Representations and Equations in an Interactive Simulation that Support Student Development in Balancing Chemical Equations

Yuen-ying Carpenter, Emily B. Moore, and Katherine K. Perkins
University of Colorado Boulder

Abstract
The ability to balance a chemical equation is a foundational skill in chemistry, yet it is still most frequently taught traditionally, through explicit instruction followed by drill-and-practice. Using a guided-inquiry activity coupled with feedback from a PhET interactive simulation offers an opportunity to foster student development of this skill via an inquiry-driven approach. Here, we describe how student groups in a preparatory (pre-General) chemistry course make use of the Balancing Chemical Equations simulation to build increasingly expert-like practices with non-redox equation balancing. Student discussions during this process offer insights into the ways that multiple representations in the simulation – including symbols, molecular pictures, and balance scales – each facilitate different stages of student development.

Introduction
Balancing chemical equations is a foundational skill for the learning and practice of chemistry. Yet, equation balancing is typically taught via traditional methods; namely, direct instruction, followed by drill-and-practice. As teachers, we provide our students with a definition of a balanced equation, but often struggle when it comes to supporting our students in non-algorithmic approaches to balancing. Often, our advice to students relies on heuristics -- helpful hints such as balancing the largest molecule first or hydrogen atoms last. While such tips can be helpful, heuristics also lend themselves well to memorization, leading students to later reference these half-remembered guidelines as if they were absolute rules for the process of balancing [1].

In addition, little is known about what makes an equation challenging for novice balancers, nor even what distinguishes expert and novice approaches toward an unbalanced chemical equation. Literature on equation balancing has historically focused either on providing new algorithmic approaches to balancing to reduce cognitive load [2] or on studying student balancing as a binary of success or failure [3, 4].

Here, we will focus on understanding and supporting student process development in equation balancing, using an inquiry-oriented approach facilitated by an interactive simulation. We will show not only that students are able to learn to balance chemical equations without explicit instruction, but also that the representations used in the simulation impact the development of student balancing practices.

In the Classroom
The focus of this paper is an in-class activity which uses guided-inquiry prompts coupled with feedback from a PhET interactive simulation to introduce students to equation balancing. The activity took place in a Preparatory Chemistry class at a primarily

undergraduate public university in the western United States. The course targets students identifying as underprepared for traditional first-semester General Chemistry. Course content was primarily delivered via in-class group work on guided inquiry activities, occasionally supported by PhET simulations. In earlier classes, students had covered content on empirical and molecular formulas. This activity marked the students first in-course exposure to the topic of balancing chemical equations.

On the day of the activity, students were seated in 12 groups of 2-3 students and provided with activity worksheets and laptops pre-loaded with the PhET interactive simulation, *Balancing Chemical Equations* [5]. The instructor told students that the day's activity would focus on chemical equations and then directed them to begin the activity, alternating control of the laptop and simulation amongst group members. No directions were given on how to use the simulation.

Part I of the activity focused on the Introduction screen of the simulation (Figure 1) and prompted students to compare the total number of molecules and atoms on the left and right sides of the equation once balanced. Each of the three available equations provided visual and audio confirmation when successfully balanced.

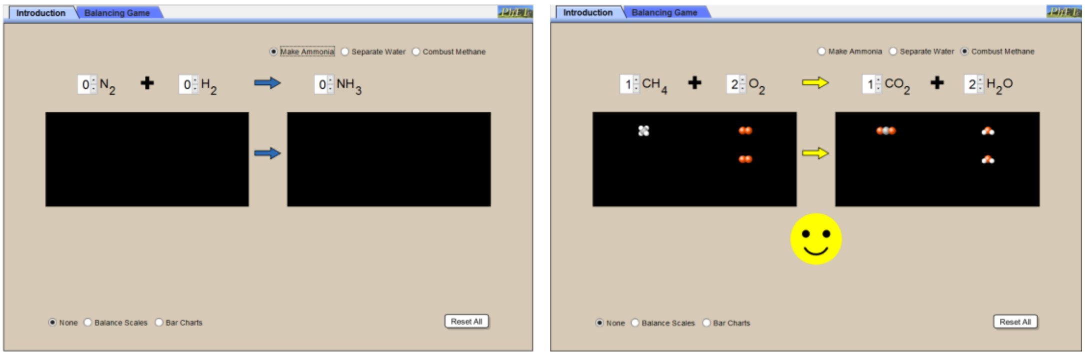

Figure 1 - The Introduction screen of the PhET Balancing Chemical Equations simulation when first opened by the student (left) and when an equation is balanced (right).

Part II of the activity focused on the Balancing Game screen of the simulation (Figure 2), and asked students to specifically focus on the strategies they were using to balance the equations presented at each progressively more challenging level of the Game. Each level presented students with five equations randomly drawn from a pool of questions of similar challenge. Level 1 offered equations with only 3 coefficients, *i.e*. either decomposition or combination reactions. Level 2 and 3 both presented equations with 4 required coefficients, with larger coefficients being generally required at Level 3. At all levels, students had two chances to enter the least coefficients for a balanced equation, receiving feedback each time they submitted an answer to be checked by the simulation (Figure 3).

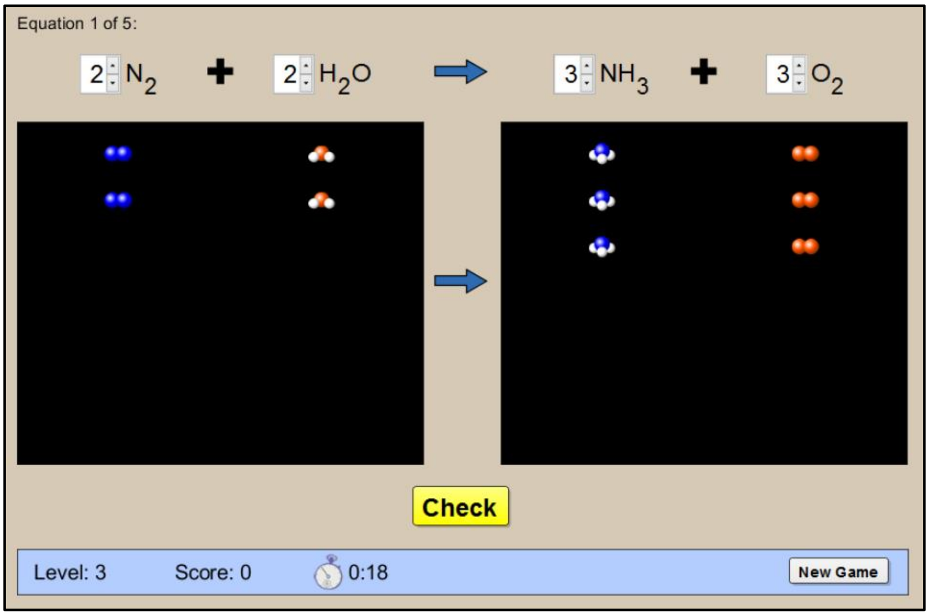

Figure 2 - An example challenge equation in progress at Level 3 of the Balancing Game screen.

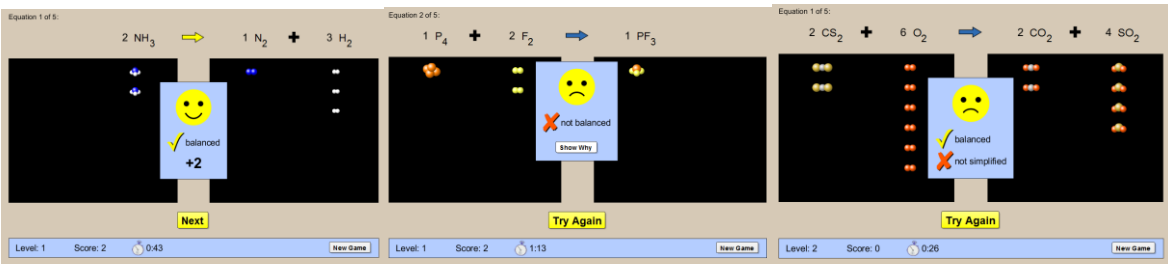

Figure 3 - Examples of feedback which could be received by students from the Balancing Game portion of the simulation.

During the class, the instructor facilitated several whole class discussions to solicit student views on the requirements of a balanced chemical equation and their balancing strategies. Including class discussion time, student groups spent a total of 30-50 minutes on the activity. Groups who finished early moved onto another related activity about chemical equations and stoichiometry. We collected simultaneous audio and screen capture recordings from each student group during the class period. In total, we successfully recorded and analyzed data from 10 student groups.

Results and Discussion

When student groups in Preparatory Chemistry were provided with a guided-inquiry activity which leveraged interaction and feedback from the PhET *Balancing Chemical Equations* simulation, all groups were able to craft operational definitions of equation balancing and successfully balance chemical equations of varying difficulty.

It is encouraging to note that these students were able to balance equations without explicit instruction, but we were specifically interested in looking at changes in students' process of balancing. We will report a more detailed analysis of students' evolving practices elsewhere, our early analyses of student actions and discussion around balancing tasks offers several insights particularly useful for teachers.

Here, we focus on student groups' use of different representations in the simulation and reflect on how these usage patterns may inform our approach to teaching balancing, with or without an interactive simulation.

Student use of symbolic and pictorial representations

Throughout the activity, the simulation supports student balancing by displaying concurrent symbolic and molecular-scale pictorial representations of the atoms and molecules in the chemical equation (*e.g.* Figure 2). The simulation was designed to cue students to the connection between these two disciplinary representations, with additional molecules appearing as coefficients are increased.

Because these representations offer a shared visual for all group members, they can be leveraged to facilitate communication between students and clarify meaning. For example, in one group, a student initially declared that a balanced equation was one with equal numbers of *molecules* on both sides. The student then demonstrated his meaning for the group by counting the number of *atoms* of one element and indicating these atoms on-screen with the mouse. This behavior suggests that the student was, in fact, correctly counting the atoms on each side of the equation, but simply used the incorrect term in his statement to the group. This type of terminology mismatch is not uncommon among early chemistry students, so it can be valuable that the representations in the simulation may help the group members more accurately convey their intended meaning.

More than this, we suggest that the concurrent availability of both symbolic and pictorial representations supports chemistry learners in bridging these two key disciplinary modes of thinking. We analyzed student actions and dialogue while groups balanced equations presented in the Balancing Game, looking specifically for cues that students were leveraging either the symbolic or molecular representations.

Cues indicating student use of the symbolic representations included "mousing" over equation terms with the cursor while counting aloud, reading formulas aloud as written, or verbalizing the multiplication of coefficient and subscript to calculate the total number of atoms of an element. Notably, student focus on the symbolic representations was highlighted in groups who balanced the equation for the combustion of ethanol (presented in the simulation with the formula C_2H_5OH). All groups who encountered this equation initially treated the ethanol molecule as if it contained only *five* hydrogens. For example, one group (i) set the coefficient of ethanol to two, (ii) indicated the subscript "5" with the mouse cursor, and then (iii) verbalized their total as ten, demonstrating that they were not attending to the sixth hydrogen in the formula. In none of these cases was there any indication that groups were miscounting the number of hydrogen atoms with reference to the pictorial representation. Instead, this common error likely resulted from students unfamiliarity chemical formulas that include functional group information.

Cues indicating student use of the molecular-scale representations included mousing over each atom or molecule while counting aloud, or making verbal reference to the colour or size of the atoms depicted. For example, students referred to hydrogen atoms while balancing by saying that, "There are too many white ones on this side" or that "We need more of the small ones." Groups who referred extensively to the pictorial representations also tended to immediately increase all coefficients from zero to one when presented with a new equation, allowing them to view and leverage these images for balancing.

Student groups who seemed new to balancing tended to consistently leverage the pictorial representations in their practice, but all groups engaged with the symbolic representations. This suggests that novice balancers may be served by concurrent support from both representations, but that their heavier use of molecular-scale representations in balancing does not preclude them from attending to and using symbolic representations. In fact, it seems likely that their use of both representations will support them in coordinating these key disciplinary modes in future practice.

Student use of a "balance scale" representation

In addition to canonical symbolic and pictorial representations, the simulation also offers the option of additional representations to focus students' attention on the core idea of equation balancing.

When students first load the simulation, the Introduction screen presents three typical unbalanced equations (Figure 1). Unlike the Game screen previously highlighted, the Introduction focuses on student exploration of balancing and allows students to add bar chart (Figure 4) or balance scale representations to their view (Figure 5). Both of these representations were designed to focus attention on whether there are an equal number of atoms of each element at any given time. Combined with the "happy-face" feedback students receive when an equation is balanced, this design was intended to support students in developing their own operational definition of a balanced chemical equation.

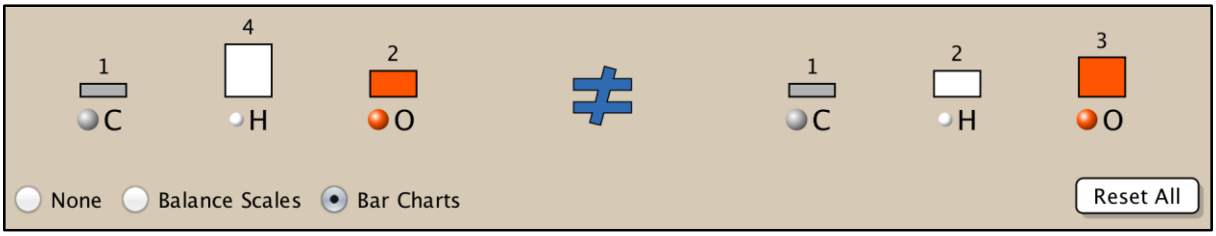

Figure 4 - Bar chart representation in the PhET simulation, showing the number of atoms of each element.

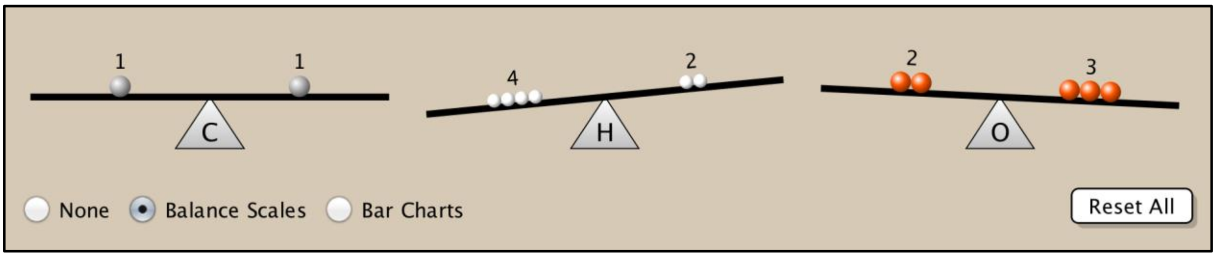

Figure 5 - Balance scales representation in the PhET simulation, showing the number of atoms of each element.

In our study, no student groups made active use of the bar charts, although some did open this view in passing after balancing the equations. However, 4 of the 10 groups made use of the balance scales while still engaged in balancing. In addition to keeping the balance scales visible during their balancing process, the students also indicated their use of this representation with mouse gestures or verbal references.

For student groups with members that seemed to have little or no prior exposure to equation balancing, the balance scales seemed extremely valuable to their ability to figure out the task at hand. For example, one pair of students exploring the simulation makes multiple attempts to adjust the coefficients in the equation for the synthesis of ammonia, all without balancing the equation. One asks, “What are we looking for?” and the other replies, “I don’t know.” When the pair adds the balance scales to their view, both students immediately indicate that the “H” scale is unbalanced and, in only 2 actions, adjust the coefficient on H_2 to balance the reaction.

Balance scales also assisted groups in self-correcting misunderstandings about balancing. One group assumed at the start of the activity that the equation must be balanced when no more molecules could be added, but revised this idea as soon as the balance scales were viewed.

These examples highlight the potential for this non-traditional representation to facilitate student conceptualization of their task. The dynamic feedback from the balance scales supported new learners to clarify that the number of atoms of each element must be equal on either side of a balanced equation and helped to disconfirm incorrect prior ideas about the role of the total number of molecules or total atoms in balancing chemical equations [6].

However, a limitation of the balance scales is that an emphasis on balancing individual atoms can encourage balancing practices that focus on each element in isolation. When relying primarily on the balance scales, students may not be looking at the bigger picture - which elements are connected together in molecules, or relationships between molecules in the equation as a whole. The balance scales seemed to provide a useful stepping stone to the basics of balancing, but further development was needed as more challenging equations were faced. In this study, once students moved onto the larger pool of equations Balancing Game, where the balance scales were unavailable, students developed more expert practices and transitioned beyond their earlier elements-in-isolation focus.

Conclusions

Our analysis of students engaged in a guided-inquiry activity around the PhET *Balancing Chemical Equations* simulation suggests that students leveraged multiple representations in developing their balancing practices. Students who seemed to have little or no prior background in balancing chemical equations seemed to particularly benefit from the use of concurrent symbolic and molecular-scale pictorial representations, as well as the less traditional balance scale representation. The balance scale representation seemed to support student understanding of the basic goals of balancing chemical equations, *i.e.*, that an equation is balanced when the atoms of each element are equal. For these students, further development of practice was needed to move beyond a focus on individual atom types towards a more holistic perspective of the chemical equation.

References

1. Nyachwaya, J.M.; Warfa, A.-R.M.; Roehrig, G.H.; Schneider, J.L. "College chemistry students' use of memorized algorithms in chemical reactions." *Chem. Educ. Res. Pract.* **2014**, *15*, 81-93.
2. *See, for example,* (a) Porter, S. "How should equation balancing be taught?" *J. Chem. Educ.* **1985**, *62*, 507-508. (b) Tóth, Z. "Balancing Chemical Equations by Inspection." *J. Chem. Educ.* **1997**, *74*(11), 1363-1364. (c) Hutchings, L.; Peterson, L; Almasude, A. "Pre-matrix balancing of challenging chemical equations with a simple formula register and middle school arithmetic." *J. Math. Sci. Collab. Explor.* **2007**, *9*, 119–133.
3. Niaz, M.; Lawson, A.E. "Balancing chemical equations: The role of developmental level and mental capacity." *J. Res. Sci. Teach.* **1985**, *22*, 41–51.
4. Staver, J.R.; Jacks. T. "The influence of cognitive reasoning level, cognitive restructuring ability, disembedding ability, working memory capacity, and prior knowledge on students' performance on balancing equations by inspection." *J. Res. Sci. Teach.* **1988**, *25*, 763–775.
5. A revised version of the activity is available for download at http://phet.colorado.edu/en/contributions/view/3955. The simulation is available online at http://phet.colorado.edu/en/simulation/balancing-chemical-equations.
6. AAAS Project 2061 Science Assessment Items. http://assessment.aaas.org/