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# The ChemCollective—Virtual Labs for Introductory Chemistry Courses

A collection of online activities emphasizes the design and interpretation of experiments.

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Chemistry concepts are abstract and can be difficult to attach to real-world experiences. For this reason, high-school and college chemistry courses focus on a concrete set of problem types that have become canonized in textbooks and standard exams. These problem types emphasize development of the core notational and computational tools of chemistry. Even though these tools may form the underlying procedural knowledge base from which the "real stuff" can be approached, when taught out of contexts that show their utility or that draw connections to core ideas of science, they can appear as a disconnected bag of tricks (*1*).

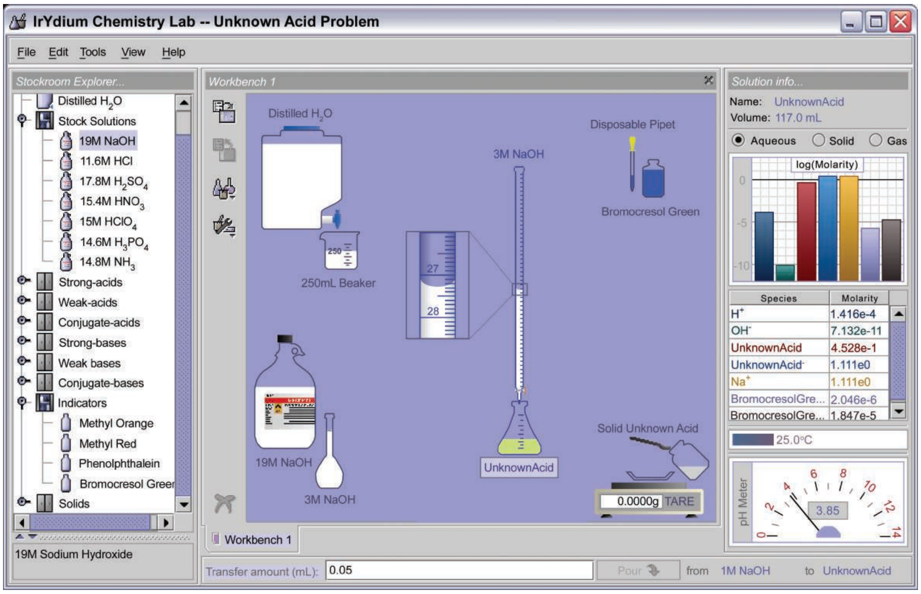
The ChemCollective (www.chemcollective.org) is a digital library of online activities for general chemistry instruction that engages students in more authentic problem-solving activities than those found in most textbooks. Our goal is to create activities that allow students to use their chemistry knowledge in ways that resemble the activities of practicing chemists. Our guiding hypothesis is that better conceptual understanding is obtained if algebraic computations are complemented with design and interpretation of experiments. This is achieved through the ChemCollective "Virtual Lab," which allows students to design and carry out their own experiments while experiencing representations of chemistry that go beyond what is possible in a physical laboratory. The goal is not to replace, or even to emulate, the physical laboratory, but to supplement textbook problem-solving by connecting abstract concepts to experiments and real-world applications. We believe that such authentic activities may improve learning and may better help to bring the essence of science into the introductory chemistry classroom.

In the virtual lab (see the figure, right), the panel on the left is a customizable stockroom of chemical reagents, which may include common reagents or fictional materials that have properties specified by the instructor. The middle work space provides an area for performing experiments. The right panel provides multiple representations of the contents of the selected solution, including the temperature and pH, and a list of chemical species with amounts shown as moles, grams, or molar concentrations. These quantities are the players in the computational procedures of the course, and so this panel provides an explicit link between the paper-and-pencil calculations of the traditional course and the chemical experiments the student performs on the workbench.

The virtual lab supports new forms of problem-solving. Consider how the concept of limiting reagents in a reaction is usually taught. A student's practice with this concept typically centers around learning a standard computational procedure for predicting the final amount of chemical reagents, given the initial amounts. Our "unknown reaction" virtual lab activity provides a different mode of practice. Students are given four unknown chemicals (A, B, C, and D) and asked to design and perform experiments to determine the reactions between them (i.e., $A + 2C \rightarrow 3B + D$). We found that roughly 50% of students in our course (363 of 647 students over a 4-year period) misinterpreted the results of their experiments in a way that revealed fundamental conceptual misunderstandings. When these students mixed A with C and found that A remained in the solution, they concluded that A is a product of the reaction, as opposed to leftover reactant, and wrote an equation such as $A + C \rightarrow B + D + A$, in which A is both a reactant and product.

This group of students has high proficiency in limiting-reagent calculations, as each was required to achieve a score greater than 85% on a mastery exam of stoichiometry before enrolling in the class. Therefore, this result indicates that it is possible to be proficient in the algebraic procedure while still missing core aspects of the underlying concept. The virtual lab provided immediate feedback that explained the conceptual aspects of this error and allowed the student to answer the question again.

Virtual lab activities also challenge students to move beyond problem-solving strategies that are effective for completing homework but may not support deeper conceptual learning. For instance, we gave students stock solutions of two reactants and asked them to design and carry out an experiment to measure the enthalpy of their reaction. In this case, the experimental design is fairly simple: Mix known amounts of stock solutions




**The ChemCollective virtual lab.** A java applet that allows students to design and carry out their own experiments (www.chemcollective.org).

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together and measure the temperature change of the resulting mixture. We were surprised to find that students struggled much more with the virtual lab problem than the textbook problems. Our student observations suggest that, as in physics, students solve the textbook problems through a means-ends analysis that provides a powerful, but potentially superficial, approach to such word problems (*2*). In means-ends analysis, the problem statement is first analyzed for given and unknown quantities, and algebraic relations are then sought that can link the givens to the unknowns. In contrast, a problem posed in the virtual lab cannot be approached by this strategy, because the student must decide what information to generate to achieve the desired goal.

Analysis of a full-semester lecture course (177 students) showed that homework using the virtual lab with real-world scenarios contributes significantly to learning (*3*). A structural equation model that predicts 48% of the total variance in students' overall course achievement showed that the virtual lab homework accounts for 24% of the total variance in course achievement. Virtual lab homework scores were not predicted by what the students knew before the course began (pretest scores), which suggests that even students with weaker backgrounds found opportunities to learn.

In an online course that we developed on stoichiometry, engagement with the virtual lab, as indicated by number of virtual lab manipulations, was the best predictor of posttest performance (as compared with overall time in the online environment, Scholastic Aptitude Test score, and gender), even though the final assessments were traditional stoichiometric calculations (*4*).

We chose to develop online homework to ease integration into undergraduate courses. Most instructors feel personal ownership of their lectures, and physical labs are difficult to modify because of practical and economic constraints. However, instructors often assign textbook problems as homework, making a collection of online homework that substitutes for part of these textbook assignments a viable strategy for shifting toward an improved instructional approach.

The virtual lab allows others to develop problem scenarios. Of the 117 virtual labs in the current collection, 56 were contributed by 11 different groups in the user community. Contributions include both instructional materials and translations to other languages, and they come from instructors at universities, community colleges, and high schools. A broad author base helps ensure that activities meet the needs of diverse classrooms, including laboratory courses where virtual activities have been used as prelaboratory assignments and to teach the relation between laboratory procedure and measurement precision (*5*). Because the software is freely distributed at our exhibit booth at conferences and via our Web site, usage is not fully monitored, but the virtual lab was run more than 100,000 times from our Web site last year and downloaded over 25,000 times.

We continue to add activities and topics, including a number of scenario-based learning activities that embed chemistry concepts in real-world contexts so as to highlight the utility of chemistry to bigger problems in everyday science or the broader scientific enterprise (*6*). One such activity is Mixed Reception, which allows students to use concepts covered early in a high-school course to solve a murder that occurs in a research group whose work focuses on synthesis of an antitoxin for spider bites.

The ChemCollective's growing collection of tutorials, which combine instruction on key concepts with practice activities, is being developed in collaboration with Carnegie Mellon's Open Learning Initiative. These tutorials focus on core concepts that are powerful for reasoning about chemistry but difficult to learn. For example, our analysis of the ways in which chemical equilibrium is usually taught revealed key components of the knowledge that were left implicit in traditional instruction. We have found that instruction that explicitly addresses these components more than doubled student performance on related problem types (*7*).

The virtual lab can record all student interactions for analysis. In collaboration with the Pittsburgh Science of Learning Center, we are working on ways to analyze these data to better understand how students learn and to identify ways to best support student problem-solving through immediate feedback generated while monitoring their actions (*8*).

The student experience in introductory chemistry courses is largely set by the activities they practice. The current canon of problem types evolved when student activities outside the physical laboratory were limited to paper and pencil. The availability of online interactivity, combined with recent advances in our understanding of how people learn, creates the opportunity to reconceptualize the set of activities in a way that better conveys the power and beauty of chemistry to the large student populations enrolled in our introductory courses (*9*).

**ChemCollective members.** From left to right: Michael Karabinos, James Greeno, David Yaron, and Gaea Leinhardt

**David Yaron** is an associate professor of chemistry at Carnegie Mellon. In 1998, he began development of the virtual lab with Donovan Lange, who was then an undergraduate student in computer science. Donovan has since moved to Microsoft, where he is a software design engineer. Michael Karabinos joined the project in 2000 and oversees curriculum development and community support for the ChemCollective. Also in 2000, Gaea Leinhardt, a professor of education at the University of Pittsburgh, began working on the design and implementation of studies on how students learn with the virtual lab and the other online resources in the ChemCollective. In 2006, the ChemCollective began collaborating with James Greeno on analysis of what makes certain chemistry concepts particularly challenging to learn and on instructional approaches that can help students reach better understandings. James is also a professor of education at the University of Pittsburgh.

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