Scenes and Labs Supporting Online Chemistry

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Nature of introductory chemistry

This project is creating and disseminating online activities for introductory level chemistry that are designed to support and integrate into traditional college chemistry courses. Such courses typically consist of a large lecture, regular homework (graded or ungraded), and weekly or biweekly hands-on laboratories. Our activities complement the current paper-and-pencil homework by allowing students to engage in authentic [Chinn & Malhotra. 2002] chemistry activities, with the educational goals of increasing the cognitive flexibility with which new information is held, and supporting transfer of new information into a variety of distinct situations. These goals are met through simulations such as our virtual laboratory (http://ir.chem.cmu.edu/) that allow for varied practice to increase *flexibility*, and through scenario-based activities that make the *applicability* of the knowledge explicit and provide in-context learning [Yaron et al, 2001a].

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.

Learning challenges and interventions

Learning challenges

Given that chemistry concepts are abstract and initially are difficult to attach to real world experience, high school and college chemistry courses have evolved a standard set of paper-and-pencil manipulations (dimensional analysis, balancing equations, stoichiometry, and Lewis dot structures) canonized in the exercises of textbooks. Traditional high school 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 extremely 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–that of inquiry–and leaves behind a confusing bag of tricks. The following two sections discuss the interventions we are developing to address these challenges.

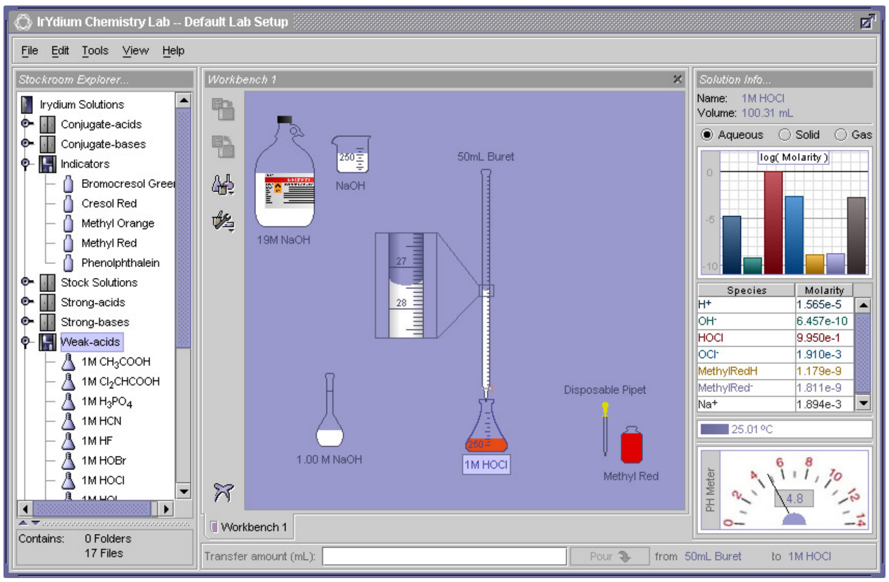


Figure 1: The virtual lab (http://ir.chem.cmu.edu/) provides a flexible learning enviromment in which students can design and perform their own experiments. The panel on the right shows multiple representations of the contents of a solution, which would not be possible in a physical lab.

Use in chemistry: The Virtual Lab

Our virtual lab 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]. The conceptual physics movement has achieved significant improvements in students' conceptual understanding by complementing traditional mathematical problem solving, such as using Kirchoff's laws to calculate properties of electronic circuits, with activities that emphasize conceptual problem solving, such as predicting the relative brightness of light bulbs arranged in various configurations [McDermott et al, 2000]. Most traditional chemistry courses continue to focus on mathematical problem solving and could likely benefit from a shift to conceptual teaching. However, construction of conceptual problem solving activities for chemistry is as challenging as that faced by physicists due to the abstract nature of chemistry and its occurrence at multiple time and length scales.

Our virtual lab 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 that 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 that promotes *flexibility* and making such connections more explicit and increasing *applicability*.

Classroom observations, involving 30-35 students working alone or as pairs solving virtual lab problems, have been used to gain insight into student interactions with various types of activities in the virtual lab. These observations have informed the design of our activities and allowed us to formulate targets to be addressed by more controlled experiments. Students at both the high school and college level take about 5 minutes to become sufficiently familiar with the user interface that their focus shifts to acheiving the chemistry goals set forth by the assignment.

Converting a traditional problem solving activity to a virtual lab activity on the same concept often reveals something interesting about student difficulties. Consider, for instance, the traditional problem, “When 10ml of 1M A was mixed with 10ml of 1M B, the temperature went up by 10 degrees. What is the heat of the reaction between A and B?” Many students who are proficient in such calculations are still unable to design a virtual lab experiment in response to the prompt “Construct an experiment to measure the heat of reaction between A and B?”. This student difficulty reveals that the traditional problem fails to place this procedure in a context that conveys its utility. So although students can perform the procedure, this procedure is not activated in response to appropriate prompts. Since the virtual lab supports experimental design activities, it enables a type of practice that may reinforce activation of such procedural knowledge.

Observation of students interacting with challenge problems has also revealed unanticipated errors, and these errors may form the basis for instructional design. For instance, students were given solutions of four chemicals (A, B, C, and D) and asked to design and perform experiments to determine the reaction between them (i.e. A + 2B --> 3C + D). The intent was to give practice in determining the stoichiometric coefficients (1, 2, 3, and 1 for the example reaction). However, almost all students mis-interpreted 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 --> C + D + A. In actuality, A remains in solution not because it is a product, but because it is an excess reagent.) Such errors provide a basis for an elicit-confront-resolve educational strategy [McDermott, 2000], in which an incorrect prediction is elicited from the student, confronted by pointing out its logical inconsistency and then resolved with the goal of giving the student a deeper conceptual understanding.

Observations of, and artifacts from, students performing challenge problems 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 posed with a complex problem involving multiple interacting chemical equilibria (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 virtual lab to support and assess conceptual learning.

The University of British Columbia has compared our virtual lab, which provides a flexible and open-ended learning environment, to a more constrained virtual lab [Jones and Tasker, 2001], in which students are offered more limited choices. Both were used as pre-lab exercises to prepare students for a physical laboratory experiment. Their informal observations suggested that students who use our more flexible virtual lab were better prepared for the physical laboratory [Nussbaum 2002].

Transfer to the real world: Scenario based activities

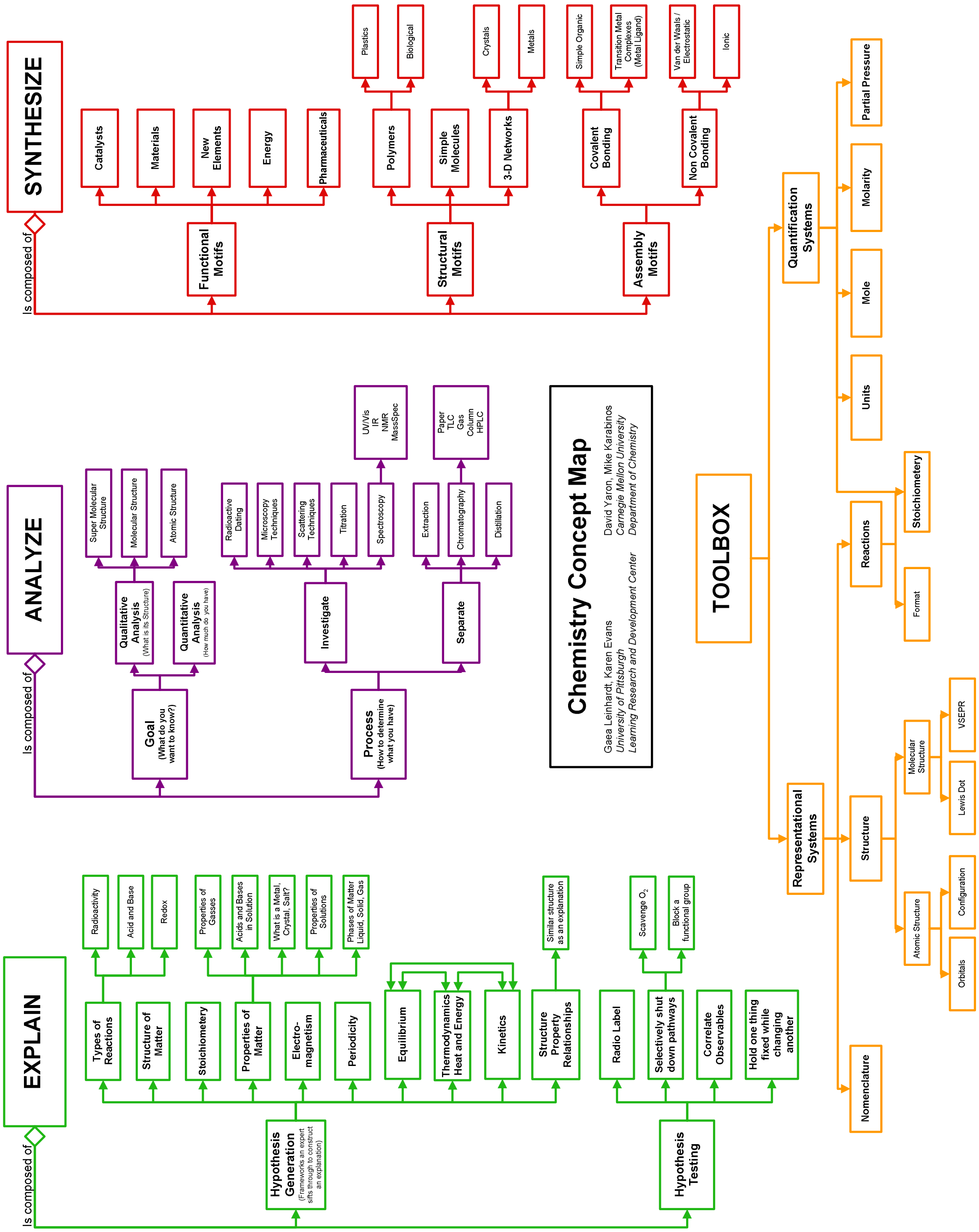
The second learning challenge mentioned above is helping students understand the applicability of their knowledge to a real world setting. Our instructional approach here is to embed the procedural knowledge in a scenario that highlights its utility.

Our design of scenarios was and will be guided by the concept map of Figure 2. This map was developed jointly by research professors in chemistry (first author) and in education, an instructional designer (third author), and a high school chemistry teacher (second author). The design of such a map was motivated by the sense that part of the difficulty in learning chemistry stems from the bottom up organization of chemistry content that has become reified in the curricular cannon. The design process was based on review of recent chemical research, chemistry articles from the *New York Times* and *Scientific American* News Scan columns, National Science Education Standards for Chemistry, and various chemistry textbooks. The design process was recursive and the product is dynamic since it can be revised in response to future changes in the domain. A more detailed account is presented at this conference by the second author (session 31.032, Science Learning and Instruction New Member Poster Session Hyatt Exhibityion Hall)

The top of the concept map 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***.

While articles from the scientific press and Nobel Laureates' prize work in chemistry for the past 50 years 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. Because the ***Toolbox*** underlies the subdomains of chemistry, educators have tried to build a solid base; but chemists work through a particular subdomain by linking the demands of the problem at hand to the appropriate tools needed for execution of a solution. Use of a particular tool is embedded within the context of the problem itself. When instruction focuses exclusively on the ***Toolbox***, learning will be disconnected from

Figure 2 Chemistry Concept Map



intellectual and practical use. We know that such inert knowledge will rarely be available or usable, let alone memorable. The goal of our scenarios is to move toward authentic chemistry activities that mirror the work of those in the discipline. Scenarios allow us to place the skills of the traditional course in appropriate contexts. Gradual incorporation of such materials in a course creates a smooth pathway to educational reform.

Figure 3: Mixed Reception activity, illustrating CreateStudio's ability to construct activities in which students explore a virtual world to collect samples for analysis in the virtual lab. This activity combines 40 minutes of video (initial murder, suspect interviews, etc.) with 4 locations (crime scene, victims apartment, etc.)

Our CreateStudio tools enable instructors to modify and create scenario-based learning activities by combining the virtual laboratory and other simulation and visualization tools with multimedia [Yaron et al., 2001b, Yaron et al 2002]. A powerful approach is to use CreateStudio's multimedia components to create virtual worlds that students explore to collect samples for analysis in the virtual lab. For instance, a hot spot can be placed on an image that, when clicked, causes a solution to appear in the virtual lab.

Although the structure of many courses assumes otherwise, we believe that students can reap the benefits of working on real-world, contextualized applications before they master most of the basic notational procedures, in part through the use of simulations. In the absence of technology, paper-and-pencil problems involving real-world phenomena – not just cover stories – can lead to assignments that are interesting, but overly complex or too demanding on working memory for students [Sweller, 1988; Kotovsky, Hayes and Simon, 1985]. By offloading some tasks to the computer, we enable students to focus on the issue of current pedagogical interest. This approach is used in our *Mixed Reception* activity, to allow students to use concepts covered in the first few weeks of a high school course to solve a murder mystery. In our *Mission Critical Chemistry* activity, students use simulations to calculate rocket trajectories, such that they can focus on development of new fuels for a mission to Mars.

By using common scenarios across the various course topics, we can promote coherence between these topics. For instance, we are currently developing a scenario around the arsenic contamination of the Bangladeshi water supply, that touches down at three points in the course (stoichiometry, atomic and molecular structure, and chemical titration).

Dissemination challenges and community building

Target audiences

College chemistry courses are surprisingly uniform, as reflected in the overlap of topics and exercises contained in the best selling textbooks. Although this leads to a single target with regards to content, the varying levels of student preparedness at our current sites requires construction of materials that span a range of challenge levels. For college chemistry, we focus on online homework since this modalities is most likely to be adopted by a large audience of instructors. Most instructors feel personal ownership of their lectures, and the physical labs are difficult to modify due to practical and economic constraints. However, most instructors assign textbook problems as homework, and our online homework is designed to substitute for part of these assignments. The activities are therefore tagged both against the content areas of the traditional course, and the higher level organizational structure of our concept map. In addition, our user community has developed pre/post lab activities that are designed to improving learning and efficiency in their physical lab programs, especially at sites where economic constraints are forcing a scale back in lab time.

We have a growing user base in high school and AP chemistry, and are working to better understand the needs of this community. Although there is substantial overlap between the content of high school and college chemistry, differences in treatment of this content are spurning changes in the representations provided by the virtual lab. Since solution chemistry appears fairly late in the high school curriculum, we are extending the virtual lab to display the contents of solutions as total grams or moles, as opposed to moles/liter. Fewer differences are anticipated for AP chemistry since it is, by design, similar to college chemistry. However, differences in classroom practices between college and high school classrooms may be reflected in both high school and AP chemistry. In response to early classroom trials of our *Mixed Reception* murder mystery, we designed this scenario to function as a capstone activity that could be used in a computer room, with students working in small groups, or in a classroom with a single computer projector, with students working together via classroom discussion.

Community building

Our primary means of attracting new community members is via our website (http://ir.chem.cmu.edu/) and education conferences. Our project web site receives about 1000 page requests per day and 80 instructors have joined our mailing list for information and support of the virtual lab. Over the past year, we have received 36 emails asking to become test sites for our materials and at least 7000 students have done one or more activity with our virtual lab.

By renting booths in the exhibition hall at chemical education conferences, we give individualized demonstrations of our materials to at least 75 instrutors a day. In addition to recruiting new users, these experiences are a rich source of feedback on instructors' perceptions of the utility of the materials and barriers to adoption. Many instructors see the virtual lab as lab replacement, and have a strong negative reaction to the perceived displacement of the physical lab. Confronting this negative reaction by explaining our intended use has led to some of our stronger advocates. We also have a significant number of instructors who see the virtual lab as a tool only for their lab program, as opposed to the course as a whole. This may indicate a disconnect between the lab and lecture portion of the traditional course. Our work with the concept map of the field of chemistry and our use of scenarios may help eleviate this difficulty.

Our first external users were at University of British Columbia (4200 students over 3 semesters), Florida Atlantic University (1500 students over 2 semesters), and University of West Virginia (150 students over 3 semesters). (The UWV instructor recently moved to University of Arkansas at Little Rock). All three sites were recruited at conferences, and were unknown to the developers between these conferences. The ability to customize the software to their needs was important for all three sites. For one site, customization was desirable because the instructor was interested in curriculum development and viewed our technology as an enabler. The other two sites wanted to create pre-lab and post-lab activities and customization allowed the software to be adopted to the existing laboratory experiments.

Our experience with external users convinced us that the ability to author or modify student activities was important to early adopters and prompted us to develop tools to make customization as easy as possible. We are currently beta testing a graphical authoring tool that makes it easier for instructors to construct activities in our virtual lab. In addition, our

CreateStudio authoring tool is designed to allow instructors to embed virtual lab activities in scenarios. Of the 35 student activities built around our virtual lab, 15 were designed by external users.

Summary

The online activities discussed here are designed to integrate into existing introductory chemistry courses and address two fundamental learning challenges. The first challenge is connecting the procedural knowledge of the traditional course to actual chemical phenomena. This challenge is addressed by our virtual lab, which allows students to engage the subject matter in a way that more closely resembles that of practicing chemists. The second challenge is showing the applicability of chemical knowledge to the real world, which we address by embedding the topics of the traditional course in scenarios that highlight their utility. Scenarios that touch down at various points in the course are meant to illustrate the connections between the various topics covered in the course and thereby increase coherence.

The early stages of this work focussed on a few topics (acid-base chemistry, thermochemistry) that are regarded as difficult by instructors. Expansion to the remainder of the course prompted us to develop the concept map of Figure 2, which can serve to organize the existing activities and guide future development. The concept map will also be used to guide learning studies, as we expect the three subdomains (explain, analyze, and synthesize) to have different properties with regards to the frequency and location of common misconceptions. The concept map can also serve to build a conversation between the current course, which resides almost exclusively in the toolbox and lower levels of the map, and the target future course, organized around the three high level subdomains. Although our initial strategy is to develop materials that integrate smootly into existing courses, reform movements in other domains have shown the tendency for small changes to reveal deeper flaws in the existing structure and so to grow to bigger changes [ref]. The concept map provides a structure to analyze and guide this process.

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