Creation of an online stoichiometry course that melds scenario based leaning with virtual labs and problem-solving tutors

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This paper will discuss an online review course in stoichiometry aimed at students who are about to enter college chemistry and need a review of this important foundation material. The course uses the ChemCollective's virtual lab (http://www.chemcollective.org/) and the course delivery and problem solving tutor tools of Carnegie Mellon's Open Learning Initiative (http://www.cmu.edu/oli/). The course is set in the context of arsenic contamination in the groundwater of Bangladesh. This scenario highlights the utility of stoichiometry concepts in a real world problem and allows us to, as the course progresses, shift the theme to the challenges facing modern analytical chemistry. The course contains 15 modules ranging from the mole and molecular weight up through reaction stoichiometry, empirical formula and limiting reagents. Modules typically start with a video explaining the concepts followed by a few simple tutors that serve as interactive worked examples and then either a virtual lab or more extensive problem solving tutor. Our experiences with creating and evaluating this course will be discussed.

Introduction

This paper discusses an online stoichiometry course created through collaboration among chemists, educational psychologists, and learning technologists at Carnegie Mellon University and the University of Pittsburgh. Our principal motivation was that stoichiometry is important base knowledge for introductory college chemistry and one that remains a barrier to success for many students throughout a one-year introductory chemistry sequence. An online course seemed a potentially useful way to give students an opportunity to learn this material before or during the early portion of the college course. In particular, Carnegie Mellon, as well as many other universities, provides only a brief review of this material in lecture and instead requires students to self-study and pass a mastery exam sometime during the first semester course. In 2005, we offered students who were planning to take introductory chemistry in the fall the option of taking the online course during the summer before arriving on campus.

Why build an online course when there is no shortage of textbooks and study guides on stoichiometry? Stoichiometry is hard because it uses an opaque and somewhat ambiguous notational system and because it relies on proportional reasoning. Both of these features, notational and mathematical, have been shown to be very challenging even for science majors. However, stoichiometry is not THAT hard. In fact we might consider the following thought experiment: Suppose we offered students a $50,000 award if, after using text books alone, they could pass a tough test on stoichiometry. It seems likely they would pass. But if the offer were only $5, would they also pass? This seems less likely. So while such text-based materials do seem sufficient for learning, the learning may be quite challenging and effortful. If that is true then the question is perhaps better posed as "Can we create an online course that lowers the effort required to learn and retain stoichiometry?"

In designing our course, we had two factors that made us hopeful. One factor was that our team combined expertise in chemistry and educational psychology. This would allow us to incorporate core principles of learning and develop a task analysis that included not only the components of the computational procedures, but also how this knowledge fits into the content and practice of the domain. The other factor was the use of technology to provide better, dynamic explanations and to give students practice that is both scaffolded and authentic. What remains less clear is the extent to which we were able to use the technology in service of learning as opposed to vice versa.

One of the first design decisions related to linearity versus modularity. The course is packaged as a linear sequence of topics. The linearity guarantees complete coverage and integration among procedures and concepts. However, linearity (with internal branching) means that the uses of stoichiometry are presented as ends in themselves. The alternative would be to introduce stoichiometry as needed in the service of other more significant chemistry topics. To the extent that stoichiometry is a toolkit that experts invoke while working on larger issues, it may be better to teach the material as needed in service of these more authentic pursuits. Such a just-in-time approach could instill more flexible and robust learning, such that students can better access the knowledge as needed in their future learning. We have, to some extent, created the materials in a way that the linear sequence may later be decomposed and the various components used in such a learn-as-needed approach. In addition, we have attempted to provide some of the benefits of learn-as-needed within the linear sequence by setting the learning in a real-world scenario (arsenic contamination of the ground water of Bangladesh) and by providing virtual labs that allow students to apply their knowledge in an environment that is more authentic than that of paper-and-pencil. The extent to which these structures help us meet our learning goals will be considered in more detail below.

The course contains:

- 29 flash presentations that set the context of the practice (arsenic contamination in the ground water of Bangladesh), give instruction in the course concepts, and provide worked examples. These presentations average about 3 1/2 minutes each.

- 42 flash questions that provide hints to guide students through calculations (each provides 3 to 6 hints for each response, with the last being a bottom out hint that gives the answer). These play a role similar to that of worked examples in a textbook.

- 6 virtual labs, including feedback that checks for common errors.

- 3 parameterized tutors that help students learn the more complex stoichiometric calculations (empirical formula, limiting reagents, and mixture composition). The parameterization is sufficient in that the variation among instances is comparable to the variation among end-of-chapter problems in a textbook. The style is that of assistments, [1] which ask students for the response to a multistep problem and give step-by-step help only if needed.

Course features and rationale

This section discusses some of the course features along with the rationale for these features. Taken together, these rationales capture our assumptions regarding the nature of the learner in these environments.

Topics covered

The target audience is students who have had high school chemistry but who need a review of stoichiometry. We assume a basic familiarity with the meaning of chemical formulas, such as H_2O, and reactions, such as that for the burning of hydrogen in air: $2\ H_2 + O_2 \longrightarrow 2\ H_2O$, but the students may have forgotten most of what they learned about stoichiometry as a tool.

The effort began with an analysis of the topics and concepts that are typically covered in a high school course and are measured by ACS and AP exams. This list of objectives was used as a guide to the development. The course begins with foundation topics such as dimensional analysis, significant figures, the mole, and molecular weight (molar mass) followed by solution, composition and reaction stoichiometry. The most advanced topics are empirical formula, limiting reagents, titrations, and mixture composition. The syllabus can be easily customized to offer any subset of these topics.

One area in which we intentionally deviate from the typical sequence is by covering solution stoichiometry early in the course. This allows us to include solution-phase reactions while covering topics such as limiting reagents. Our goal here is to better prepare students for topics such as equilibrium and acid-base chemistry, where these concepts show up almost exclusively in solution. We also include titration, since it provides a nice example of a quantitative analysis technique and serves as an authentic application of the limiting reagent concept.

Scenario

Since the course was to be a linear sequence, we felt the strong need, as discussed earlier, to set the course in a real-world application that serves to contextualize the tools of stoichiometry. The scenario we chose is arsenic contamination in the groundwater of Bangladesh. The emphasis shifts from casting this as a human tragedy that chemists can help alleviate to the challenges facing modern analytical chemistry.

One goal of the scenario is to help make the uses of stoichiometry in the domain more explicit. In a previous work we compared what we teach in chemistry to the activities of the domain. [2] Our analysis of what chemists actually do identified three core behaviors: *analysis*, *synthesis*, and explanation. Of these, current instruction occurs almost exclusively in the *explanation* category, and our goal was to choose scenarios that bring this more into balance with the domain. Since stoichiometry is perhaps most central to *analysis*, we chose an important application of analytical chemistry. *Synthesis* is addressed by the portion of the course that discusses the attempt to convert local materials into powders that absorb arsenic. Some attempt to include *explanation* is made by setting the empirical formula practice in the context of analyzing ground samples to determine the form of arsenic that is present, but this is rather weak since we do not connect back to an explanation of how arsenic got into the groundwater of Bangladesh.

In addition to the motivational advantages, the arsenic scenario may provide cognitive advantages. In particular, by using the scenario to highlight the utility of the stoichiometry tools, we may be providing a memorable location to which students can attach their knowledge. Some examples of how this particular scenario may serve such a role include:

- The world health organization limit is phrased in micrograms of arsenic (As) per liter, but As exists in water as oxides. Composition stoichiometry allows one to extract the mass of As from the mass of oxide.

- The scenario brings out the distinction between quantitative and qualitative analysis by providing examples of both in the scenario context.

- The scenario discusses empirical formula as a type of qualitative analysis by using it to provide information on the form As has in the groundwater.

An additional layer of benefits can be envisioned for scenarios that enable one to more easily navigate the problem space. This requires that the scenario have aspects or characters that map to specific aspects of the problem solving process. A potential location where this occurs in the course is when students are asked to determine the amount of arsenic that can be absorbed by a powder made from locally available materials. The proportional reasoning required by this problem may be aided by being attached to the powder in the scenario, invoking the intuition that twice as much powder will absorb twice as much arsenic. In the latter part of the course, the emphasis of the scenario switches to the difficulties that arise when detecting small a mounts of material. The scenario may at this point aid the problem space by focusing attention on the relative magnitude of the numbers involved.

Video explanations

In addition to videos that convey the scenario, most of the explanations are done through videos with voice over narration. A principle goal and review criteria for these videos was that the explanations include not only the how, but also the why of the procedures. An attempt was made to go beyond explaining each step in the problem solving process, and include both the bigger picture of the problem solving strategy and the motivation for each step in the problem solving process. As an explicit example of emphasizing the "why", consider the video on the mole, [Understanding the mole] which attempts to explain the utility of the mole concept and give instances when it is useful.

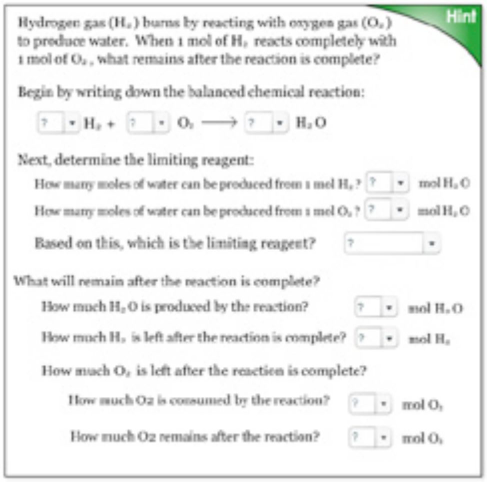
As discussed in more detail below, creation of videos is considerably more demanding than producing the equivalent content in a text-only manner. Our hope is that the video accrues a number of advantages that lower the barrier to understanding the material. In particular, videos may allow students to keep their visual attention on a chemical or algebraic representation while hearing various aspects of this representation described. Such an approach may be especially helpful, since the various numbers and symbols in a chemical reaction are loaded with meanings regarding microscopic constructs. For instance, in $CH_4 + 2\ O_2 \rightarrow CO_2 + 2\ H_2O$ the subscripts convey molecular structure while the inline numbers convey rules for combining molecules to make new molecules. As we identified earlier, this is a location of cognitive complexity because the notation does not directly support the differing meanings of the numerals. Video demonstrations with voiceovers allow students to hear such distinctions through inflection and gesture while focusing attention on the representation itself.

The issue of the relative benefits of video versus text is complicated by the possibility that the ideal modality may depend strongly on the where the student is in the learning process. It is possible that students who are learning a new set of complex material may benefit from video due to the arguments given above. However, students who are reviewing material and refining their knowledge may not need more than the text; the auditory information, while not harmful may not be helpful to such students. Some recent work by Kurt VanLehn supports this idea.[3]

Tutors

A video explanation is typically followed by a simple tutor that serves as a bridge between the expository presentation and autonomous practice of a concept's procedures. These tutors pose a series of questions that walk students through a problem solving process.

Two forms of scaffolding are provided, feedback and hints. Feedback on an incorrect response causes the entered response to turn red and invokes a message that helps guide the student to the correct response. A correct response turns green and gives reinforcement through a brief explanation of why the response is correct. Hints, about 3 to 6 per response in a tutor, can be invoked at any time by clicking on the hint button. The first hint typically reminds students of the goal of that particular problem solving step (relating to the *why* of the procedure), with follow-on hints giving more detail on how the step may be carried out. The last hint is a "bottom out" hint, meaning it gives an explanation that includes the answer.



Hydrogen gas (H_2) burns by reacting with oxygen gas (O_2) to produce water. When 1 mol of H_2 reacts completely with 1 mol of O_2, what remains after the reaction is complete?

Begin by writing down the balanced chemical reaction:

? ▾ H_2 + ? ▾ $O_2 \longrightarrow$? ▾ H_2O

Next, determine the limiting reagent:

How many moles of water can be produced from 1 mol H_2? ? ▾ mol H_2O

How many moles of water can be produced from 1 mol O_2? ? ▾ mol H_2O

Based on this, which is the limiting reagent? ? ▾

What will remain after the reaction is complete?

How much H_2O is produced by the reaction? ? ▾ mol H_2O

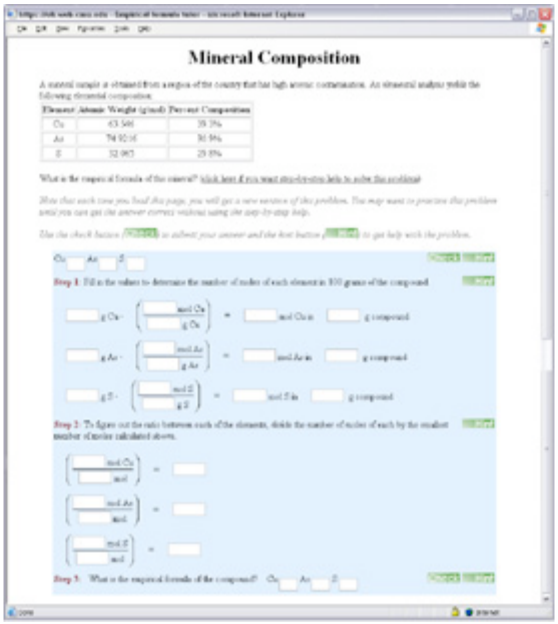
How much H_2 is left after the reaction is complete? ? ▾ mol H_2

How much O_2 is left after the reaction is complete?

How much O2 is consumed by the reaction? ? ▾ mol O_2

How much O2 remains after the reaction? ? ▾ mol O_2

Example of a flash tutor



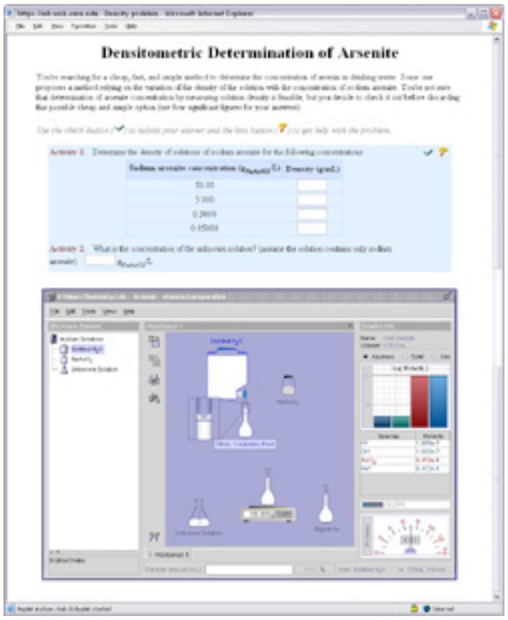
Empirical formula tutor

The goal of these tutors is to provide a simple form of fading in the problem solving support. At one extreme, students can drill down to the bottom-out hint, in which case the tutor serves as a fully worked example. At the other extreme, students may answer each question without reading hints, taking advantage of only the feedback mechanisms. Studies on similar tutors [4] suggest that effective use of such help systems varies depending on the student's prior knowledge and metacognitive skills. Ideally, students would use the hints frequently when they first encounter a topic and then have their use fade as they shift to a practice mode. Analysis of student behavior with the tutors through examination of log files, for instance, may help us determine the extent to which beginning college students can make effective use of these help systems

The course also includes three more involved tutors that help students with the more complex calculations (empirical formula, limiting reagents, and mixture composition). The parameterization is meant to provide variation between instances that is comparable to that found in different end-of-chapter textbook problems. These tutors, especially that on empirical formula, provide a more fine-grained support for the problem solving with the interface capturing essentially every step. [snapshot and link] The interface needed to enable monitoring at this level of granularity has the disadvantage of providing strong cues to the problem solving, making it especially important that this scaffolding fade appropriately. Our current approach to fading is to first ask students for the answer to the problem and then fall back to the heavily scaffolded interface if they request help or fail after two attempts [1].

Virtual labs (V-Labs)

When appropriate, a course section ends with a V-lab that allows students to apply their knowledge in an environment that is more authentic than paper and pencil problem solving. Example tasks include determining the As content in a sample of well water, carrying out dilutions, and designing and performing titrations. The system provides hints that remind students of the goal of the activity and give some general advice on how to solve the problem. Feedback on the student response to the problem is also provided. In addition to correctness, the system analyzes the responses for anticipated student errors and provides appropriate feedback if such an error is discovered. The problems are parameterized by, for instance, randomly generating unknowns. After three failed attempts to solve a problem, the system gives the student the correct answer and then requires the student to reload the problem such that new random parameters are assigned.



Virtual Lab density activity

The V-labs are meant to help students attach the mathematical procedures they are learning in the course to authentic laboratory chemistry. Our student observations suggest that such attachments are not automatic and instead require explicit practice. For instance, after performing a dilution calculation prompted by the question, "What volume of 5.7 M glucose is needed to create a 100.0 mL of a 0.32M glucose solution?", it can take a student some time to figure out how to carry out the dilution in the virtual lab. This is not a user interface issue. Rather, the student appears to have translated the initial chemistry goal into an algebraic problem solving goal and once the algebraic goal is met, it can take some effort to remap this back onto the chemistry goal. It is tempting to dismiss this phenomenon as students failing to "transfer" what they learned, but a closer or more fine-grained task analysis shows that students have been asked to practice one thing and then are assumed to be able to do something else that is quite different. Practice in the V-Lab is designed to ameliorate that situation.

More advanced virtual lab problems ask students to design and carry out their own experiments. In such cases, students must connect the procedures and concepts they learned in the course to laboratory manipulations. Our hope is that such connections will make it more likely that the procedures and concepts are retained and invoked as needed in future learning.

Assessment efforts

This course was developed as part of the Open Learning Initiative (OLI, http://www.cmu.edu/oli), whose goal is to provide a collection of "cognitively informed," openly available and free online courses and course materials that enact instruction for an entire course in an online format. The OLI course delivery system supports collection and analysis of log files that include time-stamped data on student views of web content, and interactions with tutors and simulations. In the summer of 2005, 40 students volunteered for a study and were randomly assigned to either the online course or a control condition. The control provided students with a detailed text review of stoichiometry whose content is parallel to that of the online course, but with the scenario removed, and without feedback. The contrast could therefore show effects of the scenario, virtual labs and online tutors. Analysis of the data is underway and will be reported in a later publication.

This course is now also part of the Pittsburgh Science of Learning Center (PSLC, http://www.learnlab.org), whose goal is to support research on robust learning through a research facility named learnlab. The learnlab provides technologies to facilitate experiments that combine the realism of classroom field studies with the rigor of controlled theory-based laboratory studies. This course has some significant advantages for such learning studies. The intent is that students would take this as an optional or required course either before arriving on campus or very early in the school year. As a purely online course, it provides a well-controlled learning environment for delivering various conditions. In addition, since students go on to enroll in a chemistry course, access to their performance in this course, and perhaps follow-on courses, provides a means to measure the robustness of their learning. The chemistry learnlab invites instructors and researchers who would like to participate in or carry out learning studies in real classrooms. Please contact us (info@chemcollective.org) if you would like to explore this further.