Bringing useful insights into student thinking to course design, delivery, and evaluation using the beSocratic formative assessment system

Michael W. Klymkowsky[1], Sam P. Bryfczynski[2] & Melanie M. Cooper[2]
[1]Molecular, Cellular & Developmental Biology, University of Colorado Boulder, Boulder, CO, 80309
[2]Chemistry, Michigan State University, East Lansing, MI 48824

Abstract: Key questions in the context of science education are i) what do students know at the start of a course or curriculum and ii) what have they learned and what can they do with that knowledge by the end. To understand what and how students are thinking, the classic Socratic model is to ask students questions and to consider and respond to their answers, with the goal of promoting metacognitive reflection leading to improved understanding. To facilitate such Socratic interactions we developed the beSocratic system. Among web-based systems its unique feature is its ability to deliver questions that require various forms of graphic responses; the system can be set to respond in various ways based on what the student draws. Here we describe the use of the system in both a revised general chemistry course (DUE-1359818) and an introductory evolutionary and molecular biology course, and how student data can be used to drive more effective course design. beSocratic provides educators and researchers with a way to assess how students construct models and explanations. Based on these insights we have reconsidered how key concepts in chemistry and biology are presented to students and how students can be helped to understand ideas and their application in a wide range of course size and instructional contexts.

Introduction

Over the last decade there has been much focus on the transition from lecturing to more engaged pedagogies.[1,2] Surprisingly, what is often missing from this national conversation is a critical consideration of what is important to teach and what students come to master, as well as what is involved in students' development of an accurate understanding, their ability to apply these ideas to new situations, and how course design must adapt to facilitate our learning goals.[3] Courses, and their pre-requisites, need to be designed (scaffolded) based on logical, engaging, and realistic progressions as well as a meaningful appraisal of what students already know or think they know.[4] The development of a realistic picture of what students know before and after instruction is not a trivial task, but becomes increasingly important given variations in students' preparation (see [5]), which may make it difficult or impossible for them to productively engage with complex scientific ideas without appropriate scaffolding.[6,7]

So how best to gauge what students are thinking, what they can be effectively taught, what background materials need to be reinforced, and how to structure (scaffold) the presentation of course content and practice in order to maximize both engagement and learning? Assessments, including concept tests (inventories), designed to monitor conceptual and factual knowledge, reasoning, and problem solving ability can reveal what students do not understand, but often fail to provide evidence about what students are actually thinking or able to do with their knowledge (DUE-0405007).[8] It is now time to move forward to more nuanced assessments that provide actionable insights as to what it is that students know and can do, insights that can drive improved course design and presentation.

Historically the way to understand what a person is actually thinking involves subjecting them to a Socratic interrogation through which they are asked to articulate, clarify, and defend their thinking. Such an interrogation reveals whether they can clearly explain scientific phenomena, using concepts and their logical integration, or whether they are simply repackaging language they remember hearing. That said, Socratic conversations are time consuming and can be irritating to those questioned (as witness Socrates' own fate). Our approach to the need to understand what students know (or think that they know) before instruction (diagnostic data) and what course design and instruction help them to master (formative and summative assessment data) has been to use the scientific practices of developing and using models, and constructing explanations. Students are asked to draw (construct) a response to a particular situation or phenomenon; these artifacts then provide more robust evidence about what students know and can do than their responses to forced choice instruments or even (in many cases) extended text-based responses. As described below, the beSocratic system provides powerful affordances in the context of course design and delivery, as well as research data for the evaluation of educational outcomes.

Making student thinking visible: The beSocratic system, which emerged from various precursor projects, is an online, cross-platform, system designed for the recognition, evaluation and analysis of free-form student drawings.[9] It consists of a simple instructor interface for the development of activities using modules that allow for the drawing of graphs or the input of free-form drawings, text, and chemical structures. Activities can be easily developed that provide responses to students' graphs and drawings; responses are based on pre-specified rules established by the activity designer (the instructor). Such rules can include the number of curves drawn, the number of maxima/minima in a curve, the area under the curve, the curve's slope, and its intersections with defined coordinates or regions within the graph area. In more free-form (non-graph) questions, the researcher/instructor can use a visible image and an invisible coordinate system to specify correct and incorrect features of a student's drawing. The system also allows for feedback on chemical structures. In addition conventional multiple-choice questions and open response prompts can be included. Typically, we ask students to explain their reasoning and the logic of their answers. An instructor can easily construct an activity that requires ungraded responses (drawings and text) in a matter of minutes. Students can access the beSocratic web site through a range of browsers, with the installation of the Microsoft Silverlight plug-in. The analysis of student data is also simple and examples of student work can easily be presented to the class as the focus of further discussion.

The original beSocratic system is currently housed in the chemistry department at Michigan State University, and as part of the Chemistry, Life, the Universe & Everything (CLUE) general chemistry course, is serving over 3000 students per semester. The MSU site is also used by a smaller introductory molecular biology class (Biofundamentals) of ~100 students at the University of Colorado Boulder, as well as a small number of other institutions. To provide more general access, we are currently in the process of installing a cloned version of beSocratic (beSocratic.colorado.edu) at UC Boulder and exploring other strategies to make the powerful affordances of beSocratic more widely available. A user guide for how to author *beSocratic* activities can be found on the original beSocratic.com website.

An example of an activity that illustrates graph drawing and interpretation is provided in figure 1. Biology students were asked to generate a graph of the concentration of a reactant over time in a highly thermodynamically unfavorable reaction A ⇌ C + D. The activity can be designed to provide feedback as to the correct response, or feedback can be turned off. Whether students draw the curve for [A] correctly (**FIG. 1A**) or incorrectly (**FIG. 1B**) can be used as a focus for in class discussions. In a follow-on activity, students are asked to consider the effect of reaction coupling. They are told that C is involved in a thermodynamically favorable reaction (C ⇌ E + F). They are then asked to predict the [A] as a function of time and the effect of changing the concentration of E (**FIG. 1C**). This is a complex task and serves as the starting off point for in class discussions of the dynamic behavior of coupled chemical reactions using student supplied examples.

As part of the response to the student input (beyond hints or acceptance of their response), the system can be set up to require the student to explain their thinking, or can send the student to a tutorial. A particularly useful feature of beSocratic is that it allows students to return to and edit a previously constructed drawing or text by making modifications according to their newly acquired understanding.

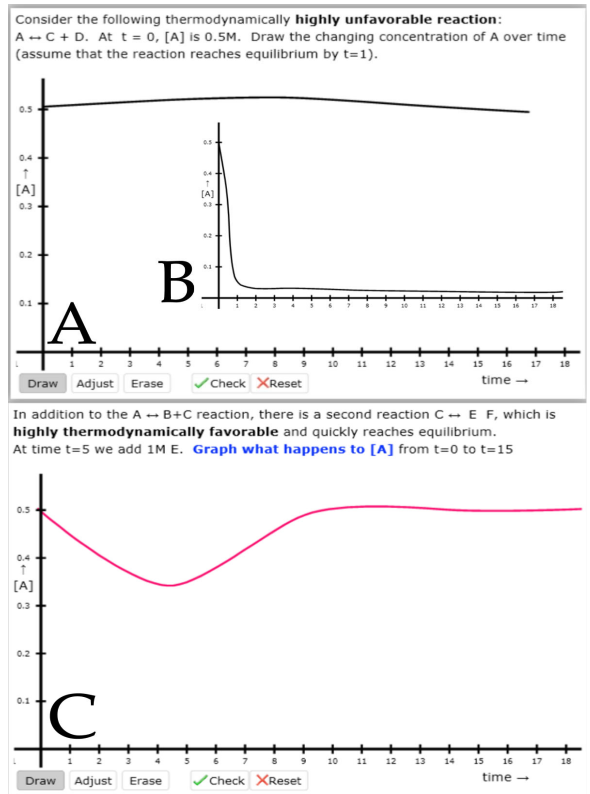

FIG.1: Students are asked to draw, as a function of time, the concentration of a reactant in a highly unfavorable reaction. While many can draw the behavior correctly (**A**) a significant number do not (**B**) indicating the need for further instruction and practice. As an extension of this activity, they are asked to predict the behavior of the system when the initial reaction is coupled to a thermo-dynamically favorable reaction together with the effect of adding a product of the second reaction (**C**); a plausible graph is shown (red line).

Using beSocratic in Chemistry Courses: We have been using beSocratic as the main homework system for CLUE for three years. We have developed over 60 activities for general chemistry and another 30 for organic chemistry. After each class students are provided with homework assignments that allows them to use what they have learned and may also provide an introduction to the next class. Each class begins with a whole class review of the homework, which typically involves showing the “grid view” first in order to illustrate for students the range of responses from the class. Several actual student responses can then be called up (by clicking on the square) for a more detailed discussion.

One common homework type is to ask students to draw a molecular representation of a chemical phenomenon and use that representation to provide a causal mechanistic explanation. For example **FIG. 2A** shows a sequence of student drawings (which in this case do not receive automated feedback because the drawings are too complex), as part of an activity to help students understand why dissolving a salt results in a temperature change. **FIG. 2B** shows student responses when asked to draw and identify the inter-molecular interactions between ethanol molecules. In the case of dissolving NaCl, by separating out the sequence of events involved we are able to see what the students understand about the process of solution. Similarly, asking students to identify the intermolecular interactions between molecules has revealed confusions between covalent bonds and non-covalent interactions that can be addressed through instruction. [see 10] Through this process, we are able to tie together ideas and pose questions designed to help students reflect productively on their underlying assumptions.

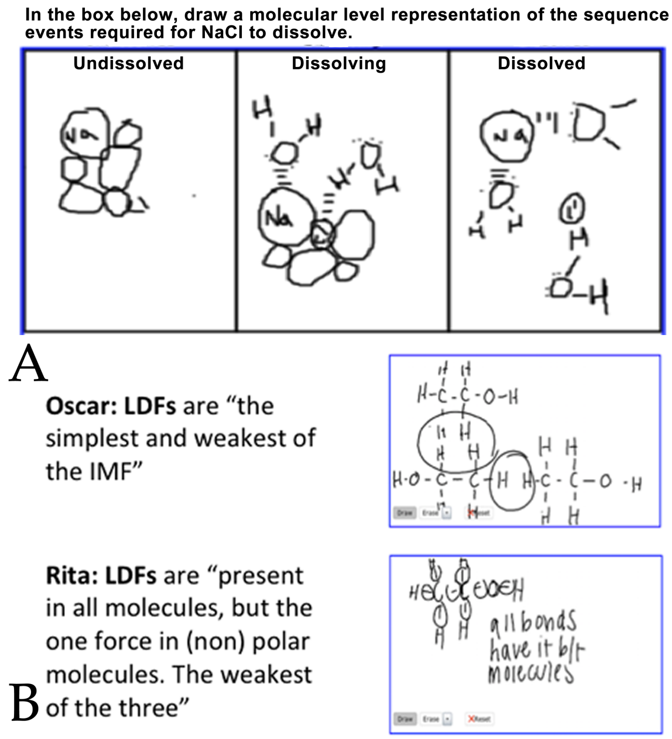

FIG. 2: Students are asked (**A**) to draw the steps in the process by which NaCl dissolves in water and (**B**) to indicate the intermolecular interactions (forces) between molecules of ethanol.

It should be noted that many of the homework activities are graded only for completion. That is, while students receive feedback on graphs and simple diagrams, the text and more complex diagrams are not (yet) machine-readable. However we have found (by reading and scoring the work for research purposes) that the vast majority of students take the homework seriously. In fact, we take great pains to explain to students that the beSocratic homework is for their benefit and that this is a space to explore their thinking. There is no penalty for being wrong on a particular homework, which we believe encourages students to answer honestly about what they do and do not know.

beSocratic in biology: We have used essentially the same strategy to generate beSocratic formative assessments in an introductory molecular (and evolutionary) biology course, a few of which are illustrated in figure 3. As with chemistry, we do not give credit for getting the activity correct, but rather for the student's serious attempt to complete the activity by the pre-class deadline. All student activities can be downloaded at the end of the semester as a spreadsheet from which completion scores are calculated. Activities include questions on the major topics addressed in the course, including selection, genetic drift, molecular interactions, and recognizing structures, such as hydrophilic versus hydrophobic amino acid R-groups (**FIG. 3A**) and peptide bonds (**FIG. 3B**), as well as the behavior of coupled chemical reactions (**FIG. 1**) and the effects of mutations on the intracellular localization of proteins (**FIG. 3C,D**). The activities themselves, as well as illustrative student responses, are presented and

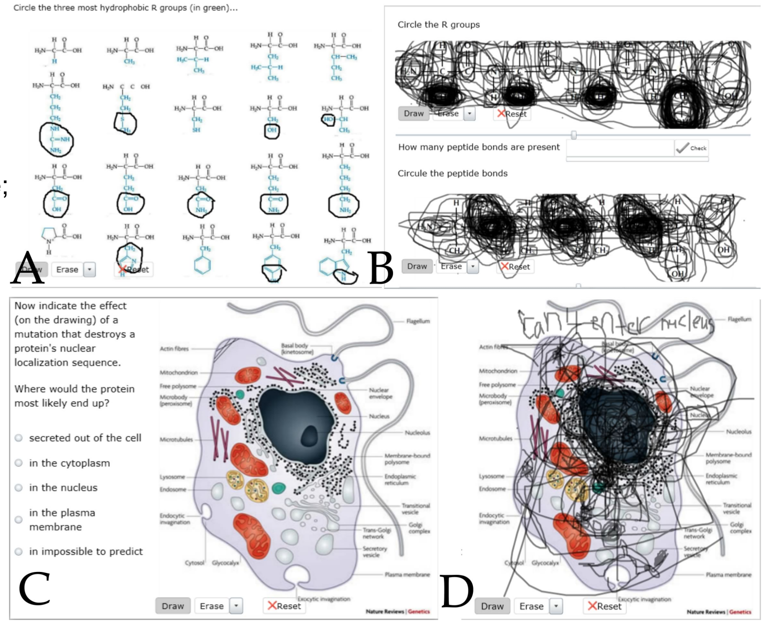

FIG. 3: Displayed are some activities used in a biology course (Biofundamentals). These include **A**: selecting the hydrophobic R-groups of amino acids; **B**: circling the R groups and peptide bonds of a short polypeptide; **C,D**: Indicating the effect of a mutation on a protein's localization within a cell.

discussed in class in the context of individual and group activities, so as to highlight what is important and relevant, what is distracting and irrelevant, and what core ideas are involved in generating a correct response and illustrated by incorrect responses. Responses to multiple-choice type questions are used in the same way clicker questions are typically used, as a focus for in class discussions with the goal of understanding the logic of the answer, and to identify what, exactly, makes wrong answers wrong.

beSocratic as a research tool: All of the responses (texts, drawings, and graphs) are stored for later playback and can be analyzed, either using the built-in coding tools of beSocratic, or the data can be exported and coded in other systems (for example NVivo). We have used beSocratic extensively as a data collection and analysis tool for a wide range of projects. For example, in an investigation of how students understand intermolecular forces (IMFs), we asked students to write and draw about IMFs (**FIG. 2B**). We found that the drawings were far more informative than the writing. In their written responses to a prompt asking them to tell us what they know about a particular IMF, students typically gave textbook definitions.[10] However, when we asked students to show us the location of IMFs in a drawing the answers were much more informative. We found that students who are able to answer multiple choice questions, or provide appropriate descriptions of IMFs often drew the location of the IMF within a molecule, the incorrect position.

We have found that the nature of the prompts for both writing and drawing tasks can be critical, and beSocratic has allowed us to perform multiple iterations of an activity with slightly different prompts, to help us develop activities that encourage students to show us what they know, their often implicit (incorrect) assumptions. This has led us to recognize that many students need help in generating logical written scientific explanations that are based on clearly articulated assumptions. In addition to the built in coding tools for text and drawings, beSocratic also has built in automatic analysis tools to cluster the coded data, which enables us to search for patterns in student responses.

Summary, on-going & future work: What beSocratic makes accessible are activities, whether diagnostic, formative, or summative, that move from passive recognition of the correct answer to monitoring students ability to construct a plausible response, and to use their responses in subsequent teaching to identify and address misunderstandings and the misapplication of concepts and data. Analysis of responses to beSocratic activities enables us to discern when students are understanding versus when they are using various recognition heuristics to answer a question.[11] As an example, we have found that students who can correctly identify relative boiling points of compounds often use incorrect reasoning.[12,13] The use of well designed beSocratic activities enables us to discover and address these problems, which are likely to become increasingly serious obstacles to students' disciplinary competence as they progress through a major, or attempt to apply their "knowledge" to other disciplines, such as the application of concepts from physics and chemistry to biology. The next tasks we face are the practical need to move beSocratic to HTML5 and, the ultimate goal of any learning practice and evaluation system, to develop a version of beSocratic that can itself respond socratically to students' textual responses, asking the hard questions that reveal clear thinking and true content mastery.

Literature cited

1 Powell, K. Science education: spare me the lecture. *Nature* **425**, 234-236, doi:10.1038/425234a (2003).

2 NRC. Discipline-Based Education Research: Understanding and Improving Learning in Undergraduate Science and Engineering. (National Academies Press, 2012).

3 Klymkowsky, M. W. in *ASBMB Today* Feb. (ASBMB, Washington, D.C., 2011).

4 Schweingruber, H., Keller, T. & Quinn, H. *A Framework for K-12 Science Education:: Practices, Crosscutting Concepts, and Core Ideas*. (National Academies Press, 2012).

5 Rich, M. in *New York Times* (New York, 2015).

6 Vygotsky, L. Interaction between learning and development. *Readings on the development of children*, 34-41 (1978).

7 Bliss, J., Askew, M., Macrae, S. Effective teaching and learning: Scaffolding revisited. *Oxford Review of Education* **22**, 37-61 (1996).

8 Garvin-Doxas, K. & Klymkowsky, M. W. Understanding Randomness and its impact on Student Learning: Lessons from the Biology Concept Inventory (BCI). *Life Science Education* **7**, 227-233 (2008).

9 Cooper, M. M. *et al.* A Short History of the Use of Technology to Model and Analyze Student Data for Teaching and Research. *Tools of Chemistry Education Research* **1166** (2014).

10 Williams, L. C., Underwood, S. M., Klymkowsky, M. W. & Cooper, M. M. Are Noncovalent Interactions an Achilles Heel in Chemistry Education? A Comparison of Instructional Approaches. *Journal of Chemical Education* **92**, 1979–1987 (2015).

11 Maeyer, J. & Talanquer, V. The role of intuitive heuristics in students' thinking: Ranking chemical substances. *Science Education* **94**, 963-984 (2010).

12 Cooper, M. M., Corley, L. M. & Underwood, S. M. An investigation of college chemistry students' understanding of structure–property relationships. *Journal of Research in Science Teaching* **50**, 699-721 (2013).

13 Underwood, S. M., Reyes-Gastelum, D. & Cooper, M. M. When do students recognize relationships between molecular structure and properties? A longitudinal comparison of the impact of traditional and transformed curricula. *Chemistry Education Research and Practice* **in press.** (2016).