Teaching Chemistry to Non-Science Majors by Modeling Research Activity

Francis J. (Frank) Schmidt, Department of Biochemistry, University of Missouri-Columbia, Columbia MO 65212, U.S.A.; schmidtf@missouri.edu

John E. Adams, Department of Chemistry, University of Missouri-Columbia, Columbia MO 65211, U.S.A.; adamsje@missouri.edu

Abstract

Teaching Chemistry to non-majors remains an important challenge to the chemical educational community. We teach Chemistry as a component of an interdisciplinary two-semester course sequence. The course explicitly models the research activity of professional scientists: reading the literature, brainstorming to develop hypotheses, testing and interpreting the results. In support of this concept, we have changed the traditional prescriptive format of laboratory exercises to a format that explicitly models the scientific literature. The outcome of the courses suggests that the format supports scientific reasoning and understanding of science as a process.

The Setting and the Courses

Second-tier students (Tobias, 1990) are academically capable of studying Science, Technology, Engineering and Mathematics (STEM) but choose not to concentrate on them in college. Studies of second-tier students, and our own experience, suggest that they really are different from STEM majors: they are less mathematically inclined and more focused on everyday experience, among other characteristics. Our experience and the literature indicate that they are much more inclined than STEM majors to reason by extrapolation from the particular to the abstract, rather than by logical derivation from a known principle.

Teaching science to non-majors, however, is an essential role for sciencist/educators. Second-tier students in later life will make decisions that affect the future of science and technology. They will be elementary teachers, journalists, school board presidents and legislators after graduation. An understanding of science as it is practiced may make them more supportive of it. Personally, as consumers, they will need to make informed decisions on which medicines to take, whether to support a particular development for environmental reasons, etc.

The University of Missouri-Columbia (MU) has been called the quintessential state university. It admits about 4500 first-year students each year and has a total of enrollment of 24,000 in all divisions. Along with similar requirements in Humanities and Social Sciences, the University has a General Education requirement for all undergraduates of three courses (9 semester hours) in Science or Mathematics. These courses must include both physical and biological sciences; at least one course must have a laboratory.

We provide non-STEM students with a two-semester interdisciplinary course sequence through the MU Honors College. These students, primarily in their first year, are classic second tier. The Honors College enrolls the top 10-15% of entering students, based on High School grades and ACT scores. This percentage is typical of the number of Honors-eligible students at large state universities. Like the entire undergraduate population, our students have met the Universitys admission requirements of three units of Science and four of Mathematics during high school. While they have been academically successful at it, they have no interest in science as a career choice. About half of the students in our courses are in pre-Journalism, with the remainder in Humanities, Social Science, Education and Business concentrations.Commonly, they express their frustration at having learned (in practice, memorized) the material in their pre-college courses without mastering it.

We designed two courses whose approach is to model science as it is practiced by researchers (White and Fredriksen, 1998). The courses are entitled The Warm Little Pond and The Warm Little Planet. They may be taken independently or in sequence, and as a selling point, can be used to fill distribution requirements in either Physical or Biological Sciences. The sequence operates with a small annual budget for supplies and materials, less than or equal to the per-student budget of a traditional laboratory-based introductory course. Tenured faculty and a non-tenured coordinator teach the course as an overload and receive a small supplement that can be used for books, meetings, etc. Enrollment is limited to fifty students per semester due to two factors: first, the emphasis of the Honors College on close student-faculty interaction, and, second, the availability of the laboratory space, which is essentially donated by academic departments.

The Material

What exactly does a second-tier student need to know about Chemistry? Where might these students encounter Chemistry in their post-college life? What principles can be applied to ordinary life? How can they become intelligent consumers of scientific knowledge? It's pretty easy to think of topics from an introductory course for STEM majors that are of little interest to a nonscientist. (Some are of little interest even to the STEM majors!) The list includes many things that are important, near and dear to a chemist or biochemist: quantum theory, Lewis acids, the chemiosmotic mechanism of ATP synthesis, to name a few.

We consciously adopted a less is more strategy regarding content. Each semester consists of only six topics, taught in blocks of one and a half weeks. The blocks feature an introductory lecture, a laboratory exercise, and a second lecture. The balance of the semester is devoted to discussions of two popular science books (e.g., Rachel Carson's *Silent Spring* or Walter Alvarez' *T. Rex and the Crater of Doom*) where students are expected to find themes from the course in the books. Finally, we have the students do a capstone laboratory project. The topics covered in both courses proceed from the personally observable to the molecular scale through the semester.

The Warm Little Pond http://web.missouri.edu/~esiwww/GH161.html uses a decorative pond on the campus as a focus. The overall theme of the course relates to biological and chemical transformations and cycles. Key concepts from Chemistry, Biology and Environmental Science include trophic relationships and their foundation in Chemical Thermodynamics, biological adaptation and evolution, population dynamics, biogeochemical cycles involving oxidationreduction reactions, and acid-base chemistry. In class sessions, we make a continual effort to refer back to the material already covered. For example, we point out that the concept of biogeochemical cycles explicitly depends on the conservation of matter.

The Warm Little Pond starts with a simple exercise. We provide the student groups with graph paper, string and tape measures and tell them to measure the area of the pond. The answers are interesting: the estimates of the area vary from less than 800 to more than 2000 square feet but almost always are reported to four or more significant figures, i.e., to a claimed precision on the order of a few square inches. The set of wildly varying estimates furnishes the starting point for class discussion about random and systematic error, which leads naturally to the concept of significant figures. Given the varying estimates of the pond area, we can make sense of these estimates only by assuming that the errors are randomly distributed around the mean. Using the students experience and pre-existing knowledge (for example, that more measurements are better than fewer), we develop the equations for standard deviation and show how the mean cannot claim to be more accurate than the least accurate single measurement.

This exercise reinforces several themes of the course:
1. Science as modeling. The students drawings and measurements are smaller and simpler than the actual area of the pond, i.e., they are a model of the real phenomenon. The mean and standard deviation of their measurements model their actual data. Models, however, are always underdetermined--anything we say about a system is less complex than is the system itself.
2. Data as an inexact representation of a real situation. There is always a moment of truth when one brave student asks What is the area, really? and our answer is We don't know, but it's probably pretty close to the average measurement that the classes have gotten through the years. (This response has, one at least one occasion, elicited an audible gasp from the students.) This exchange exemplifies the fact that measurement depends implicitly on the means of measurement, as illustrated by Mandelbrots (1983) classic question How long is the coastline of Britain? and its answer The answer you get depends on the length of your ruler.

3. Mathematics from the bottom up rather than the top down. We develop the idea of standard deviation as a way to describe (model) the uncertainty in their data instead of providing a formula and asking students to compute the answer. The idea of significant figures flows naturally from the study of errors. All of our students have heard of significant figures and some can apply the rules, but none can state what the concept means or is good for. (In this respect they dont differ from first-year science majors whom we have taught in other contexts.)

4. The need for concrete experience. Data that students have argued over, identified the weaknesses in, and presented to their peers is more meaningful than any better measurement, such as a map of the pond derived from aerial photographs.

As we developed this exercise, it became apparent that this measurement mirrors the process that research scientists often use when approaching a problem: Identify an objective (hypothesis or measurement), get the data (experiment), and analyze what you get (conclusion). We have pushed this concept through the course and now explicitly model research activity as a way of teaching concepts.

The Laboratory as Model Research Experience

1. Hypothesis testing. We tell our students that we expect them to use the laboratory for hypothesis testing. We want them to carry out the same activities as do professional scientists, albeit within a defined context: brainstorming, hypothesis development, proposal submission, peer review, experiment, appropriate record-keeping (i.e., in a professional notebook format). We start by presenting laboratory exercises in the format of a mini-journal rather than as a set of steps to follow. Students are expected to carry out an experiment that builds on the paper they have read.

> For most experiments there is a lot of trial and error involved in devising the right procedure to answer the question that is being asked. Because this is usually very time-consuming, student science labs have most of the trial and error worked out of them in advance. The only real unknown is whether the students will be able to follow the directions carefully enough to get the expected results... We have put some of the trial and error back into the process.

The students aren't graded on the results they get. Instead, we grade them on their ability to evaluate the data they do obtain, identify sources of error and write up a coherent report. Often, the entire class pools data; the students write individual reports using the pooled data (thus diminishing the problem of outliers).

2. Source material All of this activity flows from the original presentation of the experiment and concept in a mini-paper format. The chief difficulty then is in finding the source material for the students to read for background in planning their experiments. One possibility would be to use the current chemical literature; however, that approach fails for several reasons. Usually the techniques are not readily adaptable to a beginning undergraduate laboratory, the questions and hypotheses build on rather than explain the introductory concepts, and the language is often opaque. Even teaching classic experiments by providing students with the original papers can lead to problems because non-STEM students seldom have the mathematical and other background knowledge to follow the logic. Additionally, the concepts that we teach often are not explicitly stated in the original source. For example, Rumford's original paper on boring cannons states that work and heat are equivalent, and that heat is a form of motion but omits that the energy change at equilibrium is zero, although it is possible for a technically trained person to make that induction.

We needed to find a rapid and accessible means of developing the mini-papers. With the large number of well-established laboratory exercises available, there was no need to re-invent specific topics; rather, we present the experiments in a format that explicitly models the scientific literature: Title, Abstract, Introduction, Experimental Procedures, Results, Discussion and References. The example "An Estimate of the Molar Heat of Reaction for the Decomposition of Hydrogen Peroxide" is simply a measurement of the heat released by the $Fe(NO_3)_3$-catalyzed decomposition of hydrogen peroxide to water and molecular oxygen. The material is written up in the mini-paper format, and, in contrast to the professional literature, we present the students with a leading question for their experiments.

3. Final Laboratory Project. The students also carry out a longer-term project. In the Warm Little Pond, for example, they set up a Winogradsky plate (http://www.microscopy-uk.org.uk/mag/indexmag.html?http://www.microscopy-uk.org.uk/mag/artaug02/gchabitat.html). Winogradsky plates are an adaptation of the Winogradsky column, an aquatic microbial ecosystem which segregates into layers with photosynthetic organisms on top, oxygen-using metabolizers below and finally organisms on the bottom that metabolize sulfate to sulfur to support a chemosynthetic lifestyle(Charlton et al., 1997). Students write and present a research proposal based on a plausible (i.e, mechanism-based) hypothesis that predicts the distribution of the organisms (kind and number) depending on the chemical composition of the water in which they grow. They review, revise and carry out the experiments over a period of about six weeks. They then write a final paper and present their results in a poster session. This sequence follows that carried out by professional scientists and, we believe, increases students' understanding of science as ***process***.

Evaluation - lessons learned

As the course has developed, we have obviously learned a few things about our audience and how to reach them. At this stage we can draw a few conclusions:

1. Less is more. We try to let the students see how concepts from various branches of science carry through to other areas. This means that we have to prune the coverage of many subjects. For example, we only treat acids as proton donors, omitting the Lewis concept of acids and bases. Doing this, however, allows us to treat the concept of acid rain more fully, emphasizing that it follows from oxidation reactions during metabolism or burning.

2. Group is good. All of the laboratory work and the final paper are group projects. We find that our students, many of whom perceive themselves as not good in Chemistry, are much more comfortable in group settings. A good group experience (measured by scores on peer evaluations) was also correlated with higher class scores ($r = 0.435$, $p = 0.003$), though it is impossible to tell whether good group dynamics led to better grades or better grades left students more satisfied with their group experience.

3. Math from the bottom up. Mathematics is essential in science, yet second-tier students are often intimidated by it. We try to overcome this difficulty by starting with results and data, usually from experiments that the students carry out. We try to get them to identify the problem e.g., these points do not fall on a straight line; how do we find the best line for the points we found? The students brainstorm various possibilities for solving the problem. For example, they might decide to minimize the sum of the differences between the line and the experimental points; however, this leads to a possibly false result because the differences cancel each other out. They them might try to take the absolute values of the differences, and, finally, for computational simplicity, the squares of the distances of the experimental points and the constructed line. Then they can apply the least squares formula on their calculators or spreadsheets. This contrasts with the more common approach of starting with a formula and applying it to the data. Such an approach often causes non-STEM students to tune out completely, since they are not supposed to be good at Math.

3. KISS (Keep it simple, Sherlock). We intentionally go low-tech wherever possible: thermometers rather than probes, measuring ammonia, nitric oxide and nitrous oxide with the test strips used for aquariums, etc. We found that when we used more sophisticated apparatus, e.g., temperature probes and PC's, the students spent much more time trying to understand the apparatus than they did doing the experiments. We try to use the most direct apparatus wherever possible.

4. Lab and Lecture are connected. There are six conceptual units, and each has a lab with it that depends on an understanding of the key concept of the unit. Initially we thought simply associating the unit and the lab in time would be enough for students to see the connections. However, we have gradually had to increase the amount of lecture time used to explain the lab and how it fits into the overall picture. This tradeoff is necessary because we are introducing more uncertainty into the lab experience and seeking a fairly high level of conceptual understanding.

5. This works. We tested the student for their ability to reason scientifically using a content-neutral test of scientific reasoning ( ). Students achieved a statistically significant increase in their reasoning ability over the semester. We are currently doing comparative studies with a similar population of students in a conventional course.

6. This is NOT for everyone. Non-STEM students really are different from science majors. When STEM majors take the course, they commonly are frustrated with the slow pace and emphasis on the underlying bases for current knowledge.

Where we are and where we're going

So far, the curriculum appears to be working according to plan: the students are active participants in the course, they seem to be learning something, and we have had a few students take more science even when doing so was not required (one journalism major even did an independent research course in one of our laboratories). In the future we want to:

1. Expand the course approach to new audiences. Perhaps the most important scientific educators are also those who are the most neglected: elementary school teachers. Most of what children learn about inquiry is introduced in the primary grades. Typically, though, Education majors take very few science courses, and they often express negative attitudes about the ones they do take. We hypothesize that an inquiry-driven course would help overcome these perceptions, which can often be communicated to students in subtle but unfortunately effective ways.

2. Make it instructor-friendly. Trial and error is the lot of a scientist. Even so, we cannot ignore the fact that an instructor in a large class often has neither the time nor the resources to convert existing materials from the standard protocols to a mini-paper. We are currently identifying the roadblocks to converting these cookbook labs into the inquiry format.

3. Semester lab projects. Is the final project cost-effective? Does it lead to new knowledge on the part of the students? Given the time and effort involved, one would hope so, but that assumption has not been validated.

4. Find out if the course makes a difference long-term. Are students who take this course different from their peers? Do they eventually have different attitudes toward science and Chemistry than do their peers who take conventional courses? Follow-up studies are notoriously difficult with a mobile population; however, this kind of evaluation seems to be a national need given the emphasis over the last ten years on inquiry-based learning.

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