Heuristics for Creating Assignments to Incorporate Simulations

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Abstract

The use of simulations in learning physics is a topic of growing interest in physics education research circles. While prior research has been conducted to understand the factors that promote engaging and interacting with sims in an interview setting, little work has been done to understand how assignments affect students' interactions with the sims in various environments. This paper explores this issue through analyzing two different case studies in radically different settings. One is a study done in a middle school classroom using the build-a-molecule PhET simulation, and the other investigates the use of a PhET quantum tunneling sim used in a college-level modern physics course. These assignments were created with a tentative list of "heuristics" we felt would be useful in writing these assignments, and through these studies we present a list of refined and expanded heuristics that are more representative of our findings. In addition to these heuristics, we present a framework which is more inclusive than the set of heuristics alone in accounting for the design of these assignments across different contexts.

Introduction

The spotlight in educational research today is largely directed towards computers. Computers not only play a fundamental role in the exchange of information, but also provide a means for communicating ideas in ways not possible with conventional text and language. A growing body of research now exists within the field of physics education research regarding the use of computers in the teaching and learning of physics, and a particular subset of that research focuses on the use of simulations in physics settings. This paper attempts to extend this body of research by investigating how existing simulations can be used to create new assignments that facilitate productive and interactive use of the simulations.

The PhET Interactive Simulations Project at the University of Colorado develops simulations through a research-based approach and posts these sims on the web for free use worldwide [1]. These simulations are intended to be highly interactive, intuitive, and engaging so as to promote interest and curiosity in the underlying physical concepts of the sims[14, 13]. While the research presented in this paper is strictly based on the use of PhET sims, it is possible that many (if not most) of the findings may be applicable across domains with other simulations. The primary reason for this is that this study takes in to account what *features* of the sim lead to developing new assignments in the ways presented. Since those features are likely to be found in all simulations, this framework should be expected to be fairly general.

Along with an analysis of features of the sims that influence the creation of an assignment, it is necessary to account for elements of context that affect student use of these sims. As will be shown, an understanding of how to create these assignments is only possible when viewing a particular situation intended for student learning as a complex system. Not only does the simulation influence how students react and learn, but the environment present, the particular assignment, the students' prior knowledge, and other elements of context shape the ways the assignments are used. The aim of this paper is not to attempt to account for all contexts that might be present while students use an assignment, but rather to investigate elements that are particularly important to account for when writing assignments for use across different settings.

Importance of Context

The overarching theory being used to approach the question of how to create these assignments is drawn from cultural psychology [4, 5, 6]. At the heart of the theory is the idea that humans use artifacts for goal-directed action. While artifacts are commonly thought of as objects found in ancient ruins, this definition is more broad. An artifact[1] is anything that has been created by humans to serve a particular purpose. Though artifacts are always material, they are simultaneously *ideal*, a term used to imply that the object has some significance. An example is a toothbrush. It is by nature material, being composed of a handle and bristles, and it is ideal in the sense that its intended purpose is (most often) to clean teeth. A more abstract example is words. They are by nature material, formed by movements

[1] Another word that is commonly used in place of "artifact" is "tool," and these will be used interchangeably throughout this paper.

of the mouth and sound waves moving through the air, but they are always ideal in the sense that each word carries a particular significance.

The main point to make about this is that humans use artifacts to interact with the world. Often times this is depicted by a mediational triangle, shown in Figure 1. Basically, we (the subject) are simultaneously connected with an object directly (in an unmediated manner) and indirectly (in which our interaction is mediated by a particular artifact). Of course, a complete analysis of how humans use tools must account for the situation they happen to be in. This is where the idea of context comes in to play in the mediational triangle picture, depicted in Figure 1 as the underlying circle that "surrounds" or "weaves together" this mediational triangle. The key point is that tools themselves are not the only things that influence the ways we use those tools, but rather the context of a particular situation also plays a role. Returning to the previous example, if situated in a bathroom, the toothbrush is probably used to brush teeth. However, if one happens to be in the military, the toothbrush might be used to scrub floors instead. The different contexts inspire different types of use of the same tool.

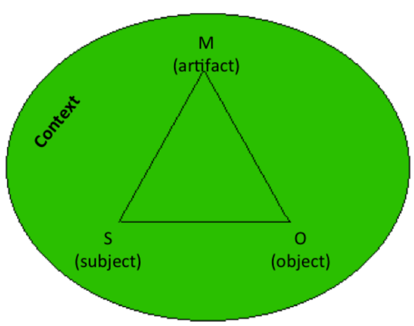

Figure 1: Mediational triangle in which the subject simultaneously interacts with the object through unmediated and mediated paths. The context surrounds or "weaves together" this interaction. Adapted from [4]

With this general theory in mind, we can now look at how this applies to the use of simulations. From this perspective, a simulation is yet another type of tool, and the key idea is that context influences how students use this tool to achieve certain tasks. Often this tool is described in terms of its affordances (what the user perceives features of the sim to be used for) and constraints (the limitations on the actions possible with the sim) [12, 14]. Though the sims are characterized in these terms, this does not provide a complete understanding of how students will use the simulation. Factors such as the number of students per computer, the particular questions on the assignment, the role of the teacher in the classroom, and many others, all influence the students' use of the sim. Without this general framing or outlook on this problem, it would be difficult to start to characterize how to create assignments that account for the different situations in which they are implemented.

Project Overview

Originally, this project began with the goal of creating heuristics, or general guidelines, that could be used to modify assignments to incorporate simulations. Through reading existing literature and drawing on prior experiences of witnessing simulations being used in physics classes[10, 8, 9], we developed a tentative list of heuristics we felt would be important when creating assignments. After creating this initial list, we wrote assignments in different classes that utilized those heuristics and collected data to investigate how well the heuristics applied in those different contexts. The initial goal was to be able to refine the list of heuristics to be as inclusive and helpful as possible. However, upon conducting this research, we felt that the data collected indicated the need for a more inclusive framework in which the heuristics are just one piece of a larger structure. This framework will be presented later in the paper.

Six assignments in total were created and used in drastically different environments. This included: two homework problems in an upper-division classical mechanics and math methods course (PHYS 2210), one using the projectile motion sim, and one using the resonance sim; two homework assignments in Physics of Everyday Life 2 (PHYS 1020), one using the Snell's law sim, the other using the lasers sim; one quantum tunneling tutorial used in a modern physics course (PHYS 2130); and one in-class assignment in a middle school setting using the build a molecule sim.

Data was collected in a variety of different ways, and different types of data were collected for each of the different assignments. The data includes observations of the students using the assignments and written field notes, recorded and transcribed audio conversations of students using the sims, Camtasia screen-capture and audio videos taken while students used the sims, survey results collecting feedback from students about the effectiveness of the assignments, survey results collecting feedback from the instructors regarding their use of sims and the value they perceived in using them, the designer's (Rehn's) notes about the development of the assignments, and lastly any relevant data found in existing literature about related topics. In this paper, we focus on the Build-a-Molecule assignment and the quantum tunneling assignment. For each, we first give an overview of the details about the assignments and the environments the students were situated in while using them, and then give a detailed account of the data collected and its relevance to developing a framework and set of heuristics.

Case Study 1: Build-a-Molecule

The PhET project at the University of Colorado recently received funding to design sims targeted towards middle schools. One of the sims created in this research was the "Build-a-Molecule" sim[2], which allows students to manipulate atoms and combine them in various ways to form molecules. [2]

The assignment used in this study was created for use in a charter school classroom near Dallas. Particularly important to understanding the implementation of this assignment are some of the situational aspects present while students used this sim. Each student had their own computer and a two-page assignment in front of them. They were situated at desks in groups of four, and the teacher was particularly careful about making sure that the entire class of around 30 students stayed on task and moved to the next "section" of the assignment together at the same time. Specifically, she often stopped the class when students were sufficiently close to moving to the next section and asked everyone to move on to the next section regardless of whether they were done with the previous section or not. As will be argued, both the actions of the teacher and the environment the students were situated in play a critical role in understanding how the students interact with the assignment.

The data collected from this assignment was drawn from analyzing Camtasia screen capture (plus audio) videos of three different students. Two of these students were sitting next to each other in a group of four and one was sitting alone on one side of the table in a group of three. Through this, it was easy to take note of what the students were working on building, and also to get a sense of how their conversations with both the teacher and the other students influenced the ways they worked on the assignments. Pre- and post-tests were given to the students, though the data is not presented here. From a brief read-through it appeared that the students did, in fact, learn a great deal and the assignment was successful to at least some degree. However, the purpose of this paper is to focus more on how the students use the assignment and the simulation in order to develop some sort of framework that accounts for their actions. While the results and evidence of learning gains are nice to have and help to demonstrate the overall effectiveness of the assignment, the findings from the data presented in this paper are not contingent upon the results of the pre- and post-tests.

Assignment and Sim

The learning goals for this assignment were threefold:

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

The simulation itself, part of which is shown in Figure 2, has a "work table" on which students can pull atoms from a bucket and move them around to combine them in various ways. On the right side of the simulation are boxes labeled with different molecule names. Once the students create a particular molecule, the box blinks and lights up and directs the student to drag the molecule in to that particular box.

Figure 2: Screen capture of the build-a-molecule sim. Students create molecules on the work table and can drag them to the boxes on the right.

In addition, there are three different tabs in the sim, each of which presents a new type of learn-

[2]The sims are designed in a cyclic process, first creating a basic structure for the sim and then conducting student interviews where students are asked to think aloud while using the sim. The data from the interviews is then used to change and improve the simulations before being posted online and implemented in the classroom. For more info, see [7]

ing goal. The first tab deals strictly with single molecules, such as O_2, N_2, or NH_3. The second tab introduces coefficients and to fill all of the boxes, students must make the correct number of molecules. For instance, $4H_2$ requires students to create and move four H_2 molecules in to the same box. Only after filling all of the boxes can students move on to more complicated molecules. The third tab is completely free-form, and in the particular assignment referred to here, students were instructed to play around and try to make the biggest molecule possible while using this tab.

The structure of the assignment itself contained four primary sections. The first simply asked the students to play with the sim and familiarize themselves with it, while the remaining three sections each corresponded to using one of the three tabs. Questions asked were presented in a tabular and open-ended structure. While using the first tab, students are given a table on the assignment to fill out, in which they must write down different molecule names, the corresponding chemical formulas, and draw a picture of what each molecule looks like.[3] The remaining questions in the assignment were presented in slightly more guided ways, but still present goal-like situations. For instance, students are asked to try to make $4H_2$, and then must draw a picture representing $4H_2$ and explain what the subscripts and coefficients mean. The effects of the sim and the assignment together are detailed in the next section.

Data and Analysis

From watching the Camtasia recordings of the students using the sims, several observations stood out as particularly important. Each student generally spent several minutes at a time playing with the sim and building molecules, and would then stop playing with the sim to spend several minutes writing down their findings. During this time of writing, they would frequently click on the 3-D view of the molecules in order to make their drawings as accurate as possible. This process occurred in all sections of the assignment, and overall they chose to build several molecules in a row before they would stop to fill out the assignment.

These findings suggest that the assignment largely allowed for play and "messing about" with the sim itself. Had the assignment distracted from their engagement, we would have expected them to play with the sim for shorter periods of time, and look to the assignment for guidance as to what to do next. In addition, we would expect their actions to be more hesitant and controlled when using the sim. Of course, this was not the case, even though several minutes at a time were spent writing.

During their time playing with the sim, the effect of affordances and constraints were clearly present. Students had little trouble figuring out that the molecules should be dragged to the boxes and that once they filled enough boxes they could move on to another level. In addition, students quickly figured out that molecules can be split at different bonds by hovering the mouse over the junction between two atoms and waiting for the scissors tool to appear, after which they could cut apart a bond. These features of the sim taken together helped to create a game-like environment. The goal for the students using the sim was implicit, and this allowed for interactive engagement.

An example of this arose in one student's attempts to build $2NH_3$. The student began by creating N_2 and connecting three H atoms to one of the N atoms. He then tried to drag the molecule to the $2NH_3$ box, but the sim would not allow for it. This constraint forced the student to reevaluate the meaning of $2NH_3$, and he quickly cut off one of the N atoms and placed the remaining NH_3 molecule in the box.

There are several important aspects to point out in this particular example. First of all, features of the sim itself were crucial in the student engaging in the particular ways that he did. The obvious or intuitive game-like situation present led the student to attempting to create this particular molecule and place it in the box. Second, the constraints present in the sim would not allow for the student's incorrect reasoning about what the 2 in $2NH_3$ means to lead to completion of that particular game-like situation.

Less obvious in this interaction are the other layers of context that influenced the student's use of the sim. The assignment was not so guided that the student would not engage and play in the manner described. Had the assignment been more guided and instructed the student on *how* to build $2NH_3$, he never would have been forced to confront his incorrect reasoning about the role of the coefficient. In addition, the teacher's role can have dramatic effects on the student's use of the sim. While he was playing in the third tab of the sim, the teacher came over to this same student and asked him various questions.

At the time the teacher came over, the student was engaged in trying to build the largest molecule he could. He had already built Chloro(trifluoro)methane, $CClF_3$, and was unsuccessfully trying to connect more molecules to this

[3] See Appendix 1 for the precise format of the question

structure. When the teacher came over, she asked if he could separate the molecule in to a smaller molecule. This fundamentally changed the student's goals, as he was no longer focusing on how to make the molecule as large as possible. Soon after, the teacher asked the student what the name of the molecule was. The student gave a valiant attempt at pronouncing the name, and this eventually led another student to ask, "Miss, can people pronounce these names?" and "How do people come up with these names?"

Two things are clear from this interaction. First, the teacher was able to fundamentally change the task the student happened to be working on. Second, her asking a question about the pronunciation of a name led to more student questions about the nature of creating names in chemistry, and whether or not anyone can pronounce those names. The important point here is that the teacher's role in how the students interact with the simulation is in no way accounted for by looking only at the design of the simulation. It is only in taking this context-dependent view of simulation use that we can begin to understand how these simulations are used.

Heuristics drawn

The results from this particular case study provided a means for revising the list of heuristics that had previously been created. There were three general findings from this study. First, the game-like situations allowed for student engagement and provided a means for the student to interact with the sim in ways that led to productive use of the constraints and affordances present in the simulation itself. Second, the types of questions in the assignment forced the students to take the time to more carefully analyze what they had seen in the sim, and this provided some means for internalization of the material which would have otherwise not been achieved. Third (and not discussed previously in this paper), the explicit call of attention to visual features on the sim helped students to notice a feature of the sim that might have otherwise gone unnoticed. In this assignment, one of the first questions was "How do you know you have made a molecule?" While this may seem obvious, the purpose of the questions was for the students to realize that a molecule is only made when the chemical name appears above the molecule created, and that other conglomerations of atoms can be made which have no actual chemical name. This turned out to be important later on in the assignment when students are asked to build the largest *molecule* (not amalgam of atoms) possible. In effect, this explicit call to visual features helped to clarify ideas what constitutes creating a molecule.

These findings are suggestive of heuristics that should be used when attempting to write these assignments. These are:

1. **Set up game-like situations**

   This helps to engage the students in the sim and allows for the constraints and affordances of the sim to guide student understanding. This can come in two flavors: allowing the game-like scenario present in the sim itself be naturally used, or setting up a game-like situation through the use of guided questions. The former of these is apparent in the build a molecule assignment; we give an example of the latter later in this paper.

2. **Ask students to recreate or re-present visual features on the sim**

   Asking students to write formulas, draw pictures, or explain something shown on the sim in words are all possible ways of fulfilling this heuristic. The key point about this is that it allows for time to reflect on the material presented, and forces the students analyze particular features of the sim more carefully. Both of these serve as mechanisms for the internalization of important ideas or concepts.

3. **Ask about visual features on the sim**

   Writing a question that addresses a feature of the sim that might otherwise be glanced over or go unnoticed can often be helpful in allowing the students to recall the usefulness of that particular feature while they engage with the sim. For example, asking the students how they knew they built a molecule was something that might have otherwise gone unnoticed. This heuristic should most likely be used sparingly, and only when there is no other way to draw attention to the importance of a particular visual feature.

The findings from this case study and the heuristics drawn served to refine some of our previous ideas about which heuristics would be useful, and gave us evidence of the necessity of developing this list of heuristics. In addition, knowledge of the context of this particular situation helped to generate a more detailed view about how these heuristics are implemented and what their roles in these assignments are. Before detailing the framework that we developed to account for these contextual features, it is helpful to look at another case study in a radically different environment and see how the heuristics drawn from another situation compare to those presented from the study just described.

Case Study 2: Quantum Tunneling Tutorial

The second study presented draws on data taken from a college level modern physics course of around 150 students total. Students in the class are primarily electrical engineering seniors or mechanical engineering sophomores and have had no previous experience with quantum mechanics before. This study took a subset of these students (11 total) and looked at how they used tutorials one day outside of their typical class time. All 11 students met at one time in a small classroom in the physics building and the students were divided in to four groups.

Two different tutorials were written for the students, one using the quantum tunneling PhET sim[3] [4], and the other without a sim. Both assignments were created with the same basic structure, but different types of questions, with the exception of the introduction of the tutorial, which was the same for both. There were two groups of students using the PhET sim, one with two students and the other with 3 students. Each of these groups were sitting on one side of a table in front of a laptop computer, and the tables were separated by 6 or 7 feet. The remaining six students in the non-PhET group were situated at one large table, and though they initially started as two separate groups, they ended up collaborating together, and the distinction of "groups" became less obvious throughout the tutorial.

Three primary types of data were collected: field notes and observations of the interactions, the completed assignments handed in by the students, and audio recordings of the conversations. Two audio recorders were used, one being placed on the table of the group of two students using the PhET sim, and the other placed on the table near one of the groups using the non-PhET tutorial. Dialogue was often heard across different groups in both audio recordings, and in total three voices were present in the PhET group tutorial, and four voices were present in the non-PhET group tutorial.[5]

Assignments and Sim

There were significant differences in the ways these two assignments were written, despite the fact that each assignment covered the same basic material. The underlying goal in both was to address the idea of a quantum particle (an electron) subject to a step potential barrier, and analyze the cases of the particle having a greater energy than the potential barrier, or less energy than the potential barrier. Mathematically, we could write this as:

$$V(x) = \begin{cases} 0 & \text{for } x < 0 \text{ and } x > L \\ V_0 & \text{for } 0 \leq x \leq L \end{cases}$$

where L is the width of the potential barrier, and E (the total energy) satisfies either $E > V_0$ or $E < V_0$. Often the region of $x < 0$ will be referred to as region 1, the region under the potential barrier as region 2 and the region $x > L$ is referred to as region 3.

To introduce the students to the case of a quantum particle, each tutorial started with an identical section on the case of a classical particle traveling over a potential barrier and back down, shown below.

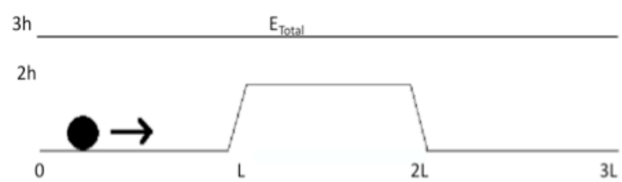

Figure 3: Both tutorials started by looking at the case of a classical particle, total energy $E = 3mgh$, rolling over a potential barrier of height $2h$.

This short part of the assignment was created to address the idea that the classical particle travels slower on the top of the ramp, and therefore the likelihood of finding the particle in that region is greater than in the other two regions separately. After this, the tutorials diverge in the types of questions asked.

To get an idea for the differences in the two assignments, it is first necessary to describe the quantum tunneling PhET sim. The simulation shows 3 main windows on the interface, stacked vertically on top of each other. In addition controls are present on the right side of the interface, allowing users to adjust various features, such as the direction of the inci-

[4] For more information on the development of the tunneling sim, see [11]

[5] One of the students in the PhET group of three students talked particularly loud and sometimes addressed the group of two using the PhET sim. In the non-PhET groups, two students were particularly quiet, thus only dialogue from the remaining four students was collected.

dent wave, the parts of the solutions that are plotted, and so on. The window on the top of the simulation shows the potential barrier just described, and allows for students to adjust the total energy, the energy of the potential barrier, and the width of the barrier. The middle window shows a plot of the wave function changing in time, and the window below that shows a plot of the probability density of that particular situation. The bottom two windows have no directly controllable features (other than a zoom in or out option), but both change simultaneously as the user adjusts the parameters shown in the top plot. A picture of the interface is shown below.

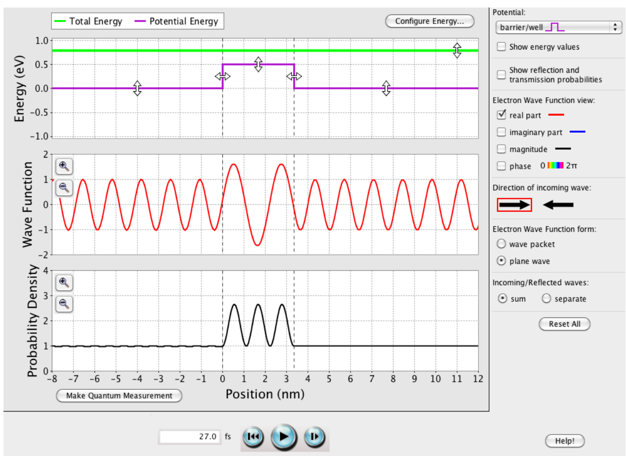

Figure 4: Interface of the tunneling PhET sim

After the introduction, the PhET tutorial proceeds by asking the students to set up the sim with $E > V_0$ and to describe and analyze the wave function shown on the sim in the three regions. The non-PhET tutorial, on the other hand, proceeds by asking the students to solve the time-independent Schrodinger equation for the cases of $E > V_0$ or $E < V_0$, and then use that information to eventually draw a picture of the wave function in each of the three regions. The PhET tutorial ends with the case of $E < V_0$, again asking questions primarily addressed at explaining certain features that are shown on the sim. More details about the types of questions asked in these two tutorials will be presented as we describe some of the results found from the data collected.

Results and Analysis

After analyzing and transcribing the audio taken from the student conversations, there was a clear indication that students using the non-PhET tutorial were more engaged in conversation than the group using the PhET tutorial. The four students in the non-PhET group who were recorded asked each other a total of 90 questions during their discussions, while the three students recorded on the PhET tutorial asked each other a total of 27 questions during their discussions. In addition, the types of questions asked by the students in the non-PhET group were radically different. In general, the non-PhET group asked questions about what they expected the wave function to look like, and *why* it should look that way, whereas the PhET group primarily asked questions about what was shown on the interface window without attempting to understand the physics behind those images. A particularly good example of this is apparent towards the end of the tutorial when both groups are working on the case of $E < V_0$. This is the focus of the next section.

Issues concerning discourse

Recall that both tutorials began with a section on classical probabilities, and then moved on to the quantum case of $E > V_0$. The purpose of writing the assignment this way was to have the students notice the similarities between the classical and quantum cases. They are similar in that in both cases the kinetic energy in regions 1 and 3 are the same, and the probability density is, in general, less in regions 1 and 3 than in region 2 for both the quantum and classical cases.[6] Both assignments led students to notice these similarities through a series of questions directed towards that purpose.

However, this classical analogy completely breaks down in the case of $E < V_0$, and students can no longer use the same reasoning that the amount of kinetic energy directly determines the probability of finding a particle in a particular region in space. The non-PhET group confronted this difficulty head-on when they were attempting to finish their drawing of the wave function for the case of $E < V_0$ in region 3. Their dilemma is demonstrated in the following dialogue:

S4: "The reasoning we used before, at least I did,

[6]This is not, strictly speaking, always a true statement, since to fully understand the probability density of the quantum particle, it is necessary to calculate transmission and reflection coefficients. However, this is not a learning goal for this sophomore-level class, and we felt that the conceptual idea of a quantum particle moving "slower" in the potential barrier, thus leading to a greater probability density, was worthwhile since it bears similarity to the case of a classical particle. In the latest version of this tutorial (intended for an upper division course), we abandon asking about the probability in the potential barrier since this bears little physical significance in actual tunneling applications.

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?"

S3: "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 $\frac{1}{2}mv^2$*."*

S4: "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 precisely what we wanted the students to go through when trying to generate a picture of the wave function for this particular scenario. From prior knowledge, the students knew that the wave function should have a lower amplitude after tunneling occurs, but the tutorial made them confront the question of why.

In the analogous part of the PhET tutorial, no similar reasoning was shown. This was largely due to the fact that the students already had the wave function plotted in front of them, and were never asked to attempt to generate a plot on their own. The questions they generated when they began working on the questions that asked about what the wave function looks like in the case of $E < V_0$ are typical of the types of questions they tended to ask throughout the tutorial. Referring to the wave function in region 3, they say:

S1: "That one is still sine right? Like if you decrease it is it still sine or is it always zero?"

S2: "Well this is technically a sine wave."

Again, these questions are primarily about what is shown on the interface itself, without ever delving in to the reasons for seeing what is shown.[7]

At this point it becomes interesting to think about the reasons why the students' discourse differed so drastically. When designing these questions, we specifically tried to use one of the heuristics we thought would be important: "Call attention to visual features shown on the sim." Asking the students what the wave function looks like falls under this category, and yet in this case it was clearly not effective in getting the students to think about the underlying physics of the situation.

We argued earlier that this heuristic should be used sparingly and only when a particular visual feature of the sim might be difficult to notice or otherwise glanced over, and the results of this assignment suggest the same. The fundamental reason for this is that asking students to notice a visual feature is different than asking about what causes that feature, or better yet, asking them to generate that feature, e.g. by drawing a picture, thus forcing students to coordinate other forms of knowledge and think deeply about what information is important for doing so.

In general, a question about what the sim shows will promote little discussion, whereas a question about what something will look like (be it a plot or sequence of events or something else shown on the sim), or why the sim exhibits a certain feature, are more likely to promote thought, discussion, and sense-making.

If questions that ask students to predict or explain what something will look like are important, we must understand what the important pieces of knowledge needed to make those predictions and explanations are. In this case, it was clear that the non-PhET tutorial succeeded in this when the students successfully made graphs of the wave function. Therefore, analyzing the questions leading up to their completing this task gives insight in to the pieces of knowledge that led to their success.

The non-PhET tutorial first asked the students to write down general solutions to the Schrodinger equation in each of the three regions for both the cases of $E > V_0$ and $E < V_0$. They then had to use that information, combined with subsequent questions about what they expected the wavelength and amplitude of the wave function to look like in each region, to generate (draw) a graph of the wave function.

In contrast, the PhET tutorial never addressed solving the Schrodinger equation at all. The initial idea was that the same type of conceptual grasp (larger wavelength, less KE, higher amplitude) would be accessible in using the PhET sim, without the need for solving equations. While it is possible that students picked up on this conceptual idea, a fundamental gap in their knowledge and reasoning about the wave function in the different regions was clearly present (not once in the tutorial did the PhET students refer to the Schrodinger equation).

A reasonable conclusion to draw about these differences in discourse is that because the PhET group was never asked to think about the mathematics underlying the features on the sim, their discussions never had the potential to explore the "reasons" for what is shown on the sim. In addition, since they were never asked to plot the wave function, they never had to coordinate the different pieces of knowl-

[7] It is possible in this example that S2 understands why the wave function is a sine wave in region 3, but they never discuss this (largely because the tutorial doesn't ask them to). Either way, it is clear that the tutorial is not helping to promote discussion around why the function looks the way it does.

edge that are necessary for completing such a task. This suggests two possible ways we ought to write assignments to use simulations.

First, the sim might be used as a way to compare and contrast features that the students were asked to generate without using the sim. In this example, we could have asked the students in the PhET group to generate a plot of the wave function and then compare it with what is shown on the simulation. In this way, the information needed to reason about the underlying physics has already been accessed, and the sim now serves an entirely different purpose than it did in the case presented. (Again, more evidence for the context-dependence of the ways sims are used.)

Secondly, these findings suggest that the sim be used as a way to coordinate different forms of representation. Here, the sim could serve as a way to coordinate the knowledge of the mathematical solutions with the representation of that solution shown on the graph in the sim. We have turned both of these findings in to heuristics, as will be summarized later in this section, and this tutorial has already been revised to incorporate these heuristics.

Issues concerning guidance

An additional issue with the PhET tutorial not yet described concerns the amount of guidance given to the students. Each of the cases of $E > V_0$ and $E < V_0$ started with a question asking the students to set up the sim in a particular manner. For example, the first question in using the sim for $E < V_0$ was:

Now, using the PhET sim, decrease the size of the wire gap to 1 dashed-line wide and increase the height of the potential energy line all the way to the top. What type of function do you see in region 1 and 3 (e.g. sinusoidal, exponential, linear, quadratic, etc.)?

There were several negative effects of asking questions like this, as can be noticed in both the audio recordings and the field notes taken while observing the students. First, this made the students feel like they couldn't play with the sim. At one point a student asked me to adjust the sim for them because they didn't know how they were supposed to set it up. This led to little "interactive engagement" while using the sim, and didn't allow for a student sense of "ownership" to form. Both of these are described in existing literature as essential elements for effective use of simulations.

Second, this led the students to wait for the tutorial to instruct them on what to do next. Often times the term "cookbook lab" is attributed to labs that exhibit some of the same properties. These are notorious for being solely task-oriented activities that provide little to no guidance in concept formation.

Third, the level of guidance present set limitations on student conversations. Because the tutorial told them how to set up the sim in certain ways, there was no debate about how they could or should use the sim. No discussion was centered around ways of manipulating the sim in a way that would give them insight in to underlying physical concepts, and this prevented conversations about those physical concepts from forming.

Again, in retrospect, it is easy to wonder why we wrote the tutorial in this certain way. As it turns out, the main reason for telling the students how to set up the sim was based on a heuristic that we felt would be important: "Set up the sim to look at illuminating cases." We felt that often times illuminating cases serve to give unique insight in to underlying physics concepts, and we wanted to implement this by telling the students about these particular cases. In the question taken from the assignment written above, we ask the students to set up the sim with only one dashed-line of width because this is a case in which tunneling occurs, and some of the wave function leaks in to region 3 (if the barrier is too wide, none of the wave function leaks over).

The problem with writing the question this way is that it takes away from other heuristics that are important. For instance, the students felt unable to play with the sim because of the way the question was presented. We still think that the heuristic of looking at illuminating cases can be useful, but crucial to its success is the way it is implemented. It is likely that this heuristic will be effective if implemented through a game like situation. For instance, in the latest version of the tutorial we have rephrased the question regarding the illuminating case of tunneling to say: "How can you maximize the amount of transmission to region 3?" In this way, the students come to understand an illuminating case through a game-like situation.

Heuristics drawn

Although this section so far has pointed out several deficiencies with the PhET tunneling tutorial, we in no way intend to communicate the message that sims are "bad." Rather, we view this tutorial as evidence of the complexity of the challenges presented when writing assignments to use simulations. This complexity stems from the features of the sim that influence the ways students interact with the content, the environmental or situational aspects that influence the students' use of the sim, and the nature of the assignment given to the students that influences both the environment and the interactions of the students with the simulation. Before describing the framework that accounts for these different aspects in the next section, we summarize the heuristics drawn from this particular case study.

1. **Set up situations that utilize 'Predict, Observe, Explain' or 'Elicit, confront, resolve' models**

   These models, described in existing literature, use the idea of asking the students to think about a particular phenomena through some sort of prediction, and then compare their predictions with the actual answers in order to gain perspective on the underlying concepts. In the non-PhET case, these models were implemented by asking them to draw graphs of the wave function. However, the 'observe and explain' stages or the 'confront and resolve' stages were not present. These could be integrated in to the assignment by asking them to compare what they drew with what is shown on the sim.

2. **Use the sim to coordinate other forms of representation**

   This heuristic hints at the idea of using the sim as a means to understand various representations of the same physical phenomena. An example is the coordination of mathematics and the plot of the wave function in the tunneling sim. Both the plot and the mathematics describe the same physical situation, but each allows for different ways of looking at that phenomena. This also helps to satisfy a skill necessary for all professional physicists: to be able to effectively utilize many forms of representation.

3. **Incorporate illuminating cases**

   Since often times particular scenarios in physics give unique insight in to the underlying physical concepts involved, this heuristic can often be implemented for that purpose. The way in which this heuristic is implemented is crucial to its success, and it is likely that combining this heuristic with a game-like situation is an effective mode of implementation. An example was briefly described above.

4. **Set up game-like situations**

   This heuristic seems to present itself in nearly all situations, and using it promotes effective use of the simulation through play, interactive engagement, creating a sense of ownership, and possibly in mediating discussions. This was also described in the build-a-molecule example earlier in the paper.

Development of a Framework

Throughout this paper, the idea that describing how to create simulations to incorporate sims requires knowledge of both the sim and the context of the situation has been harped on, but as of yet we have not offered an explanation of how these issues can be represented. In this section, we propose a framework that can be used when incorporating these sims to assignments, and then give a list of the heuristics that we feel are useful in implementing this framework.

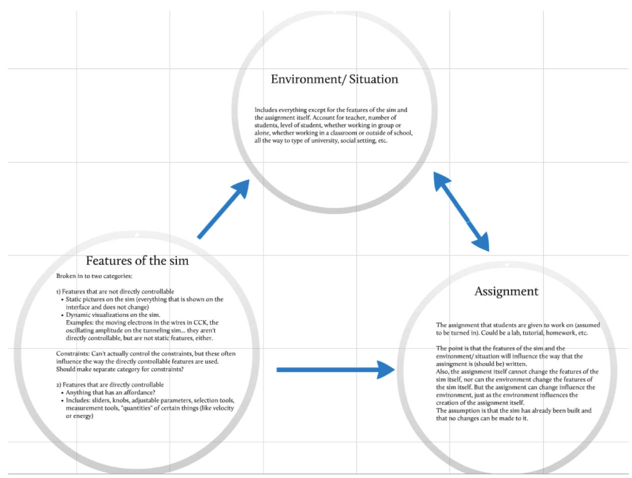

Figure 5: Framework for developing assignments. A more detailed view is shown in Appendix 2

The overall structure, shown in the figure above, is a sort of triadic relationship. In the bottom left corner are the features of the sim, at the top of the triangle are environmental or situational features present, and at the bottom right is the assignment, essentially what we see as the outcome of the project. The directional arrows indicate that the features of the sim can influence both the environmental/ situational aspects of a particular scenario, and that they also influence the development of the assignment. Environment/situation and assignment are connected by a double arrow, indicating that the type of environment affects the development of the assignment, and the type of assignment, in turn, affects the environment or situation. The reason for the single arrows emanating from 'features of the sim' is that we are assuming that the features of the sim will not change in time.[8] Since the text inside the circles is particularly difficult to read, we list it here:

Features of Sim

Broken in to two categories:

1. **Features that are not directly controllable**

   -Static pictures on the sim (everything that is shown on the interface and does not change)

   -Dynamic visualizations on the sim.

   Constraints: Can't actually control the constraints, but these often influence the way the directly controllable features are used.

2. **Features that are directly controllable**

   Anything that has an affordance. Includes: sliders, knobs, adjustable parameters, selection tools, measurement tools, "quantities" of certain things (like velocity or energy)

Environment/ Situation

Includes everything except for the features of the sim and the assignment itself. Accounts for teacher, number of students, level of student, whether working in group or alone, whether working in a classroom or outside of school, all the way to type of university, social setting, etc.

Assignment

The assignment that students are given to work on (assumed to be turned in). Could be a lab, tutorial, homework, etc.

The point is that the features of the sim and the environment/ situation will influence the way that the assingment is (should be) written. Also, the assignment itself cannot change the features of the sim itself, nor can the environment change the features of the sim itself. But the assignment can change influence the environment, just as the environment influences the creation of the assignment itself. The assumption is that the sim has already been built and that no changes can be made to it.

This framework provides insight in to the ways the different elements interact, but it is useful to think about where the heuristics fit in this picture. We see these heuristics as being implemented at the junctions of 'features of the sim' to 'assignment' and 'environment/situation' to 'assignment.' Both the features of the sim and the environment will influence which heuristics are applicable and should be used to create a particular assignment. Explicating which heuristics to use in these different circumstances is a goal of future work. This structure is depicted in the figure below.

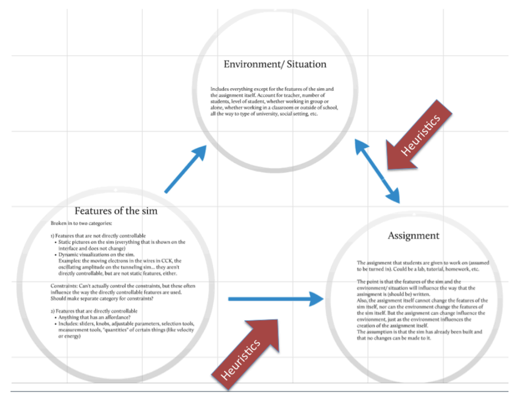

Figure 6: Revised framework for developing assignments.

While this paper has so far presented several important heuristics, our other research has indicated the need for a few more. The full list, in no particular order, is presented here:

1. **Set up game-like situations**
2. **Ask students to recreate or re-present visual features on the sim**
3. **Ask about visual features on the sim**
4. **Use the sim to coordinate other forms of representation**
5. **Use the sim to mediate discussion**
6. **Use the sim to relate formal physics concepts to the real world**
7. **Take advantage of dynamic feedback**
8. **Utilize illuminating cases**
9. **Use 'predict, observe, explain' or 'elicit, confront, resolve' methods**

[8]There have been instances where our attempts to write an assignment led us to adding features in to a sim, but we assume that this is a rare occurrence.

Conclusion, Future Work

This paper has argued for a context-dependent view of creating assignments to incorporate computer simulations. Starting with an initial set of heuristics and creating assignments that utilized those heuristics, we were able to collect data that gave us insight in to the nature of how to write these assignments and what factors stand out as most important to account for when doing so.

The two case studies presented give detailed accounts of some of the successes and failures of implementing these assignments and provide evidence for both what heuristics are generally important to use, and how contextual factors shape the implementation of those heuristics. In addition, a framework was provided that provides insight in to the different factors that play the largest roles when creating assignments.

Future work on this project will include refining these heuristics through conducting more case studies and also starting to create a more detailed account of how both the features of the sim and the environment/ situation dictate which heuristics are most important in different scenarios.

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Appendix 1: Build-a-Molecule Assignment

The following is taken directly from the assignment, during which students are supposed to be playing around with the first tab of the simulation. This allows for open-ended use, and requires students to play with the sim in order to complete the table. The effects of writing what they see down are likely fundamental in their internalization of the material. In particular, doing so gives them time to reflect on what they have seen, and also forces them to pay careful attention to what they see on the sim. For instance, when forced to draw a picture of the molecule they must look at details of the drawing that they otherwise gloss over or take for granted when simply playing with the sim.

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

Molecule Name	Drawing	Chemical Formula

Appendix 2: Framework

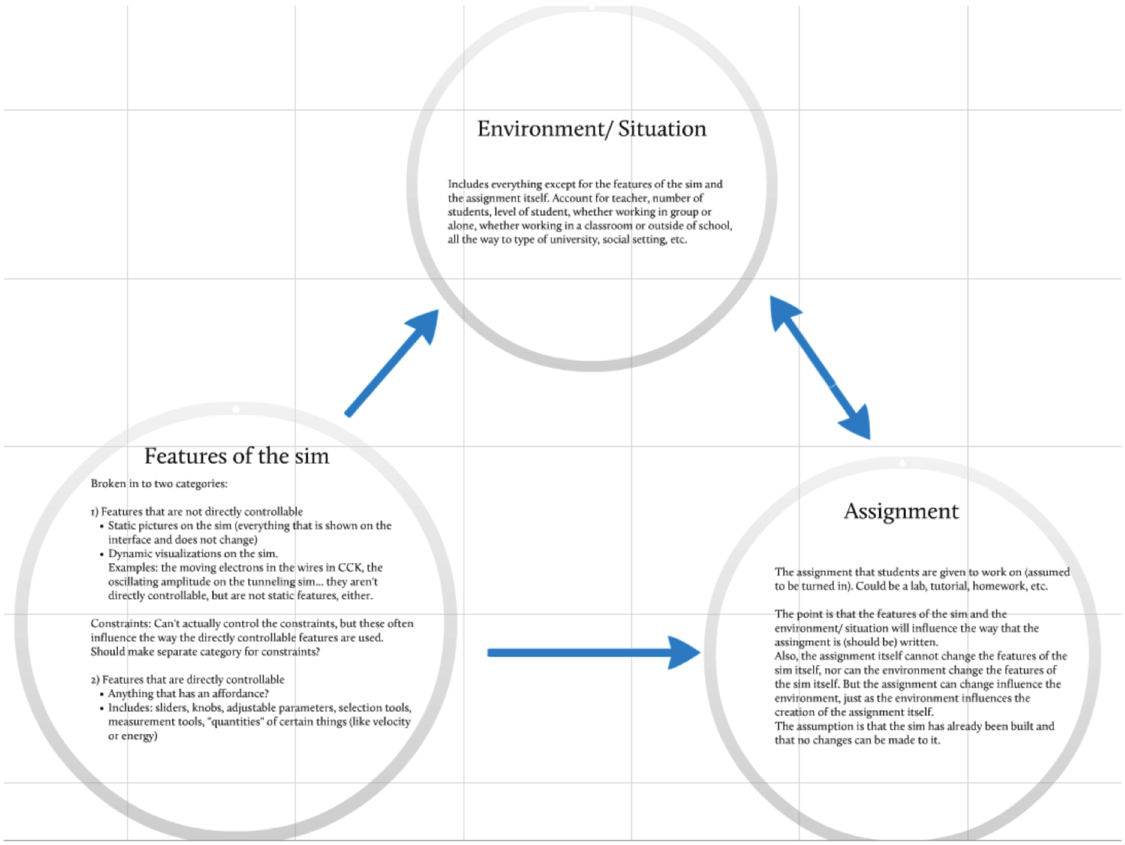

Figure 7: Framework for developing assignments.