercise 4

Examine the data below for a chemical reaction run several times under various conditions. State at least two hypotheses based on your observation. Design experiments to test your hypotheses; that is, create additional lines of data and suggest the resultant speed you expect of the reaction. Use lines 5, 6, and 7 to create additional data as necessary.

Reaction A + B ——> AB (all gases)

Reaction number	Grams A present as reactiion begins	Grams B present as reaction begins	Temp °C	Relative speed of the reaction as reaction begins
1	10	10	30	2.0
2	20	20	30	4.0
3	40	20	30	4.0
4	40	20	50	18.0
5				
6				
7				

One observation is critical in order to respond to those who argue that instructors must cover the curriculum. I believe it is the student who does this. I have diminished lecture time in my classes to perhaps 60% of the total. I was astonished that during Fall 1993 I found myself one day ahead of the syllabus after five weeks. Indeed, as Nelson has experienced in biology, the strategies that facilitate critical thinking also facilitate content acquisition (*16*). Student performance on examinations and quizzes has been excellent, and class attendance–since I converted away from lecture toward more classroom discussion and group problem solving–has improved dramatically. During Fall 1993 attendance at my general chemistry classes was at 95%. When I lectured in the traditional mode 70% to 80% was typical. I believe students can be enthusiastic active learners and critical thinkers if given the opportunity to do so. I was recognized in 1993 as the "Teacher of the Year," although general chemistry was voted one of the five most demanding courses on campus in a recent student survey.

I have observed a gradual improvement in student ability to think critically as defined by more cogent answers to exercises and by the type of questions asked by students during the course of the semester.

During Spring 1994, in "Chemistry and Society," for example, following assignment and discussion of the Exercise 2 and additional discussion of another sample exercise, I assigned a table of kinetics data (Exercise 4) on the first exam. Students performed beyond my modest expectations. Fifteen of 18 students were able to state a satisfactory hypothesis and suggest experimental changes in the table which would successfully test the hypothesis. In fact, I was able to form a hypothesis of my own about the difficulty experienced by my more advanced students in general chemistry in deciphering such data to ascertain the rate law for the reaction. What I have, heretofore, assumed to be a problem relating to thinking in exponential terms might in fact be attributable to lack of training in examining experimental data and forming hypotheses.

Finally, it is through examination of student work on problems such as these that instructors can make alterations in their teaching. I have found moments of great reward and insight from student work on exercises of the type I have presented here.

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New Editor Appointed for Journal of Chemical Education

David Lavallee, Chair of the Board of Publication of the Division of Chemical Education, is pleased to announce that the search for an Editor of the *Journal of Chemical Education* has been completed and that John W. Moore of the University of Wisconsin–Madison has been appointed the seventh Editor. He will serve as Editor for a five-year term beginning September 1996, replacing J. J. Lagowski of the University of Texas at Austin who has served since 1979.

John Moore has been associated with the *Journal* for a number of years and in various capacities. He founded the *Computer Series* feature column in 1979 and then founded the *Journal's* subsidiary publication, *Journal of Chemical Education: Software,* in 1988. the appointment means that the staff of both the print and software operations will now be under one roof.

The editorial changeover is now in progress: effective July 1, 1996 correspondence and manuscripts for submission should be sent to: Journal of Chemical Education, University of Wisconsin–Madison, Department of Chemistry 209 North Brooks Street, Madison, WI 53706; phone: 608-262-2072; 800-991-5534; FAX: 608-265-8094.