Virtual Laboratories and Scenes to Support Chemistry Instruction: Lessons Learned

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This chapter discusses our efforts to develop virtual laboratories and scenario-based learning activities for introductory chemistry courses. We begin with a brief discussion of the materials themselves. We then reflect on the decisions we've made in conceiving and developing these materials and how our experiences have altered both our goals and the implementations.

Goals and Education Materials

The project began by considering ways in which technology could improve learning in introductory chemistry courses. Chemistry concepts are abstract and initially are difficult to attach to real-world experience. For this reason, high school and college chemistry courses have evolved a standard set of paper-and-pencil manipulations (dimensional analysis, balancing equations, stoichiometry, Lewis dot structure, etc.) that are canonized in textbooks and standard exams. Traditional chemistry courses emphasize development of these notational tools as a basis from which the "real stuff" can be approached. However, these tools are taught in the absence of activities that show their underlying utility. While these tools might be considered the underlying procedural knowledge base, they become inert bits of knowledge that are difficult for students to access. The difficulty in applying these procedures occurs at two levels. One is within the formal chemical domain, where it is often difficult to connect a paper-and-pencil procedure to an actual chemical process (use in chemistry). The other level is the application of a procedure to complex real settings (transfer to the real world). More fundamentally, the traditional educational approach strips out the very essence of science and leaves behind a confusing bag of tricks.

Our goal is to use technology to complement traditional instruction with manipulatives that allow student problem-solving to be more authentic, i.e., more similar to that engaged in by practicing chemists (Bodner and Heron, 2002). The following two sections discuss the interventions we are developing.

Use in chemistry: the virtual laboratory

Our virtual laboratory (http://ir.chem.cmu.edu) addresses the first of the two learning challenges identified above: that of connecting procedural knowledge in the form of mathematical formalisms to authentic chemistry (Yaron et al., 2001). It is aimed at supporting ways in which students can see "use in chemistry." This learning challenge is similar to that observed in physics education, where the mathematical problem-solving emphasized in traditional courses has been shown to convey little conceptual understanding (Hestenes, 1992; Pushkin, 1998). Most traditional chemistry courses continue to focus on mathematical problem-solving and could likely benefit from a shift to conceptual teaching (Nakhleh and Mitchell, 1993). However, construction of conceptual problem-solving activities for chemistry is as challenging as it is for physicists because of the abstract nature of chemistry and its occurrence at multiple time and length scales.

Our virtual laboratory supports conceptual instruction by providing a set of manipulatives that enable a new type of interaction with chemical phenomena (Yaron et al., 2000). Students can design and quickly carry out their own experiments and see representations of the chemistry that go well beyond those possible in a physical lab. When instructors replace some of the existing end-of-chapter exercises with virtual lab experiences, the virtual lab provides additional representations to serve as a bridge between the traditional paper-and-pencil activities from the textbook and actual chemical phenomena. Note that the goal of the virtual lab is not to replace the physical laboratory. Rather, it is to help students connect their paper-and-pencil work to actual chemical phenomena by enabling varied practice.

Figure 1 shows the virtual laboratory. The panel on the left is a customizable stockroom of chemical reagents, which may include either common reagents and/or fictional materials for which parameters are specified by the instructor. The middle workspace provides an area for performing experiments. The panel on the right provides multiple representations of the contents of the selected solution, including the temperature, pH, and a list of chemical species with amounts shown as moles, grams, or molarity. These quantities are the players in the computational procedures of the course, and so this panel provides an explicit bridge between the paper-and-pencil calculations of the traditional course and the chemical experiments the student performs on the workbench.

Transfer to the real world: scenario-based activities

The second learning challenge mentioned above is helping students understand the applicability of their knowledge to a real-world setting. Our instructional approach here is to embed the procedural knowledge in a scenario that highlights its utility.

Chemistry is a central science. It plays a crucial role in most aspects of modern science and technology, from biotechnology to the creation of new materials and medicines. Because much of the excitement of modern chemistry is how it brings deeper insight and power to bear on issues in the environment, medicine, forensics, and space sciences, it is reasonable to expect additional motivational benefits from scenarios that highlight this broad applicability. These activities also allow students to learn and practice concepts in appropriate contexts and establish more coherent relationships during the course. Some representative scenarios follow:

Figure 1. The virtual lab provides a flexible learning environment in which students can design and perform their own experiments. The panel on the right shows multiple representations of the contents of a solution, which would not be possible in a physical lab.

- **Mixed reception.** In this multimedia murder mystery, students use early course concepts such as molecular weight and chemical structure to analyze forensic samples and interpret evidence.
- **Mission critical chemistry.** Students apply thermochemistry concepts to develop a new fuel for a mission to Mars.
- **Acid mine drainage.** Students apply acid-base and precipitation concepts to complex phenomena. Students use various models of river water and examine how the predictions vary with the level of sophistication of the model.

Lessons Learned

Using evidence to decide what to teach

Introductory chemistry is a course with a long history. A list of chemistry topics has evolved that is fairly uniform across courses and is reflected in most textbooks and standard exams. Our concern with traditional instruction is that it promotes learning of these topics in a disconnected manner that does not lead to a coherent set of knowledge. Our goal is to embed the standard course topics in activities that convey the overall structure of chemistry as a domain. We began by simply creating activities that we thought were interesting and appropriate. However, it soon became apparent that a more systematic approach was necessary to ensure that our activities actually were authentic, in the sense of capturing what chemists actually do. For this, we developed the following approach.

We (Evans et al., submitted) took as evidence for the "domain of chemistry" articles from the scientific press for the year 2002 and Nobel Laureates' prize work in chemistry for the past 50 years. This led to the development of a concept map, the top of which presents the three subdomains that comprise modern chemistry: *explaining* phenomena, *analyzing* substances to determine their chemical makeup, and *synthesizing* new types of chemical substances. Underlying these three subdomains is the *toolbox*, a collection of procedures and models that are applied selectively as needed to develop *explanations,* conduct *analyses*, or direct *syntheses.*

The results of this effort may have uses beyond our initial goal of guiding scenario development. Although articles from the scientific press and Nobel Laureates' prize work were nearly equally distributed among the three subdomains, the content standards and textbooks focused almost exclusively on the *toolbox* and the *explain* subdomain. This reveals a substantial disconnect between what is taught and what the field actually encompasses. This disconnect supports our concern that, in traditional instruction, the learning remains disconnected from intellectual and practical use. The disconnect is also troubling if one takes basic scientific literacy as a goal of an introductory course, since it indicates that current instruction ignores two-thirds of the domain of chemistry.

The outcome of this domain analysis would likely have been quite different if, instead of using scientific documents as an evidence base, we had used faculty opinions on what should be taught. For instance, our own thinking had been largely biased by the current curriculum such that the evidence led to a quite different map than we would have initially constructed. Perhaps, this approach to using evidence to determine what to teach would be a useful addition to efforts aimed at standardizing instruction.

Observing student problem-solving

Classroom observations, involving 30–35 students working alone or as pairs, have been used to gain insight into student interactions with various types of activities. These observations have informed the design of our activities and have allowed us to formulate targets to be addressed by more controlled experiments. Our activities fall into three general categories:

1. **Calculate and check.** After a traditional paper-and-pencil problem-solving activity, students perform an experiment to verify their results. The educational goal is to have the students reflect on a calculation after it is complete. Using the virtual laboratory to check the correctness of answers instead of looking them up in the back of a textbook requires a thoughtful assessment of the relation between the computation and an authentic chemistry experiment. Our observations suggest that this shift from mathematical problem-solving to performing an experiment is a nontrivial step requiring reflection on the meaning of the computations.
2. **Online experiments.** Students are given a goal and the lab is configured with various chemical solutions, equipment, and solution viewers. This is similar to setting up a physical lab and many of our activities are indeed parallel to what would be done in a physical lab. However, because experiments can be done quickly and safely, students can be given greater flexibility in the design of the experiment. This, combined with the ability to look directly inside a solution to see the types of species and their concentrations, leads to entirely new types of activities that would not be feasible in a physical laboratory.
3. **Layered activities.** Here, students perform a set of activities involving the same chemical system, but modeling the system with varying levels of complexity and approximation. The approximations can either be removed or invoked as one moves through a series of problems. These interconnected layers, particularly with the addition of structured debriefing, invite students to reflect on how the removal or addition of an assumption changes both their problem-solving approach and the predicted results.

Observing students in a flexible learning environment such as the virtual laboratory can often reveal aspects of their thinking that would be difficult to glimpse in paper-and-pencil activities. For instance, students were given four chemicals (A, B, C, and D) and asked to design and perform experiments to determine the reaction between them (i.e., $A + 2B \rightarrow 3C + D$). The intent was to give practice in determining the stoichiometric coefficients. However, almost all students misinterpreted the results of their experiments in a way that revealed a fundamental misunderstanding of the limiting reagent concept. (When they mixed A with B, they found that A remained in the solution. From this, they concluded that A must be a product and wrote the reaction as A + B $\rightarrow$ C + D + A.) This misunderstanding existed even in students who could easily perform the paper-and-pencil activities that are typically used to teach this concept. Such errors provide a basis for an elicit-confront-resolve educational strategy (McDermott et al., 2000).

Student observations also shifted our view of the potential benefits of problem-solving in the virtual lab. Initially, the goal of these online experiments was to embed the procedural knowledge of the course in a context that highlights its utility, such that students learn not only how to do a procedure, but also when to do it. This approach is supported by both Anderson's "Adaptive Control of Thought–Rational" (ACT-R) theory (Anderson and Lebiere, 1998), which models learning as a series of production rules (e.g., if X, then do Y), with the X or condition component being just as important as the Y, and the work of Lehrer and Schauble (2000), which emphasizes the deep connections between developed procedures and core authentic questions within a domain. Observations showed another benefit of these problem types: that of helping students move beyond shallow problem-solving strategies. In particular, a useful but potentially superficial strategy for word problems is to categorize the given and requested information and then find equations that relate the information. For instance, a calorimetry text problem may give a measured change in temperature (ΔT given) and ask for a heat (q requested), for which a student may identify $q = m\ Cp\ \Delta T$ as an appropriate equation. This strategy will not work on an activity that requires design of an experiment to measure the heat of a process. Experimental design requires deeper reflection, since the student must realize that this equation represents an experiment in which a temperature change is used to measure heat. Our observations show that students find the experimental design problem considerably more difficult than the text problem, suggesting that this connection between equation and physical process does involve additional learning.

Observations of, and artifacts from, student problem-solving have also revealed that many students are able to develop sophisticated problem-solving strategies, beyond the level the instructors anticipated based on these students' algebraic problem-solving skills. For instance, when presented with a complex problem involving multiple interacting chemical equilibriums (a weak acid dye binding to DNA), half of the students discovered that the phenomena was pH dependent, realized it could be controlled by a buffer, and then designed an acid-base titration that would allow them to determine the appropriate buffer without doing explicit calculations. This approach clearly demonstrates a deep conceptual understanding of acid-base chemistry and highlights the potential of the new manipulatives present in the virtual lab to support and assess conceptual learning.

Although our assessment efforts suggest a number of benefits from solving authentic chemistry problems, they also highlight the need for supporting student's problem-solving efforts. Student self-reports often mention spending considerable time "with no idea of what to do" and needing help from teaching assistants or other human tutors. Faculty users report that assigning the more challenging problems puts an extra burden of support on the teaching staff, but that they believe it is worth the investment. Our observations indicate that students working on challenging authentic problems can get stuck and struggle in ways that do not appear to promote efficient learning. Based on this information, we have begun work in developing support structures that help students get the most of their problem-solving efforts by providing hint structures that fade appropriately, keeping students challenged but not floundering, i.e., inside Vygotsky's zone of proximal development.

Community building

Although curriculum development has some overlap with one's individual teaching, the creation of materials for a broad audience requires paying considerable attention to the community of potential users for these materials. A particularly important design decision relates to the envisioned pathway for adoption of the materials. At one extreme lie fairly substantial transformations of the course structure. For instance, Process-Oriented Guided-Inquiry Learning (Spencer, 1999) transforms the traditional lecture to a team-based approach to learning in which the instructor acts as a guide or mentor. Efforts to gradually improve the lecture course include the use of concept tests and just-in-time teaching (Novak et al., 1999). JiTT uses quizzes to familiarize students with the material before the lecture and to provide instructors with feedback they can use to adapt their classroom activities to the students' knowledge. Our focus has been on the creation of materials that can be used in a large variety of course structures and instructional approaches. To support use in diverse settings, we have put considerable effort into supporting community authorship, such that we not only create activities but create tools that enable the community to modify or create their own activities (Yaron et al., 2002). This led to our recent launch of the ChemCollective, a digital library of homework activities that will allow chemistry educators to use or adapt our previously developed activities, contribute their classroom experiences, discuss issues in teaching, and author and disseminate homework activities (http://www.chemcollective.com).

The ability to modify or create materials may initially seem to be an add-on feature that can be left to later stages of a curriculum development project. However, our initial use of a model in which the community contributes as well as uses educational materials has had a number of advantages. First, authoring abilities help attract talented early-adopters who are knowledgeable about curriculum development and various approaches to teaching and make the tools part of their own development efforts. The development of the materials and a community of practice around these materials thereby occur nearly simultaneously. This can shorten the timescale usually associated with the develop-assess-disseminate-modify cycle of curriculum development by engaging the community in the development process itself. Indeed, of our 60 current virtual lab activities, 20 have been suggested by or contributed by the community. Many of these contributed materials reflect uses of the virtual lab and other tools that we, the tool developers, had not anticipated. For instance, contributed materials use the virtual lab to teach the relation between experimental technique and accuracy and to create homework activities that follow up on a demonstration performed earlier in lecture.

Closing Comments

This chapter reflects on our experiences in developing materials for introductory chemistry. The lessons we've learned come from a variety of sources. The design process itself prompted us to reflect on the structure of the chemistry domain. The resulting evidence-based domain analysis has altered our view of the misalignment between current instruction and the domain and serves to guide our current development efforts. Observations of student problem-solving also strongly influenced our development efforts. The virtual lab allows students to engage in the course concepts in a new manner, such that observations give new insight into gaps in students' conceptual understanding. Student observations also modified our view of the benefits of engaging students in experimental design. Finally, working closely with the user community, by providing tools that allow instructors to author or modify activities, has helped us better understand how to design materials that can be used in diverse settings.

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