Consumer Chemistry: Critical Thinking at the Concrete Level

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There are 10 one-semester general chemistry courses at Purdue that range from a remedial course for students with weak backgrounds to an honors course that challenges our best students. When you consider that 75% of the students at Purdue take one or more of these courses, and examine the extent to which they are tailored to serve the students who enroll in each course, it would be tempting to conclude that one of these courses must meet the needs of virtually any student at the institution. Unfortunately, this conclusion would be wrong.

These courses all have one thing in common: they teach chemistry from a mathematical perspective. The level of mathematical rigor changes from one course to another, but they all presume that a knowledge of chemistry is built on the basis of the ability to answer questions such as the following taken from the textbook for the remedial course (*1*).

> An oxide of nitrogen with an empirical formula of NO is collected in a 50-mL syringe at a temperature of 27 °C and a pressure of 100 kPa. The sample of gas weighs 0.102 g. What is the formula of the gas?

Purdue is not unique in its approach to general chemistry. Our discipline can be described as a "high consensus field" (*2*). We might argue about what topics should be emphasized (*3, 4*), and debate the best order for presenting these topics, but chemists at widely differing institutions are in remarkable agreement about the material that should be covered in a given course.

The assumption that beginning students need to be exposed to the mathematical aspects of chemistry works for students who want to become scientists or engineers; it may even work for those in agriculture or the health sciences. But it does not work for the majority of the students who pass through our high schools or even the majority of the students who enroll at our colleges and universities.

We can overcome this problem by making radical changes in existing courses or by designing new courses to meet the needs of students who do not take chemistry now. There are cogent arguments for the first alternative (*5*), but this is neither the time nor place to review them. For now, let us focus on the characteristics of a new course whose goals might include helping students understand how chemistry affects their daily lives, preparing them to make educated decisions on issues of science and technology, and fostering the development of critical thinking skills. A course we will call: "consumer chemistry".

Some would argue that our present courses already address these goals, particularly the first. But students who take these courses often focus so much attention on mastering the calculations associated with chemistry that they walk away with little if any understanding of the chemistry they encounter in their daily lives.

I teach a course for science and engineers majors. Toward the end of the first semester, I ask my students whether Fe_2O_3 is a solid, a liquid, or a gas at room temperature. The majority do not know. I describe what happens when iron rusts, talk about the difference between "rust" and Fe_2O_3, and then repeat the question. Up to half *still* do not know! At that point in the semester, virtually every one of them could tell me how much Fe_2O_3 could form when 10.0 g of iron reacts with excess oxygen. But they make no connection between the world in which they do these calculations and the world in which iron pipes corrode.

A little over a year ago, I gave my science and engineering majors the following multiple-choice question:

> Which statement best explains why a hot-air balloon rises when the air in the balloon is heated?
> (a) As the temperature of the gas increases, the average kinetic energy of the gas molecules increases, and the collisions between these gas molecules and the walls of the balloon makes the balloon rise.
> (b) As the temperature of the gas increases, the pressure of the gas increases, pushing up on the balloon.
> (c) As the temperature of the gas increases, the gas expands, some of the gas escapes from the bottom of the balloon, and the decrease in the density of the gas in the balloon lifts the balloon.
> (d) As the temperature of the gas increases, the volume of the balloon expands, causing the balloon to rise.
> (e) As the temperature of the gas increases, the hot air rises inside the balloon, and this produces enough force to lift the balloon.

The distribution of answers was almost perfectly isotropic.

Chemistry majors are no better at applying their chemical knowledge to the real world. Dudley Herron once asked a graduate student to give an example of how thermodynamics pertains to the real world and received the following answer (*6*): "There are no examples of thermodynamics in the real world!" During an orientation program for new graduate students last fall, I asked questions such as: "How does a mercury barometer work?" "Why does food cook faster in a pressure cooker?" "Why does the meniscus in a buret curve upward, whereas the meniscus in a mercury barometer curves downward?" What makes a hot-air balloon rise?" "What are the bubbles in boiling water made of?" Most of the students could not answer these questions. These students know an enormous amount of chemistry. In part due to the exhortations of Derek Davenport (*7*), they now know that silver chloride is neither green nor gaseous. But they cannot apply their knowledge outside of the narrow domain in which it was learned. They "know" without understanding. When asked, "Why does salt melt ice?", they reply, "Because it lowers the melting point." When asked *how* does salt melt ice?", they respond by drawing phase diagrams, or writing equations for the free energy of the system, and never get an answer.

The only thing more frightening than listening to our students apply their chemical knowledge to everyday occurrences is thinking about the "chemical knowledge" of the vast majority of high school and college students who never take chemistry. The students who are scared to death by chemistry courses; perhaps rightfully so. The students whose anxiety is so high they will change majors rather than take chemistry.

A course specifically designed to attract these students to chemistry would serve many purposes. At a time when the words *toxic* and *chemical* seem inexorably linked, we cannot afford to graduate another generation of political scientists, business majors, social scientists, elementary education majors, etc., who are totally ignorant of our point of view. More importanty, at a time when critical thinking is receiving so much attention (*8*), we should recognize that chemistry, even from a nonmathematical perspective, is an excellent medium for helping students learn how to think.

When poorly taught, consumer chemistry courses merely provide a pulpit from which the professor can preach a biased view of societal issues or recite the contents of one of the excellent textbooks written for this market. But when well taught, they provide a unique opportunity to encourage critical thinking because there is no longer any excuse for presenting the students with endless series of "facts" representing the end product of scientific thought.

One of the most beautiful facets of a consumer chemistry course is freedom from having to teach material that serves as the basis for future courses. There is no need to worry about preparing students for organic chemistry, or biochemistry, or engineering thermodynamics. We can avoid the trap of believing there is so much material to be covered that there is not enough time for the students to construct their own knowledge (*9*). These may be the only courses we teach where there is enough time to expose the students to the thought processes that led to our present factual knowledge.

In a course for which one of the principal goals is fostering critical thinking skills, the concept of density is no longer relegated to the role of helping us calculate the volume of liquid ammonia that would react with 10.0 g of sodium metal or the molarity of a concentrated sulfuric acid solution (d = 1.84g/mL^3) that is 97% H_2SO_4 by weight. Density becomes an example of a family of ratios of extensive quantities that are defined in order to obtain an intensive quantity characteristic of the substance or phenomenon being studied and not the size of the sample. It becomes a way of testing whether glass stirring rods and plate glass windows are made of the same substance (*10*). It becomes a tool scientists use to explain such diverse behavior as hot-air balloons and the sinking of the *Titanic*. It becomes a way of thinking about the world in which mercury is no longer "heavy". It becomes a construct that is so powerful that students can apply it on their own to understand why a bowl of natural grain cereal contains four times as many calories as an equal-sized bowl of corn flakes, even though the natural grain cereal contains only 1.3 times as many calories per ounce.

In the context of fostering critical thinking skills, the fact that a gold atom contains a certain number of electrons, protons, and neutrons is not as important as an understanding of *why* we believe in the existence of atoms and subatomic particles. Being able to calculate the frequency of light absorbed when an electron is excited from the $n = 2$ to $n = 5$ shell of a hydrogen atom is not as important as understanding *how* our present knowledge of the structure of the atom was obtained.

Those who believe we do adequate justice to these questions in our present courses should try an experiment in which they ask their students to expain why Rutherford was surprised by the results Geiger and Marsden obtained when they bombarded gold foil with α-particles. The conceit of cannonballs and tissue paper might come back to haunt them.

In the right hands, consumer chemistry courses can take an important step in the direction recommended by Arnold Arons (*5*).

> Virtually any student can tell you . . . that the Earth is spherical and that it and the other planets revolve around the sun . . . In terms of our vaunted goals for "higher education", do these students really hold any significant knowledge? Are they in any way better educated than their medieval counterparts who would have given what we now consider the "wrong" answer on exactly the same basis that modern students give the correct one—an end result received from authority? If we wish to do more than render lip service to excellence, if we are indeed serious about cultivating capacities to think and to understand, to have our students see science as a comprehensible product of imagination and intelligence rather than as an assembly of "facts" and names, it is absolutely essential that we give them a chance to follow the development or growth of several significant concepts and theories—to address themselves to the questions: "How do we know . . .?" "Why do we believe . . .?"

To paraphrase arguments Herron used in another context (*10*), the end result of such a course might be students who understand why scientists believe certain facts or models and reject others, who see science as the end product of rational thought rather than arbitrary rules to be accepted on the basis of authority, who have been exposed to the general intellectual skills often described as critical thinking, who know how to construct useful knowledge, who know the difference between "meaningful" and "rote" knowledge (*11*) and appreciate the importance of the former.

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