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Tools for high-tech tool use: A framework and heuristics for using interactive simulations

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Abstract: As the use of computer-based science simulations in educational environments grows, so too does the need for research on productive use of simulations. This paper presents ways to create effective assignments that accompany an interactive simulation in a variety of educational environments. A framework that supports the creation of assignments with simulations in any environment is provided, as well as a set of heuristics, or strategies, for how to create assignments based on the particular environment and simulation being used. Case studies are provided to illustrate implementation of the heuristics, and how the heuristics can be used to promote productive use of a simulation.

Keywords: assignment design, heuristics, physics, simulations, science, middle school, undergraduate

I. Introduction.

The use of computer technology in educational environments is now widespread and continues to grow. Classrooms throughout the country, in both K-12 and college settings, are currently using computers as an educational tool. As such, teachers are now confronted with the question of how to use this tool productively to educate students.

In science education, a common use of computers in the classroom is to run science simulations (National Research Council, 2011). There are a variety of educational science simulations available for use, and each has a unique set of features that allow users to interact with the simulation interface and the scientific content illustrated by the simulation. For the purposes of this paper, we focus on a class of simulations referred to as *targeted simulations* (Clark, Nelson, Sengupta, & D'Angleo, 2009).

Targeted simulations are stand-alone simulations designed to cover a particular topic in a scientific discipline. For instance, a single targeted simulation may cover gravitational forces in physics; another simulation may cover acids and bases in chemistry. The amount of time needed to learn how to use a targeted simulation is minimal, as the controls are designed to be intuitive and easily manipulated. Examples of targeted simulations include PhET ("PhET," 2012a), Physlets (Christian, n.d.) and TEAL ("TEAL," 1999) simulations. It is useful to separate targeted simulations from simulations that allow users to modify the code of the simulation itself, such as NetLogo (Wilensky, 1999) and StarLogo ("StarLogo," 2008).

Historically, research on student use of targeted simulations has been conducted in interview settings (Adams et al., 2008; Adams, Paulson, & Wieman, 2008; Podolefsky, Perkins, & Adams, 2010), small classrooms (Keller, Finkelstein, Perkins, & Pollock, 2005; Podolefsky, Rehn, & Perkins, 2013), and large classrooms (Finkelstein et al., 2005; Moore, Herzog, & Perkins, 2012). Research of student use in interview settings can allow for fine-grained analysis of students' actions, point out common ways that students use the simulations, reveal any bugs in

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the simulation, and provide a measure of how engaging the simulation is by itself. Classroom studies can allow for pre-test/post-test test comparisons with a larger sample size for statistical analysis. On one hand, the interviews provide moment-to-moment analysis of how students use a simulation; on the other, the overall effect of a simulation on classroom learning gains can be investigated. However, interviews do not provide a direct view of how students use a simulation in classrooms, and findings of learning gains from classroom studies do not necessarily reflect how much a student could learn from a simulation in an interview setting.

Embedding a simulation into an educational environment different from an interview setting changes many variables that can influence simulation use. For example, in a classroom setting, students might talk to one another about the simulation. Such an action clearly cannot be accounted for in interview settings with only a single student present. Factors such as students sitting in groups or individually, the number of students per computer, the time allotted to the activity, and so on, will influence how students use a simulation.

In this paper, we take the view that in any educational environment, there exist a multitude of variables that influence how students use a simulation, and ultimately, how this educational tool impacts student learning. As educators, our goal is to facilitate productive use of a simulation. In order to do this, we first need to define productive use of a simulation. However, due to the variety of contexts in which simulations are used, and the number of teachers with different goals and standards for their students, we intentionally allow for some ambiguity in our definition of 'productive use'; what a 5th grade teacher considers productive use of a simulation may be different from what a college instructor considers productive use. In the case studies below, we provide contextualized examples of productive use in two different environments. For now, a brief definition can provide some insight into what we mean, in general, by productive simulation use:

> *Productive use of a simulation occurs when students use the simulation as a tool to engage with the underlying physical principles that govern the simulation's behavior.*

In creating an educational context that supports productive simulation use for students, the design of an assignment that accompanies the simulation stands out as particularly important. Not only does the assignment influence and structure students' use of the simulation, but also is one aspect that an instructor can directly control. Writing an assignment to accompany a simulation can be a challenging task, as the assignment must be written for the particular context in which it will be used. To illustrate the interrelations between the context and assignment design, we first describe a framework that includes context elements and how each can affect simulation use.

We then present a set of *heuristics* – research-based strategies for assignment development. These heuristics are intended to provide insight into how assignments can be written, and in doing so, can help frame the ways we can think about writing assignments in a given context. Of course, which heuristics to implement will vary depending on the particular class of students, e.g., the topic being covered and the amount of teacher guidance desired during the activity.

The reason for presenting both a framework and a set of heuristics is to provide an actionable set of tools that can directly aid in assignment creation. A framework alone provides an overarching view of how different components of an educational context fit together, but does not provide direct strategies for integrating the components. At the same time, heuristics can provide actionable strategies, but do not provide an overarching view of the context or where they fit in relation to different components. By using both a framework and a set of heuristics, we can provide both an overarching view of the context and actionable strategies for integrating the components of a context.

In the second half of the paper, we provide two case studies that investigate simulation use in two radically different environments. The first case study involves the use of a quantum tunneling tutorial in a college-level modern physics (sophomore/junior level) classroom. In this case study, the tutorial used was not designed with the heuristics in mind, and the assignment did not promote productive use of the simulation in that context. The results of the study, however, provided insights into what heuristics might be implemented in the next design of an assignment using the same simulation. In the second case study, we discuss the use of a molecule-building simulation in a middle school science classroom. In this case study, the assignment utilized several heuristics, and students engaged in productive use of the simulation. The second study demonstrates the effective application of the heuristics, their applicability to a wide range of environments, and highlights approaches that span from middle school to college.

II. Framework for Simulation Use in Educational Settings.

In an educational context where a simulation is used with an assignment, we identify three elements that influence how students use the simulation. These three elements are: the Simulation, the Assignment, and the Environment. One could consider the simulation and assignment as a part of the Environment, but for the purposes of this paper, we separate out Environment to refer to anything other than the Simulation or Assignment. A more detailed definition of Environment is given later in this section.[2]

The three elements together should support students in productive use of the simulation. The following framework shows the interrelations among these elements and how they affect student use of the simulation. Note that we draw from work on mediated cognition (Vygotsky & Cole, 1978; Cole, 1996) and situated cognition (Lave & Wenger, 1991; Hutchins, 1995) in the creation of this framework. This framework consists of a ‘situation’ level of context that brings students into coordination with the simulation, assignment, and environment (Dewey, 1938; Cole, 1996; Finkelstein, 2005). Also note that, while no teacher is present in this framework, we do acknowledge the importance of the teacher and his or her influence on the educational context. The teacher can have direct control over, and/or interaction with, each of the elements in the framework.

In Figure 1, the elements with arrows pointing directly towards the ‘Student use of simulation’ element indicate that that element can directly influence how students use the simulation. The outer arrows indicate influences among the elements. For example, the Simulation and Environment both influence how the assignment is created. Additionally, these arrows contain the word ‘Heuristics’ to indicate where the heuristics included in this work can be used. With this general picture in mind, we now elaborate on the details of each of the elements and their interrelations.

[2] To be consistent with notation, we capitalize words that refer to an element of the framework itself. For example, in referring to the Assignment, we are really referring to the element of the framework labeled “Assignment”. When referring to an assignment (not capitalized), we are referring to an actual, real-world assignment, not the framework element Assignment.

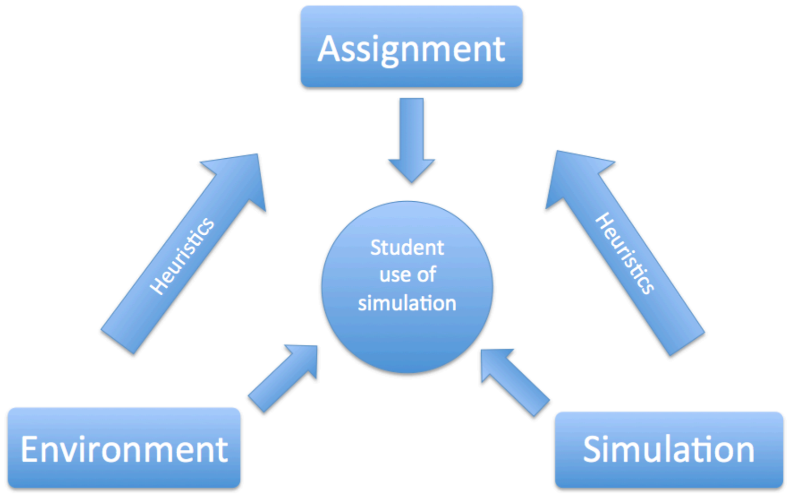

Figure 1: Framework for analyzing student use of an assignment and simulation within a context. Heuristics are implemented in the arrows shown.

From the Simulation element, an arrow points towards the 'Student use of simulation' element, indicating that the simulation itself influences student simulation use. A 'Heuristics' arrow points from the Simulation element towards the Assignment element, indicating that the development of the assignment depends on the simulation. Therefore, based on the features of the simulation, heuristics can be chosen to aid in the development of the assignment.

From the Environment element, an arrow points toward the 'Student use of simulation' element, indicating that the environment influences student simulation use. A 'Heuristics' arrow extends from the Environment element towards the Assignment element, indicating that the development of the assignment depends on the environment. Therefore, based on the specifics of the environment, heuristics can be chosen to aid in the development of the assignment.

We consider four components that characterize essential elements of the environment that shape (and are shaped by) students' use of the simulations in guided lessons. Note that, although the Simulation and Assignment may be considered a part of the educational environment, we keep these as separate from the environment strictly for utility. The entire framework together constitutes an educational 'context', while the environment is an element of that context, which we categorize as:

1. **Other students**: For any particular student using the simulation, other students serve as resources within that environment.
2. **Material resources**: Resources students might use during the course of the activity, e.g., pencils, physical (toy) models, and information written on chalkboards.
3. **Environmental organization**: Organization of resources in the room, e.g., where students are in relation to each other and the location of any material resources, such as the computers or smart board.
4. **Environment norms**: Typical behaviors and/or habits established in environments that influence student behavior during the activity, e.g., teacher expectations, and common actions or behaviors of the student.

From the Assignment element, an arrow points towards the 'Student use of simulation' element, indicating that the assignment influences student simulation use.

This framework provides a view of the learning context in which a simulation is used, allowing us to see areas in which interrelationships exist. These interrelationships allow us to see where the heuristics for assignment development can be useful. We now present the heuristics and examples of their implementation.

III. Heuristics.

Through case studies conducted in a variety of learning contexts and a review of relevant literature on simulation use, we constructed a set of six heuristics that can be useful when developing assignments for use with a targeted simulation. We do not consider this list of heuristics to be exhaustive; additional studies may help to expand and/or refine the current set.

> Heuristic 1. Use the simulation to ***coordinate multiple forms of representation***.
> Scientists utilize a variety of methods to visualize, interpret and communicate about physical phenomena, e.g., formulas, graphs and diagrams. (Roth & Radford, 2011; Kohl & Finkelstein, 2008). With an understanding of the ways scientists coordinate representational formats, one can design an assignment that supports students in coordinating these different representational formats, and therefore aid in their understanding of a particular phenomenon. This can be implemented by specifically asking students to relate formulas or graphs to what is shown on the simulation, or build this more implicitly into the assignment by asking them to complete a task that requires them to coordinate multiple representations.
>
> Heuristic 2. Use the simulation to ***mediate discussion.***
> Conversation and discussion is crucial for students learning science (Smith et al., 2009). Simulations can help students to communicate with one another by providing a common visualization to refer to and build meaning upon (Otero, 2004). This heuristic can be implemented by building student-to-student dialogue into the assignment itself. One may provide prompts that encourage students to discuss features shown in the simulation, negotiate meaning, or find a common interpretation. Depending on the context, discussions mediated by the simulation may arise naturally. For example, if a teacher consistently encourages students to discuss with one another during classroom activities, students may discuss the simulation without additional prompting.
>
> Heuristic 3. Set up ***game-like situations*** and take advantage of ***explicit and implicit challenges.***
> Consistent with prior work on “play” (Rieber, 1996; Vygotsky, 1978) and “messing about” (Hawkins, 1974), utilizing challenges or games within the simulation can encourage students to investigating a particular phenomenon. This heuristic can be implemented by writing challenges into the assignment itself, or by allowing students freedom to interact with a game-like situation or challenge built into the simulation itself.

Heuristic 4. Focus on ***illuminating cases.***
Scientists often talk about investigating limiting cases when exploring a problem; e.g. investigating the behavior of a system after a short or long period of time or at distances short or far away. Scientists may also refer to touchstone problems (Redish, 2003; Kuhn, 1962) that give outstanding insight into a particular concept. Simulations can often illustrate (or animate) what happens in certain interesting cases. This heuristic can be implemented by using prompts that encourage students to make use of interesting cases in the simulation, e.g., "What happens when friction is turned off?" or "What happens if the initial velocity of the object is infinitely high?"

Heuristic 5. Ask students to ***re-create or re-present features*** on the simulation.
The act of writing or drawing representations in the simulation can help students make sense of and internalize what the simulation shows. This heuristic can be implemented by prompting students to re-present features of the simulation on their own paper. Such prompts will allow them extra time to study what is shown, and possibly realize features that would have otherwise been missed.

Heuristic 6. Use ***"Predict, Observe, Explain"*** methods.
The "Predict, Observe, Explain" style of inquiry is found in studies done by the University of Washington (Shaffer & McDermott, 1991), and has been discussed in both theory and classroom studies (White & Gunstone, 1992; Mintzes, Wandersee, & Novak, 2005; Kearney, 2004). This heuristic can be implemented by starting a section of an activity with a prediction prompt. The prompt might describe a scenario in the simulation and ask students to think about what will happen when they observe or interact with the simulation in a particular way. Following this, students observe the scenario (run or use the simulation), and are then prompted to explain what they saw and/or resolve any differences between their predictions and observations.

IV. Application of Framework and Heuristics.

In the following two sections, we describe the implementation of the framework and heuristics in designing and analyzing two assignments in two radically different environments. The first of these is the use of a quantum tunneling assignment in a college-level modern physics course and the second is the use of a molecule-building assignment in a middle school class. The quantum tunneling assignment involves advanced physics concepts, which we describe briefly below, while the molecule-building assignment involves foundational concepts, including the meaning of coefficients and subscripts in chemical formulas. Although the content is very different in these two studies, the heuristics are applicable in both situations.

Both studies support the utility of the heuristics, though for different reasons. The quantum tunneling study involved the use of two different assignments, one with a simulation (the *sim-assignment*) and one without a simulation (the *no-sim-assignment*). In this case, the *sim-assignment* was *ineffective* in supporting productive student use of the simulation. In contrast, student engagement with the topic in the *no-sim-assignment* showed aspects of the productive student discussions and sense making that we would hope for from a *sim-assignment*. The productive aspects of the *no-sim-assignment* were used to gain insight into the heuristics that could be implemented in an updated version of the *sim-assignment*. Use of the updated *sim-assignment* was observed to support productive student use of the simulation. The molecule-building assignment supported productive student use of the simulation. Reasons for this can be understood through analysis of the heuristics present in the assignment. While the molecule-building assignment was used in a middle school classroom, a similar implementation process can be followed in a college level classroom. Student difficulties with chemistry content – specifically, molecular formulae – have been well documented at the college level (Davidowitz, Chittleborough, & Murray, 2010; Sanger, 2005), and our findings therefore likely apply to college level chemistry courses.

Both studies use simulations developed by the PhET Interactive Simulations project ("PhET," 2012a). These targeted simulations are research-based, and specifically designed to be intuitive, easy to use, and to focus on specific science concepts (Finkelstein, Adams, Keller, Perkins, & Wieman, 2006). While the following studies strictly use PhET simulations, the heuristics implemented are applicable for assignments involving other targeted simulations.

V. Case Study: Quantum Tunneling.

Here we provide an example of the use of the heuristics and their relationship to the accompanying framework in the context of an hour-long quantum tunneling tutorial. This tutorial was offered in a lower-division modern physics course at a large state research university. This course was designed for sophomore or junior-level engineering students who have a strong background in basic mechanics, electricity, and magnetism, but who may not have studied quantum mechanics in a previous course.

During participation in the reformation of a similar course, the PhET Interactive Simulations project at the University of Colorado designed the *Quantum Tunneling and Wave Packets* simulation ("PhET," 2012b) to illustrate the nature of tunneling (McKagan et al., 2008). In this study, a subset of students (11 out of approximately 150 enrolled students) volunteered to participate in an hour-long tutorial outside of the regular class time. This tutorial was held in one afternoon, in a small classroom. Students worked on the assignment in groups of two to three.

We begin by giving a brief overview of the topic of quantum tunneling. This section provides the minimum amount of background necessary for understanding the design of the assignment and simulation, and can be skipped for those already familiar with the conceptual foundations of quantum tunneling. We then describe the study by elaborating on each element in the framework presented in Section II: the simulation used, the students' environment, and the assignments. Finally, we analyze issues with the assignments, and conclude with a discussion of why the *sim-assignment* failed and how the heuristics were used to develop a new version of the assignment.

A. Tunneling Overview.

Here we summarize the content covered in the *sim-assignment* and *no-sim-assignment*. Further details on the assignment content can be found in Appendix 1. Both assignments explore the physical situation of an electron moving towards the end of a wire, separated from another wire a short distance *L* away, shown in Figure 2. In this case, the gap between the two wires serves as an energy barrier, so that the electron needs some energy to escape the left wire and move to the right wire.

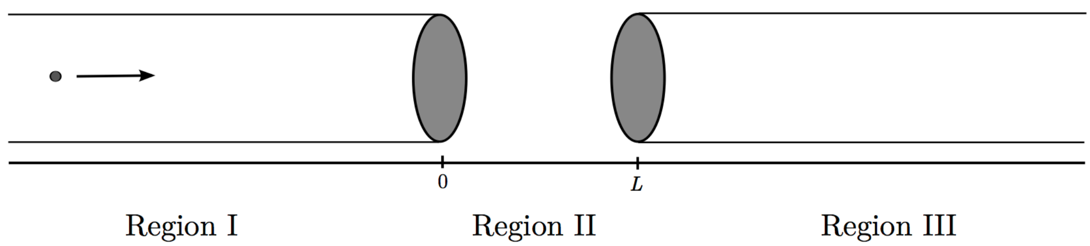

Figure 2: Schematic of an electron approaching the end of a wire separated a distance L from another wire.

The energy barrier between the wires can be represented with a plot of energy vs. distance, shown in Figure 3. Additionally, the total energy of the electron can be plotted on the same graph. For the purposes of the assignment, we focused on two cases, one where the electron has more energy than the gap (shown in green) and one where the electron has less energy than the gap (shown in red).

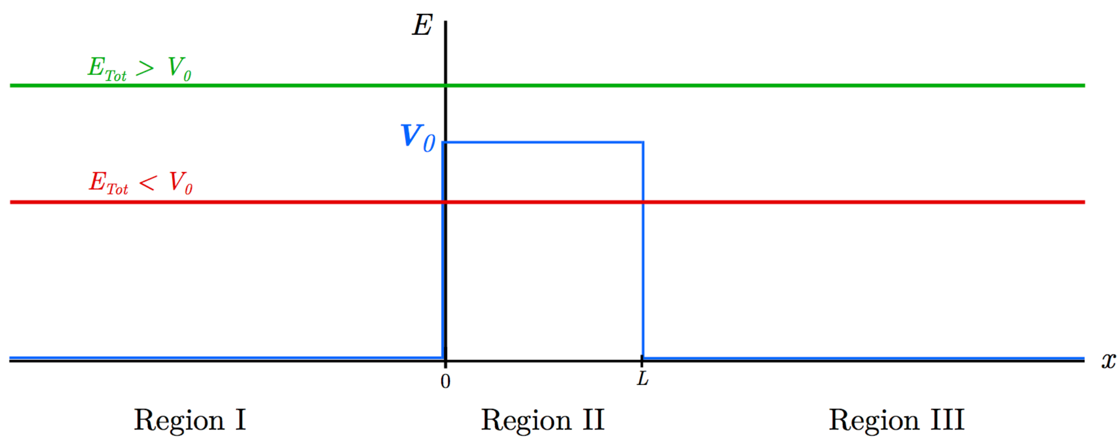

Figure 3: Quantum potential barrier, representing the potential energy, V_0, inside the wire gap.

An analogous example in classical mechanics is a ball rolling up a ramp with some total energy. In this case, if the total energy of the ball is greater than the energy of the barrier, the ball will roll over the ramp. On the other hand, if the total energy of the ball is less than the energy of the barrier, the ball will roll back down the ramp, returning to the side it came from. This situation is depicted in Figure 4.

Unlike the intuitive behavior of the ball rolling up a ramp, the electron's behavior is more complicated, due to the wave-like nature of quantum particles. Instead of behaving as a classical particle, the electron is spread out as a wave. Because it acts as a wave, some of its 'wave function' is reflected off the barrier and some of it is transmitted through the barrier. Thus, unlike the case of a classical particle with less energy than the barrier, the electron with less energy than the barrier still has a probability of making it through to the other side. Classically, this is like a ball passing through the ramp itself and continuing to travel on the other side, hence it is called 'tunneling.'

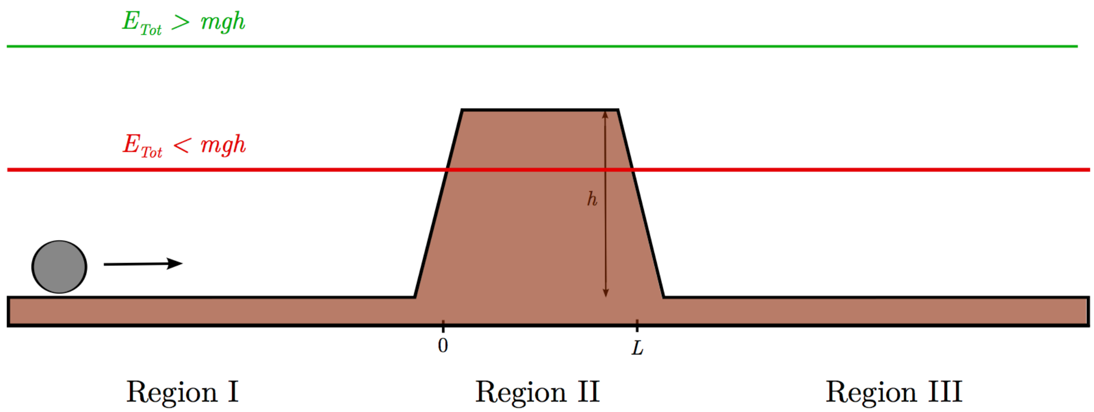

Figure 4: Classical energy barrier for a ball rolling over a frictionless ramp.

B. Simulation.

The simulation used in the *sim-assignment* contains three plots, shown in Figure 5. The top plot shows the potential barrier provided by the wires and total energy of the electron, similar to Figure 3. The middle plot shows a graph of the wave function, along with its time-dependence as it oscillates and moves towards the barrier. The bottom plot is a graph of the 'probability density', which is a measure of how likely the electron is to be found in each of the three regions. On the right-hand side, various parameters can be adjusted to change or illustrate different properties of the wave function.

Note that students can adjust the energy values on the top plot and see, in real time, how their actions affect the values of the wave function and probability density in the plots below. Other than the zoom-in/zoom-out buttons, the middle and bottom plots do not have any adjustable controls; therefore, the only way to change the wave function or probability density is to change the energy values on the top plot. This is a unique and important feature of the simulation, as it provides a productive constraint to what students can do with the simulation, and suggests how some of the heuristics might be implemented. For example, a challenge prompt for this assignment might be, "How do you make the wave function go to zero on the right side of the potential barrier?"

C. Environment.

The students' environment during the tutorial can be characterized using the four criteria listed in Section II. Below, we provide a brief description of each.

1. **Other students**: Eleven students participated in this study, including 10 male students and 1 female student. The activity was voluntary; students were offered pizza as a benefit for participating. The students received lectures on quantum tunneling previously in class and had worked on a homework set concerning quantum tunneling, though they had not worked on a tutorial covering the subject. During the tutorial, students demonstrated some familiarity with the subject, though none showed clear mastery. Students also showed some familiarity with each other, and did not appear hesitant to talk to each other. Nonetheless, four students did not speak frequently during the activity.

2. **Material resources**: Aside from the simulation, the teacher, and the assignment, students did not use any outside resources to complete the tutorial. A chalkboard was available, though it was not used.
3. **Environmental organization**: Two groups of three students used the *no-sim-assignment*. These students were situated at a large table, so that they functioned more as a single group of six. One group of two students and second group of three students used the *sim-assignment*. Each of these groups was given a laptop to access the simulation, and each group worked at a separate table. One of the students in the *sim-assignment* group of three frequently talked to the *sim-assignment* group of two, diminishing the distinction of two separate groups using the *sim-assignment*.
4. **Environment norms**: The students had likely taken introductory physics at the same university, where tutorials are commonly used. In the introductory physics environment, student groups are expected to put forth effort into understanding the material, to progress independently (without prompting from a teacher) and to ask questions of each other or the teacher when needed. These were the same expectations for the students who participated in this study.

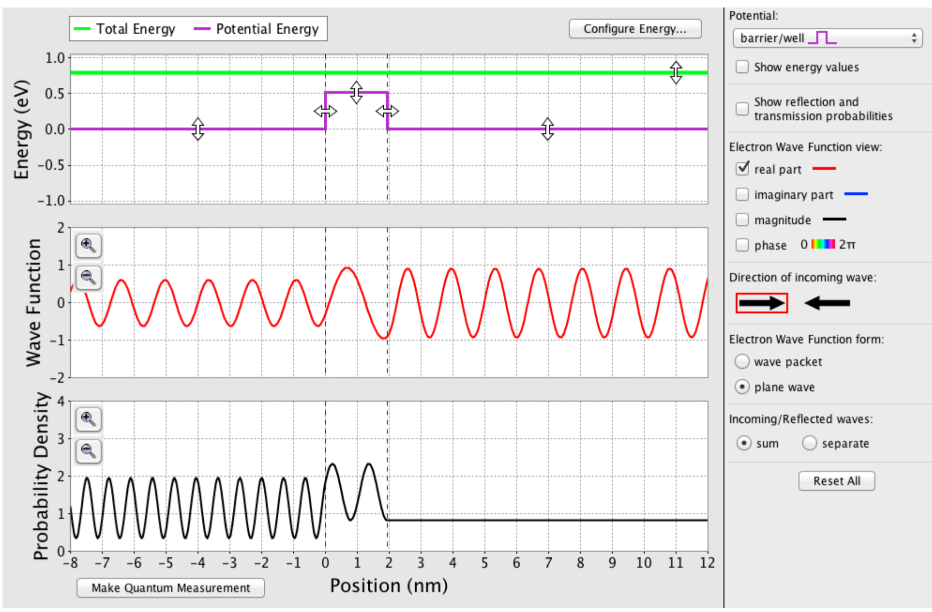

Figure 5: Interface of the *Quantum Tunneling and Wave Packets* PhET simulation.

The data collected in this study consists of audio recordings of the *sim-assignment* groups and the *no-sim-assignment* groups. Two audio recorders were used, one for *sim-assignment* groups and one for the *no-sim-assignment* groups. In total, three voices were present in the *sim-assignment* group's recording, while four voices were present in the *no-sim-assignment* group's recording. The remaining students (two from each recording) did not talk loudly enough to be heard. Additionally, field notes were taken.

D. Assignments.

In addressing this quantum phenomenon, the *sim-assignment* and *no-sim-assignment* followed the same basic structure. Each assignment starts with the same introduction in which students are asked to answer questions about a ball rolling up a ramp. Specifically, the assignments ask about the probabilities of the ball being found in regions 1, 2, or 3 separately with energy $E < V_0$ and energy $E > V_0$ (see Figure 4). After this, the assignments diverge in the types of questions asked, with the *sim-assignment* introducing the use the PhET simulation. Both assignments cover content in the following order: the case of the electron with $E > V_0$, followed by the electron with energy $E < V_0$. The full assignments can be found in Appendix 1.

E. Issues with the assignment: Discourse.

Student engagement with the topic of quantum tunneling differed significantly with the two assignments. Students using the *no-sim-assignment* explored the underlying physical principles of quantum tunneling in greater depth than those using the *sim-assignment*. In retrospect, it is clear that the heuristics were not implemented in the *sim-assignment*, while some of the heuristics were implemented in the *no-sim-assignment*. Based on the findings from these assignments, we created an updated *sim-assignment* that was more effective in supporting productive student use of the simulation.

Students using the *sim-assignment* engaged in less conversation, asked fewer questions of each other, and the questions they did ask were not as focused on conceptual understanding as were the questions asked by students using the *no-sim-assignment*. In total, the three students using the *sim-assignment* raised 27 questions, while the four students using the *no-sim-assignment* raised 90 questions. The types of questions asked by the students using the *no-sim-assignment* were strongly centered on the underlying physical principles of quantum tunneling. The types of questions asked by the students using the *sim-assignment* were strongly centered on what the simulation interface was showing, without emphasis on the underlying physical principles.

One example of the differences in student questions can be seen by comparing student discourse during the '$E < V_0$' section of both assignments. Students were asked what the probability of finding the ball in each region of its path is (see Figure 4). This was done partly to show that the quantum and classical cases of $E > V_0$ are roughly the same; that is, when the ball or electron wave function is located in the potential barrier, they move more 'slowly' and the probability of finding either one in that region is, on average, greater than in the other two regions separately.

However, this analogy breaks down in the case of $E < V_0$, since the classical ball can never be located in regions 2 or 3, whereas the quantum particle can be found in those regions. Both assignments address this point, but the ensuing discussion in the *no-sim-assignment* group was markedly different than that of students in the *sim-assignment* group. The *no-sim-assignment* group was asked to sketch what the wave function of the electron would look like in all three regions, while the *sim-assignment* group was asked to discuss the wave function they saw in the PhET simulation. When the *no-sim-assignment* group attempted to graph the wave function on their assignments, the following discussion arose:

> **S1**: "The reasoning we used before, at least I did, was that because the velocities were slower in the [potential barrier], then it had a higher probability of being found there. So if they're equal, they should have an equal probability and their amplitudes should be equal, right?"

> **S2**: "Right, well that makes sense in terms of equations, but like he said, I'm not sure you can think of it in a classical way, like ½ mv^2."
> **S1**: "I know, I know that [lower amplitude in region 3] is what it should be, but I want to be able to prove it to myself."

This type of reasoning is what we hoped students would engage in when trying to sketch the wave function. They knew from previous instruction that the wave function in region 3 should be lower than in the other two regions, but they struggled to prove to themselves why. In contrast, the students using the *sim-assignment* showed no similar reasoning. Instead of being asked to draw a wave function, the question on the assignment was: "What type of function do you see in region 1 and 3?" When answering this in reference to the wave function in region 3, they said:

> **S3**: "That one is still sine right? Like if you decrease it is it still sine or is it always zero?"
> **S4**: "Well this is technically still a sine wave."

These questions, which were strictly about what was shown on the simulation and not about the underlying physical principles that describe the simulation's behavior, are representative of nearly all questions that the *sim-assignment* students asked during the tutorial. It was clear from an analysis of both the field notes taken during the tutorial and a transcription of the audio recordings that the students using the *sim-assignment* were less engaged in exploring the underlying physical principles of quantum tunneling than the students using the *no-sim-assignment*.

F. Issues with the assignment: Guidance.

Another issue with the *sim-assignment* was the use of overly guiding questions. An example of this occurs in the part of the assignment dealing with $E > V_0$:

> Now widen the width of the wire gap (where $V>0$) to 3.5 dashed lines wide. How does the wavelength of the wave function in this region compare to the wavelength in the region to the left?

Asking overly guiding questions led to several negative effects. First, it prevented students from exploring the simulation. In observing students, there was little open-ended exploration of the simulation and instead, their use of the simulation generally consisted of reading the assignment, setting up the simulation in a particular way, and then leaving it until the next question prompted them to change another parameter. Overall, this indicated that there was little 'engaged exploration' while using the simulation, which is a crucial element of productive investigation of the physical principles embedded within the simulation itself (Adams, Paulson, & Wieman, 2008; Podolefsky, Perkins, & Adams, 2010). Second, the overly guiding questions caused students to wait for the tutorial to provide instructions on what to do next. Often, the term 'cookbook' is attributed to assignments that tend to focus on task completion, rather than on conceptual development (Singer, Hilton, & Schweingruber, 2005). Third, the overly guiding questions in the *sim-assignment* limited student conversations. Since the tutorial told the students how to set up the simulation, there was no discussion about how the simulation could or should be used. This prevented conversations from occurring about what the underlying physical concepts were and how the representations of these concepts in the simulation could or should be used to respond to the assignment prompts.

G. Relationship to heuristics and framework.

The failures of the *sim-assignment* can be understood by noting that there was a misalignment between the design of the assignment and the framework outlined in this work – the development of the Assignment had not been effectively influenced by the design of the Simulation. The overall result was that the assignment did not effectively support students in productive simulation use. To develop an improved *sim-assignment*, we would first explore the simulation, and based on properties of the simulation, choose certain heuristics to implement in writing the assignment.

On the other hand, the *no-sim-assignment* showed indications of success in promoting productive engagement with the quantum tunneling topic. Present in the *no-sim-assignment* are Heuristic 1 and the 'Predict' component of Heuristic 6. The *no-sim-assignment* asked students to coordinate the mathematical solutions of the electron's wave function in each of the three regions with a graph of the solution that they had to generate on their own. Had the *sim-assignment* used the simulation as a tool for observing the actual solution to the Schrödinger equation, and then explaining the differences between the actual solution and their predicted graphs, more conceptual discussion of the nature of tunneling might have occurred.

In retrospect, it is easy to see where the design of the *sim-assignment* went wrong. Asking students to set up the simulation in specific ways and answer questions about what they saw was an attempt to help them make connections between what was shown on the simulation and the underlying physical principles of quantum tunneling. However, because this particular simulation is a graphical representation of the mathematics involved in representing tunneling, asking students only about what they saw, rather than what the graphical representations mean, cued students to discuss only the mathematics rather than the underlying physical principles. Thus, it is clear that this assignment did utilize the features of the simulation in a useful way.

A strategy for designing an improved version of the *sim-assignment* could be:

1. Write out what productive use of the simulation could be in this environment. In this case, productive use occurred when students were investigating the physical principles that determine the simulation's mathematic representations.
2. Write out a list of the features of the simulation:
   a. Dynamic plots of mathematical solutions to the Schrodinger equation
   b. Adjustable parameters of potential height, potential width, etc.
3. Consider the environment students are to be situated in:
   a. Groups of 2-3 at tables
   b. Students sharing a computer
   c. One instructor present in classroom
4. Based on 2 and 3, choose certain heuristics to implement in writing the assignment:
   a. Understanding the features of the simulation requires some knowledge of the solutions to Schrodinger's equation in the three regions. Therefore, Heuristic 1 (Use the simulation to ***coordinate multiple forms of representation***) could have been used.

b. Students work in groups, so Heuristic 2 (Use the simulation to ***mediate discussion)*** can also be used. Students could be prompted by the assignment to "Discuss what is shown on the simulation" and to "Work together to generate a plot of the wave function."
c. There are particular scenarios in the simulation that are challenge-like, so Heuristic 3 (Set up ***game-like situations*** and take advantage of ***explicit and implicit challenges)*** could be used. One challenge could be "Find a potential width for which the wave is completely transmitted".
d. Heuristic 6 (Use ***"Predict, Observe, Explain"*** methods) can be used in a way similar to the *no-sim-assignment*. The updated *sim-assignment* could start by asking students to "Draw a wave function (a prediction phase), look at what the solution actually is on the simulation (observation phase), and explain the differences between their plots and the simulation (explain phase)." This will likely result in promoting discussion around the simulation itself – Heuristic 2.

These strategies, including use of the heuristics, have now been implemented in an updated quantum tunneling tutorial that uses the simulation for an upper-division quantum mechanics course, instead of a lower-division modern physics course. The full updated assignment and a general outline of how the assignment was written can be found in Appendix 1.

While the findings from an initial trial are not presented in detail in this paper, observations of use of the updated assignment indicate that the implementation of the heuristics led to the intended types of productive simulation use. An analysis of screen capture and audio files of the use of the updated assignment indicated that students were engaged with the simulation and that their discussions were concerned primarily with investigating the underlying physical principles of the simulation itself. Often, students found that their prediction of the wave function was in disagreement with the simulation, and turned to the mathematics involved to clarify discrepancies. Additionally, the screen capture files indicate that the challenges built into the simulation led students to interact with the simulation in an exploratory manner, e.g., adjusting the potential barrier and width, in order to find the cases of maximum transmission, reflection that were asked about in the assignment.

VI. Case Study: Build a Molecule.

In this case study, we present the use of an assignment that employs three heuristics and is aligned with the elements of the provided framework. The assignment was developed by a middle school teacher, in collaboration with a researcher from the PhET Interactive Simulations project, for use in a middle school classroom. The assignment design contributed to a set of assignment guidelines (Adams et al., 2008) and strategies that the teacher and PhET researchers found useful when creating assignments of this type (Perkins, Moore, Podolefsky, Lancaster, & Denison, 2011). Although the activity was not specifically designed with the heuristics in mind, the heuristics and framework can be used to understand the effectiveness of the assignment. Furthermore, this assignment addresses content that spans a wide range of audiences, including college students who struggle with understanding molecular formulae (Davidowitz, Chittleborough, & Murray, 2010; Sanger, 2005).

The assignment utilized the *Build a Molecule* PhET simulation ("PhET," 2012c) in three 5^{th} grade classrooms, each with approximately 20 students. The goals of the assignment were for students to distinguish atoms from molecules, to determine the meaning of coefficients and subscripts in chemical formulas, and to coordinate across pictorial and symbolic molecule representations (e.g., 2D and 3D pictorial representations and chemical formulas). The simulation had been designed to address these specific learning goals.

First, we present an overview of the context, including details on the simulation, environment, and assignment as in the framework in Section II. The assignment section also describes how the heuristics are embedded within the activity. We then present an analysis of student use of the simulation, highlighting how the activity promoted productive student use of the simulation.

A. Simulation.

The *Build a Molecule* simulation provides an intuitive interface on which users can drag atoms from buckets and connect the atoms to build molecules. The simulation has three tabs that students can explore, starting with the "Make Molecules" tab, where the simulation design focuses student interaction on the building and collecting of single molecules, e.g., N_2. In the "Collect Multiple" tab, simulation design focuses student interaction on building and collecting multiple molecules, e.g., $2SO_4$. The, "Larger Molecules" tab provides an open play area, where students are encouraged to build larger molecules and to create their own challenges (e.g., to create the largest molecule they can) by being given many atoms and a large space to build within.

The "Build Molecules" and "Collect Multiple" tabs of the simulation provide 'goal' molecule boxes on the right-hand side. When a student builds a molecule listed as a 'goal', an outline appears around the corresponding 'goal' box. Students can then drag the molecule they built into the 'goal' box, collecting that molecule. The 'goal' boxes provide encouragement for students to make sense of the molecule formulas. Students must correctly interpret the letters and subscripts in the molecule formulas to build the molecules listed in the 'goal' boxes.

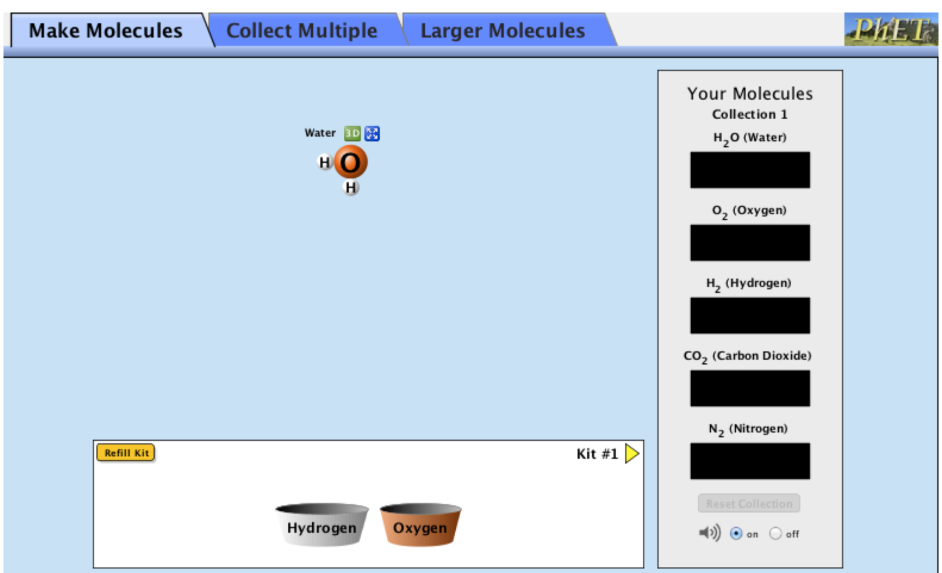

Figure 6: Interface of the *Build a Molecule* PhET simulation. Goal boxes are located on the right. Atoms are dragged from the buckets at the bottom onto the play area above.

B. Environment.

The students' environment during this activity can be described by defining each of the four characteristics listed in Section II:

1. **Other students**: Each student had a laptop and was encouraged to work with their neighbor to complete the assignment. Throughout the activity, students talked to their neighbors about the simulation and how to accomplish the challenges in the assignment (which corresponded to the 'goals' designed into the simulation). Additionally, the teacher facilitated the pacing of the assignment, asking students to complete the first few assignment prompts using the "Make Molecules" tab, then prompted students to move onto the next assignment prompts using the "Collect Multiple" tab, etc. The teacher sometimes called students to the Smart Board to demonstrate and explain to the class how they completed a goal in the simulation. This was often followed by a brief class discussion.
2. **Material resources**: Other than the simulation and assignment, the Smart Board is the primary resource students interacted with.
3. **Environmental organization**: Students were situated in groups of four to five. Everyone in the room was able to see the Smart Board.
4. **Environment Norms**: Students were familiar with using simulations and doing in-class activities similar to this one. The teacher generally requires that students pay attention when someone is talking at the Smart Board, and also makes sure that individual students are staying on task during the assignments. In general, students in the class follow these norms.

In addition, it is useful to point out that the teacher played an important role in facilitating the class in using the assignment and simulation. Generally, the teacher paced the students through the assignment, indicating when to transition to the next assignment section and when to discuss the current section as a class. We do not describe in detail the 'facilitation' heuristics that the teacher used in this paper, however we acknowledge that her facilitation contributed significantly to the success of the assignment.

C. Assignment.

The assignment used with the simulation emphasized three primary learning goals, which students read aloud at the beginning of class:

1. Describe the difference between a chemical name and a chemical formula
2. Distinguish between subscripts and coefficients in a chemical formula, and understand what each means
3. Use pictorial representations of molecules to generate chemical formulas

In addressing these goals, the assignment contains three sections, each corresponding to a tab on the simulation. The 'Make Molecules' section of the assignment begins by asking students to build molecules and write down the names of the molecules they made. This provided an opportunity for students to explore the simulation, with minimal time spent writing. After this, the assignment asks students to fill out a table, shown in Figure 7.

While only two rows are shown in Figure 7, the assignment contains six rows, prompting students to analyze six different molecules. This question demonstrates use of Heuristic 1, 3, and 5. Heuristic 1 (Use the simulation to ***coordinate multiple forms of representation***) is present by prompting students to write the molecule name, formula, and draw a picture of each molecule they find. Heuristic 5 (Ask students to ***re-create or re-present features*** on the simulation) is implemented by asking students to draw and write the three different representations for each molecule. The implementation of Heuristic 3 (Set up ***game-like situations*** and take advantage of ***explicit and implicit challenges***) is implemented in a more indirect way than Heuristic 1 and 5. The question shown above does not present a game-like challenge, but the open structure of the question facilitates play with the simulation itself, which does have an implicit challenge built in. The simulation allows for students to build molecules, collect molecules, and to complete collections – resulting in student access more goal molecules. By asking students to write down the names, pictorial representations, and chemical formulas of individual molecules, the question encourages that they complete the implicit challenges designed into the simulation itself.

2. Molecule Names and Chemical Formulas:
   a. Compare the name and chemical formula for some molecules:

Molecule Name	Drawing	Chemical Formula

Figure 7: Question taken from the "Make Molecules" section of the *Build a Molecule* assignment.

While the "Make Molecules" tab contains chemical formulas with subscripts, the 'Collect Multiple' tab contains molecule formulas with coefficients and subscripts. In this section, students are building multiple molecules, and must distinguish between subscripts and coefficients for the first time. The assignment addresses the differences with the question shown in Figure 8.

3. Make Many
   a. Fill all the collection boxes and then complete the questions for each Goal.

Goal: $4H_2$	
Draw it!	
What does the big '4' in $4H_2$ mean?	
What does the little '2' in $4H_2$ mean?	

Figure 8: Question format for the 'Make Multiple' portion of the *Build a Molecule* assignment.

While only one question set is presented in Figure 8, the assignment contains four similar question sets, asking students to analyze three other chemical formulas in addition to $4H_2$. Like the question in the 'Make Molecules' section of the assignment, this question implements Heuristics 1, 3, and 5. Students must coordinate representations between the formula ($4H_2$), the pictorial representation of that formula, and then describe what the subscripts and coefficients mean. Again, they are asked to draw and write features of the simulation by drawing the molecules. In order to complete this prompt, they are encouraged to take advantage of the implicit challenge inherent in the simulation itself; by collecting the 'goal' molecules in the simulation students could ensure that they answered the assignment questions correctly.

D. Analysis of Student Use.

During each class, 4-6 students' computer screens were recorded using screen capture software, with audio recordings from the computer microphone. We present excerpts of one student's interactions with the simulation in the 'Collect Multiple' section of the assignment – representative of the types of interaction we observed students having. Pre-tests and post-tests were given to students to assess student learning from the simulation activity. Students performed at a much higher level on the post-test compared to the pre-test, and we present example scores, as well as example student responses on the two tests as indicators of the assignment's effectiveness.

During the 'Collect Multiple' section of the assignment, one student, who will be called George, showed clear productive use of the simulation. The 'Collect Multiple' tab on the assignment starts with $2CO_2$, $2O_2$, $4H_2$, and $2NH_3$ as 'goal' boxes. At this point, George had finished using the 'Make Molecules' tab of the simulation, showing competence in constructing individual molecules. Upon starting on the 'Collect Multiple' tab, George had quickly built an O_2 molecule, dragged it to the 'goal' box, and then moved on to building $2CO_2$. George had initial difficulty with this challenge, first creating C_2O_2, and then arranging the atoms in different configurations, shown in Figure 9. After spending 50 seconds on this challenge, George moved on to the other goal boxes, next building one H_2 molecule and one NH_3 molecule, dragging both to the 'goal' boxes within 30 seconds.

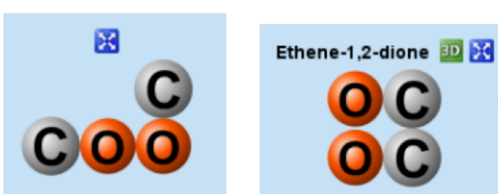

Figure 9: George's first and second attempts at building $2CO_2$.

Next, George went back to working on $2CO_2$, again creating a C_2O_2 variant – ethene-1,2,-dione, shown in Figure 9. George then began to play in what appeared to be a random way with the C and O atoms, and eventually created one CO_2 molecule and dragged it to the 'goal' box. However, George did not yet appear to understand the meaning of the coefficients at this point. Next, he built another CO_2 molecule and a molecule that looks similar to CO_2 right next to it, shown in Figure 10. However, instead of dragging the CO_2 molecule to the 'goal' box and completing the challenge, George created a yet larger molecule, C_2O_4 (also shown in Figure 10), and attempted to drag this to the $2CO_2$ box. After being rejected from moving this to the goal box, George said, "What!" with some frustration in his voice.

George continued to try to complete this goal box, but got stuck yet again when trying to build C_2O_4 in a different configuration, shown in Figure 11. Next, he separated this into two molecules that each resembles CO_2 (also shown in Figure 11), when a student sitting next to him, who will be called Jeff, made a suggestion for George.

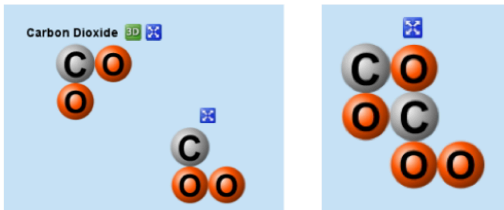

Figure 10: George's creation of C_2O_4.

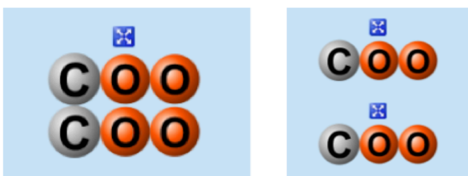

Figure 11: George's second attempt at C_2O_4 and the separation of this molecule.

George and Jeff's interaction proceeded as follows:

44:20 (*George drags C-O-O to the $2CO_2$ box, C-O-O is rejected*)
44:23 Jeff: No, cut this one [the right-side O atom] off. (*George cuts the carbon bond, thus leaving C and O-O. He then recombines them into C-O-O.*)
44:27 Jeff: No, cut this one [the O-O bond in C-O-O]. (*George cuts the O-O bond, leaving C-O, and attempts to drag C-O to the $2CO_2$ box)*
44:31 Jeff: No, put this one [the unbounded O atom] *there* [to the left of C in the C-O]
44:35 George: Oooohhhhh! (*builds O-C-O*, *the goal box lights up – indicating a molecule can be collected there. George drags CO_2 into the box.*)
44:44 George: Ooohh. Ok, I get it.

This interaction marked a turning point in George's interactions with the "Collect Multiple" tab of the simulation. After this interaction with Jeff, he appeared to understand the meaning of the coefficients of molecular formulae. Within 52 seconds, George completed all five of the remaining goal boxes without hesitation.

George's interaction with the simulation and with Jeff was approximately 8 minutes of productive use of the simulation in this part of the assignment. Heuristic 3 (Set up ***game-like situations*** and take advantage of ***explicit and implicit challenges***) led George to be able to interact with the challenge in the simulation, and this challenge helped to keep him on task so that he could eventually complete the $2CO_2$ goal box. Additionally, Heuristic 2 (Use the simulation to ***mediate discussion***) was present in Jeff and George's discussion about how to build CO_2. The advantages of Heuristic 1 (Use the simulation to ***coordinate multiple forms of***

representation) can also be seen in the simulation itself, and George eventually had to learn how to coordinate the molecular formula ($2CO_2$) with the pictorial representation of $2CO_2$.

George's interactions with the simulation were similar to other students' interactions during the assignment, and the effects of this can be seen in student performance on pre- and post-tests. The pre-tests and post-tests asked students to draw specific molecules. For most students, their drawings changed dramatically before using the simulation compared to after using the simulation. An example of a pre-test/post-test comparison for a student on one question of the test is shown in Figure 12.

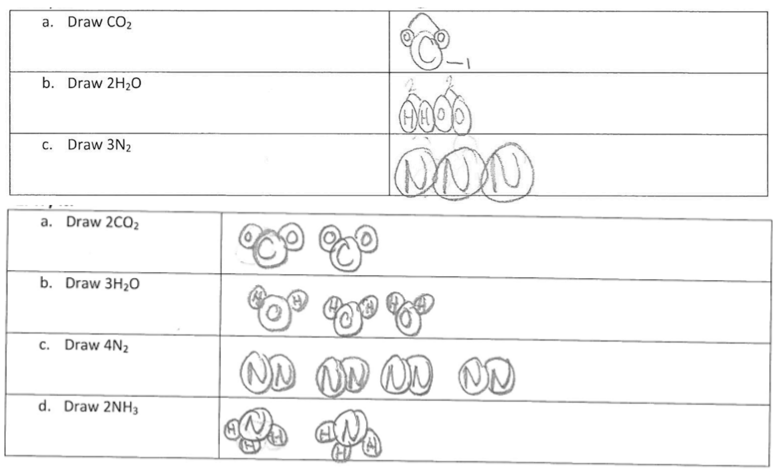

Figure 12: Example *Build a Molecule* activity pre-test (top) and post-test (bottom) results for one student.

Additionally, the overall pre-test/post-test results show high learning gains for students in the class. For example, students were asked to write the chemical formula of $4H_2$ from a picture of the molecule. No students answered correctly on the pre-test, while 63% of students answered correctly on the post-test. For a question asking students to draw $3N_2$ (on the pre-test) and $4N_2$ (on the post-test), 17% of students answered correctly on the pre-test while 78% of students answered correctly on the post-test.

This case study supports the utility of the heuristics in creating assignments to incorporate simulations. The success of this assignment can be interpreted in terms of its alignment with the framework in Section II. The assignment, the simulation, and the environment all worked together to lead to productive student use of the simulation, and this result was clear from the screen capture analysis of productive student interaction with the simulation and the pre-test/post-test comparisons. The heuristics supported this alignment of the different elements of the framework and allowed students to productively use the simulation supported by the assignment.

VII. Conclusion.

This paper presented a framework that highlights the contextual nature of writing assignments for the use of simulations. The goal of the framework is to provide a general picture for how to create assignments that help students productively use simulations. As a part of this framework, a set of heuristics was provided to help educators write assignments appropriate for their students' environments, using simulations.

This work extends technology education research by providing both a framework and a complementary set of heuristics. The framework gives an overall view of the interrelations of different context elements, while the heuristics provide actionable strategies for how to create assignments based on that context. By providing a framework and heuristics, this paper contributes an overarching view of contextual elements and how they interact, as well as actionable strategies for integrating those elements. Here, we summarize these two pieces:

The framework presented in Section II relates the Environment, Assignment, and Simulation to each other and the intended outcome; namely, how students use the simulation. In order to promote productive use of the simulation, these elements should work together to help students engage with the different context elements. Heuristics are provided as strategies for integrating these elements and promoting productive simulation use. The heuristics include: Use the simulation to coordinate multiple representations; use the simulation to mediate discussion; set up game-like situations and take advantage of explicit and implicit challenges; focus on illuminating cases; ask students to re-create or re-present features on the simulation, use "Predict, Observe, Explain" methods.

A case study of quantum tunneling was described to illustrate the need for these heuristics in creating an effective assignment, and problems that arise when assignments are written without the incorporation of these heuristics. A case study of molecule-building illustrated a successful simulation-based assignment, where the heuristics and attention to the broader framework were present in the assignment design. In this instance, we observed productive student use of the simulation, where students engaged in sense-making with the simulation, and utilized other students in the environment to mediate their understanding.

The heuristics utilized in alignment with the framework are not meant to be foolproof laws that will never fail, but instead, should be thought of as highly contextually dependent strategies that can aid in the task of writing assignments. We hope the framework and heuristics presented provide a base on which more research can be done.

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Appendix

Appendix 1. Online Reference Materials.

The assignments used in the studies, the modified tunneling tutorial outline, and the tunneling overview can all be found at: http://spot.colorado.edu/~rehnd/heuristics/ or on the JoTLT website (under Archives, Volume 2, No. 1) at jotlt.indiana.edu.

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