Chapter II

Simulation Interviews and Studies

Over the course of a year I interviewed students while they explored interactive computer simulations designed to help students understand difficult physics concepts. My prior teaching experiences allowed me to work extensively with students; however, these interviews provided a very clean controlled setting to observe student's thinking while solving problems (figuring out what the simulation was showing and answering conceptual questions about unfamiliar topics presented by the simulation). While interacting with the simulations, students' actions are guided by their own questioning as they explore the simulation. While exploring, students build an understanding of how the features of the simulation behave, making connections with what they already know to form an understanding of the ideas contained in the simulation. These interviews helped clarify my understanding of specific processes that students use while learning and various motivations that affect their interest in engaging in these processes.

This chapter begins with two papers that were published on the effective design features of simulations. These will be followed with a description of a study involving the effectiveness of the simulations when used independently for conceptual understanding. After this I will include two other papers that I wrote as part of courses in cognitive psychology that touch on possible areas for investigating why simulations help students learn. The first was on how the simulations impact the students' use of Metaphor. The second is a paper describing students' use of gestures while interacting and describing the simulations.

A Study of Educational Simulations

Part I - Engagement and Learning

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Abstract

Interactive computer simulations with complex representations and sophisticated graphics are a relatively new addition to the classroom, and research in this area is limited. We have conducted over 200 individual student interviews during which the students described what they were thinking as they interacted with simulations. These interviews were conducted as part of the research and design of simulations for the Physics Education Technology (PhET) project. PhET is an ongoing project that has developed over 60 simulations for use in teaching physics, chemistry, and physical science. These interviews are a rich source of information about how students interact with computer simulations and what makes an educationally effective simulation. We have observed that simulations can be highly engaging and educationally effective, but only if the student's interaction with the simulation is directed by the student's own questioning. Here we describe our design process, what features are effective for engaging students in educationally productive interactions and the underlying principles which support our empirically developed guidelines. In a companion paper we describe in detail the design features used to create an intuitive simulation for students to use.

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Introduction

Technology is becoming increasingly important in today's classroom and has been integrated in a variety of ways; however, computer animations and interactive simulations are among the most common. This popularity is partly due to the fact that simulations are quite easy to introduce into a curriculum. Such simulations have been developed on a large scale by a group of educators working together – e.g. Physlets (Christian & Belloni, 2001) – and on a small scale by individual educators who would simply like to communicate an idea visually to their students. Textbooks now regularly include DVDs or a URL to websites with a library of various simulations. While many educators find it appealing to use simulations in their classroom, very little research has been done to determine if simulations improve a student's understanding of or enthusiasm for science and how simulations can be designed and used most effectively. Available simulations use a wide variety of appearances, controls, graphics, interactivity, and design principles, often guided only by the designers' preferences or ease of coding. Little is known, however, about design principles and features that are important for optimal student use and understanding. In this paper we present an extensive analysis of student use of simulations, including comparisons of multiple incarnations of a single simulation. This analysis has led to an empirically determined and tested set of design principles based on our observations of student use. This work also provides a rich body of data for the study of student thinking and learning while using simulations, and it has clearly demonstrated that a carefully designed and tested simulation can be a very powerful educational tool (Finkelstein, Adams, Keller, Perkins, Wieman, and the PhET Team, 2006; Finkelstein, Perkins, Adams and Podolefsky, 2004; Finkelstein et al., 2005)

This research focuses on identifying which characteristics make a simulation effective or ineffective through the use of extensive think-aloud student interviews using simulations. This paper is part I of a two part series. This paper will focus on the simulation design process; what are desirable features – those that are found to be important for encouraging students to discover and understand physical relationships- which include and specific methods to provide engaging ways to help students 'discover' the desired learning goals of the simulation; how our design guidelines were developed; and, the underlying principles that support the guidelines. The second paper (Adams, Reid, LeMaster, McKagan, Perkins and Wieman, 2007) describes more specific details on interface design, specifically features that make a simulation engaging and easy to use, types of controls that are intuitive for the student, effective use of representations, the impact of different types of "help" and the impact of even small amounts of irrelevant information.

Background

The context of this research is the PhET project (Perkins et al., 2006; The PhET Team, 2006a), an ongoing program to develop an extensive suite of freely available online simulations for teaching and learning physics, chemistry and physical science. These simulations create animated, interactive, game-like environments that emphasize the connections between real life phenomena and the underlying science while making the visual and conceptual models of expert scientists accessible to students. Currently there are about 60 PhET simulations.

The primary target for these simulations was originally college undergraduates with a wide range of science backgrounds and interests, and this is the population that has been studied in our research. However, these simulations appear to be useful for a surprisingly large range of students and are now extensively used in many high schools as well as some middle schools. In addition, we have received numerous anecdotal reports of grade school students finding them highly engaging and have observed physics graduate students learning new physics by playing with them. An interesting area of future research would be the study of how the findings we report here might depend on the age and background of the student beyond the levels explored in this work.

Simulation Design Process

To understand how our studies have been carried out, it is first necessary to understand the PhET development process.

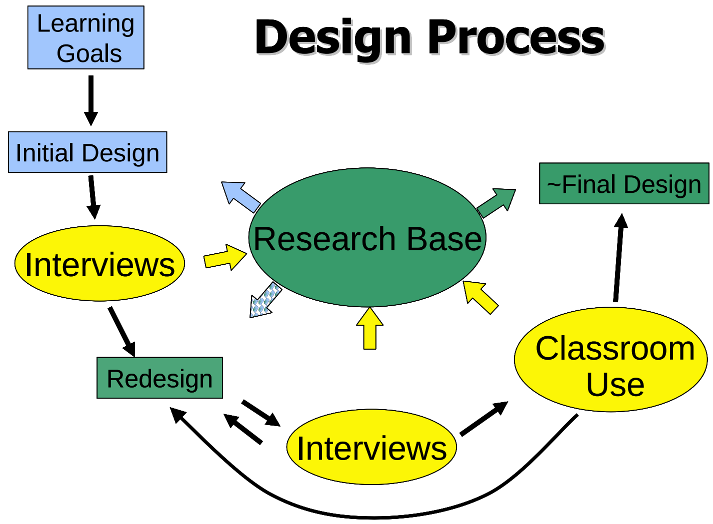


Figure I: Design Process – Flow chart showing the simulation design process.

Our process for creating and evaluating a simulation begins with the selection of the simulation design team consisting of between three or four individuals including a programmer, at least one content expert, and at least one student interface expert. The design cycle (Figure I) starts with the content and student interface experts creating a detailed initial layout for the simulation based on the learning goals of the simulation and the research base – research in education and cognitive science relating to the topic plus the current PhET design guidelines. The first set of stu dent interviews are conducted, once all team members feel the simulation is clear, accurate and engaging. These interviews always reveal interface weaknesses, resolve interface questions that were not agreed upon by the team, and often reveal pedagogically undesirable (and occasionally unexpected desirable) features and subtle programming bugs. Subsequent revisions are made, and if they are extensive, a further set of interviews are conducted. These interviews are not only used to improve the particular simulation but continue to improve our research base. More recent interview results are finding much smaller problems than the interviews conducted on simulations that were written two years ago, indicating that our empirically developed design principles are working. After interviews establish that the desired engagement and learning is being achieved, the simulation is used in a classroom setting where student use is observed and informally evaluated.

Interview Methodology

Over the past three years we have conducted more than 200 simulation interviews with 89 different students covering 52 of 60 simulations. Student interviewees are volunteers that are typically non-science majors. For the more advanced quantum simulations, we also interview physics majors. For each simulation, we typically interview a diverse group of four to six students consisting of equal numbers of male and female students, and a representative share of minority students. Care is taken to acquire a selection of students with a wide range of academic performance. We also attempt to interview students who have not yet received formal instruction on the ideas covered by the simulation.

When we began this work, we were unsure if representative information could be gained from the observation of such a small number of students per simulation; however, in the sorts of issues explored here, we have found a high level of consistency. For example, the interface problems that arose in interviews were problems for most if not all of the interview subjects. In fact, when six students were interviewed on a single simulation, the last two interviews very rarely provided new useful information regarding interface design. Responses related to physics conceptual issues, which are not the primary focus of this paper, were more varied but still show considerable consistency. In this regard, these interviews are rather different from typical educational or psychological research. Because the results are so consistent, ever such small sample numbers produce quantitative results in that they allow one to make accurate predictions. For example, in addition to these formal interviews, we have also observed numerous groups using the simulations for the first time including students in both physics and chemistry courses, physics graduate students, and high school and college teachers. The observations of use in those settings have been quite consistent with the predictions from the corresponding student interview results; the rare exceptions are noted in the appropriate sections below and in Part II.

The PhET interviews are typically conducted with the same set of students during a given semester. If major revisions are required for a particular simulation and multiple iterations of interviews are needed, we find additional volunteers so that we can observe students' first encounter with the simulation. This type of protocol is required because we observe profound differences in how students interact with a simulation once they have been instructed on its use or have had opportunities to use it on their own, compared to seeing it for the first time.

Our standard interview protocol includes the following: in the first interview with a particular student, the interviewer begins by getting to know the student, asking about their background, career and major choices, and courses as necessary to break the ice. Once the student relaxes, and in all subsequent interviews with that student, the simulations are explored in a think-aloud style format. With this approach, the students are asked to talk out-loud while they investigate the simulation. The simulation explorations are structured one of two ways: 1) The student is asked prediction-type conceptual questions (where the student describes their understanding of an idea/concept before seeing the simulation) to guide their interactions. Then, after, or more often while, interacting with the simulation, they are allowed to revise their answer; or 2) The student is simply asked to explore the simulation freely without a guiding question.

In all cases, interview results were useful for determining: the level of student engagement promoted by the simulation; if controls are intuitive and easy to use; if any definitions or ideas are misunderstood or missed altogether; and if there is any extra information that is distracting the student from the simulation's learning goals. Using the prediction-type questions is useful in evaluating the simulation's ability to help students learn particular concepts. Additionally, these questions focus the students on the particular aspect of the simulation that we are currently interested in evaluating. These questions are imperative for evaluating the more involved simulations, because these simulations are sufficiently complex, with multiple levels of controls and presentations, that fully exploring the simulation could take hours. The unguided explorations are useful for determining how people interact with the simulations on their first encounter and for evaluating how students explore and understand the less involved simulations.

All interviews are video-taped and detailed summaries are prepared for each interview, describing the student's interactions with the simulation. These summaries identify any interface difficulties encountered during exploration as well as indicate what concepts were understood/misunderstood and at what level. When studying simulation design, these summaries are more meaningful (as well as much shorter), than detailed transcripts, because the manipulation of and references to the simulation plays such a large role in the communication between the student and interviewer that it is not possible to fully understand the interview simply from a transcript. A short section of an interview transcript and an individual summary for the same interview can be found in Appendix A. After interviews on all subjects have been completed, a detailed summary of the individual summaries is compiled and distributed to the design team. The research results described in this paper draw largely from these detailed summaries. However, seven hours of interviews have been transcribed and coded for research questions (Perkins, Adams, Finkelstein and Wieman, 2004) that require this level of qualitative analysis. To ensure the interpretations and summaries are robust and not subject to interviewer bias, a number of tapes were observed, coded and interpreted independently. For a short section of coded transcription we determined the inter-rater reliability initially to be 95%, but after discussion and revision of the coding scheme, it increased to nearly 100%.

Some interviews were conducted with both an interviewer and an observer or the tapes were independently observed. Interview summaries were then completed independently by each and checked for consistency. This was done with a total of six different interviewers/observers and forty-six hours of interviews. These independent evaluations showed high levels of consistency except when there was a lack of advanced physics mastery by the interviewer or observer. In these cases, less expert interviewers/observers incorrectly interpreted some subtle misconceptions by the student being interviewed as correct physics learning. We found that a mastery of physics at the master’s level, preferably with teaching experience, was necessary for interviewing on beginning and intermediate level simulations, while Ph.D. level mastery was desirable for interviewing on student learning and understanding with the more advanced simulations, such as quantum mechanics.

Although it is not the purpose of this paper, the fact that it is necessary for interviewers to have a very high level of content mastery illustrates a general feature that we have observed for sophisticated simulations of the type discussed here, where there are complex behaviors that depend on multiple variables. These simulations will routinely engage students to raise questions and explore the underlying science topic of the simulation in great depth, and it is this depth of understanding and exploration that requires interviewers with expert knowledge. Similarly, designers also need to have expert content knowledge for the same reason.

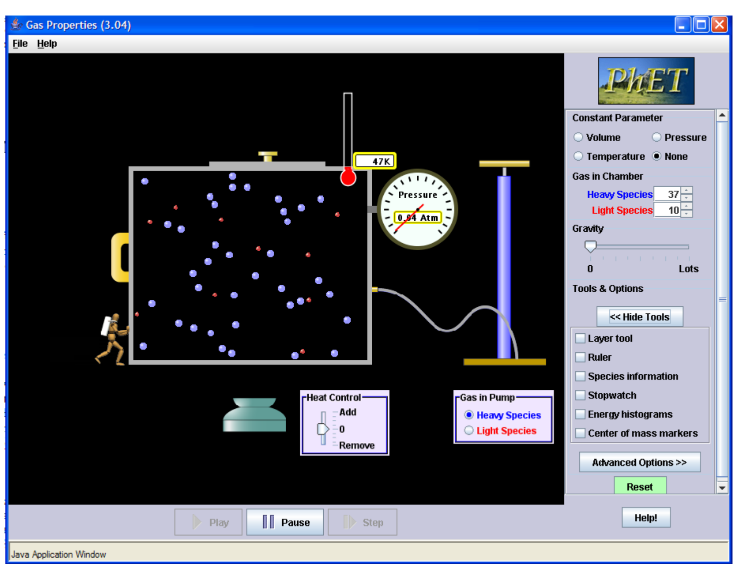
Interview Results

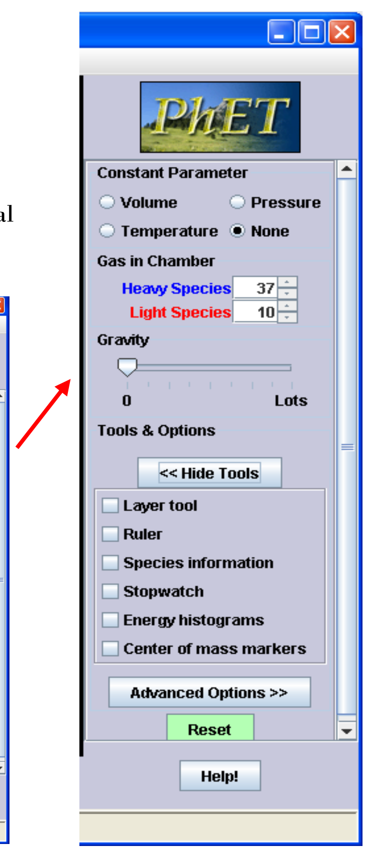
The following discussions of design features focus on the specific simulations and interviews where the problems were discovered, the potential solutions were explored, and the desirable design features first confirmed. We have checked the validity of these design features and principles in subsequent interviews with new simulations; however, in the interest of brevity, discussions of these follow up interviews will not usually be provided in these papers when the interviews merely confirmed the previously observed results. All general conclusions presented here have been confirmed with interviews on at least several simulations.

Encourage Exploration

We consistently observe that engaging students in thoughtful exploration of the simulation is necessary for improving students' understanding of the concepts. When in *engaged exploration*, students are posing questions and seeking answers by observing the results of their own interactions with the simulation and making sense of what they see. In this section we focus on the interface design (Figure II) aspects that enhance educational effectiveness. Engaging the students can be accomplished by having the students use the simulation in the appropriate context, such as with a well designed homework assignment or laboratory activity. However, we also strive to encourage the students to spontaneously ask themselves questions ("why does that happen?") that they can subsequently answer by exploring with the simulation. We see a variety of factors that influence students' engagement with and learning from the simulations, including: the *interactivity* of the simulation; the presence of *little*

Figure II – Interface Design: The black region is the play area containing the representations of physical objects that students can manipulate themselves and observe the effects of their actions instantly. The grey area on the right is the control panel which contains radio buttons, sliders and text boxes for adjusting various parameters and in the lower half of the control panel there are several tools for the students to use while working in the play area.





puzzles; strategically placed but limited text such as *legends and labels;* and features that make the simulations *fun* to play with. We have also found surprising negative influences from prior “understanding” of the topic.

Our work relating to effective engagement techniques is consistent with and builds on previous research of video games. Work done by Malone (1981) has found that video games are intrinsically motivating because they include balanced challenges, fantasy and an optimal level of informational complexity to create curiosity. Malone (1981) found that challenge is created by including personally meaningful goals and uncertain outcomes. All challenges must be attainable to foster self-esteem rather than discouraging users. His research also found that while fantasy was required, it is difficult to create fantasy that is appealing to a wide range of users. For example, most of the videogames that he studied had a scenario that appealed to only one gender. He defined a fantasy-inducing environment as one that evokes “mental images of things not present to the senses or within the actual experience of the person involved”. Mental images can be either of physical objects or social situations. Finally, curiosity is evoked by an environment that is novel and surprising, but not completely incomprehensible.

It is well established that clear goals are important for motivation. Our designs only deal with this indirectly, by attempting to make the primary goal/challenge that of being able to understand the phenomenon portrayed by the simulation. We have seen that by relating to the real world and using suitable animation and interactivity, the desired curiosity is encouraged. In the simulations that students investigate on their own time, as described below in the *Fun* section, there are fairly clear goals such as navigating a maze or creating novel circuits and exploring their behavior. These goals obviously contribute to the attraction. During our interviews, we have not found these goals or the simulations themselves to be gender biased (possibly due to the balance of men and women on the PhET team). However, we are implicitly assuming that most simulations will be used in the context of an educational setting where teachers will primarily provide the scaffolding and goals for the simulation use. In the interviews, the guiding question or the interview itself provides this structure. Because these goals and uses will vary widely with the teacher and level of student, we have, in most cases, avoided constraining their use by not building highly specific tasks or goals into the simulation. For examples of activities created by teachers for use with the PhET simulations please see the PhET Activity Database (The PhET Team, 2006b).

Animation and Interactivity

- *Students notice animated features first; however, when only observing and not interacting, students do not ask questions or make new connections.*
- *User control of every perceived potentially significant parameter is valuable.*
- *Limiting students control over certain items must be done carefully.*

One of the most obvious benefits of presenting a concept using a simulation is that the simulation is animated. Interviews show that anything in motion draws the student's attention first; but, if the simulation simply demonstrates the motion of an object, students rarely develop new ideas or insights. In these cases, students seem to accept what they are seeing as a fact, but very rarely engage in understanding the meaning of the animation. In contrast, when students see an animated motion instantly change in response to their self-directed interaction with the simulation, new ideas form and they begin to make connections. Students create their own questions based on what they see the simulation do. With these questions in mind, they begin to investigate the simulation in an attempt to make sense of the information it provides. In this way, students answer their own questions and create connections between the information provided by the simulation and their previous knowledge.

A series of interviews on ‘Radio Waves’ illustrates the value of interactivity coupled with animation. The initial version of the simulation began with the full oscillating electric field emanating out from the transmitting antenna (see Figure III). At the beginning of these interviews students had very negative reactions to this mode that they would tend to watch passively. Students commented: “*Full field view doesn’t make sense to me*” or “*I don’t like this view*”. Students then watched the simulation and attempted to correct the predictions they had made before opening the simulation, without any interaction with the simulation. Their descriptions were incorrect, very superficial, and/or simply based on bits of prior knowledge. For example,

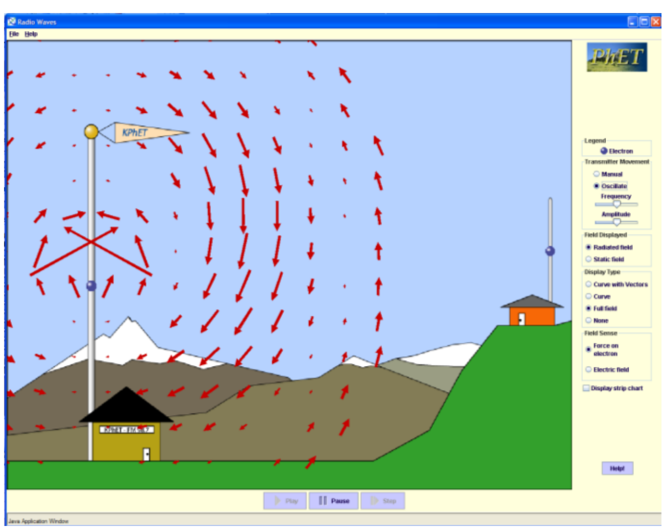


Figure III – An early version of ‘Radio Waves’. When the simulation first opens, the transmitting electron moves up and down along the antenna producing an electromagnetic wave that radiates out filling the screen with oscillating red arrows.

one student said that electric fields move in a circular direction. To answer the question of how a radio signal is transmitted students said: "*by radio waves*" or "*I don't know, I never thought about it*". Once the students began interacting with the simulation and switching views a few times, they all began to appreciate the full field view and made comments such as "*this makes sense, the wave has to go out in all directions or my radio would only work in one spot*" or "*this is my favorite view*". In all of the interviews, we've seen that interactions, guided by the student's personal questioning, are what make simulations an effective learning tool. Students engage in exploration and sense-making only *after* they begin to interact with the simulation. This finding suggests that the educational value of animations without interactivity is quite limited.

When making the simulation interactive, the choice of parameters that can be manipulated is important and several factors must be taken into account. By limiting the parameters that can be changed and by emphasizing particular controls, a simulation scaffolds and guides student thinking. While it is useful to provide scaffolding by allowing only relevant parameters to be adjusted, we find that it is sometimes also valuable to allow adjustment of parameters that students commonly think might have an effect on the phenomena, even if they do not. If students are limited to interacting with only the features that have an effect, their misconceptions about which parameters actually will/will not change a situation cannot be addressed. For example, 'Projectile Motion' allows students to manipulate many parameters including air resistance, mass and surface area. Many students believe a heavier object will have more air resistance. Since the parameter is available to change, even though they ‘know’ the answer, students try the parameter and are surprised by the result – learning from this control.

Because students learn that PhET simulations allow them to interact with the important objects on the screen, not allowing an object to be manipulated by the user also creates questioning and ideas. In ‘Radio Waves’, after users played with the transmitting electron, several tried to move the receiving electron and realized they could not directly manipulate its motion. See Figure III. Many asked, “*why doesn’t this one move?*” They investigated further and found that the only way to move it was to send a radio wave from the transmitting antenna. This lack of control sparked questioning that led to a better understanding of the effect a radio wave has on an electron.

On the other hand, disabling controls for non-physical reasons can lead to incorrect ideas because students attribute meaning to the ability to manipulate controls. We have seen many examples of this behavior. In ‘Quantum Tunneling’, for instance, the radio button that allows the user to view the incoming and reflected waves separately was initially disabled for wave packets and enabled for plane waves – implemented by graying out the radio button in wave packet mode. This restriction was not for any physical reason, but because it would have been difficult to program for wave packets and would have relatively little pedagogical value. In interviews, students became very frustrated that they could not use this control and tried to figure out the reason that it was grayed out for wave packets. In the current version, rather than graying out the control, it simply disappears in wave packet mode. Later interviews showed no problems with this implementation.

Little Puzzles/Clues (questions/answers that stimulate the student to explore and learn)

One effective way we've found to encourage exploration is to include little puzzles or tantalizing clues that stimulate the user to form questions that relate to the learning goals of the simulation. Many of these questions are easily answered by interacting briefly with the simulation and not only create understanding but increase confidence and motivation. Other questions are more involved and take some time to answer but are answerable by interacting with the simulation.

- *When students encounter small features that they do not understand, they will explore how interacting with that feature changes the simulation until they can create a working definition of the feature.*
- *Legends and control labels help students build connections, and then when they interact with the simulation, they learn a working definition of the term on the label.*
- *Multiple Representations - Simulations that have multiple views of the same item, such as beam view and photon view, facilitate further understanding and connections about the idea.*
- *Exploration is not always productive – elements that distract students' exploration in irrelevant directions must be avoided.*

Students quite often encounter a word in the simulation that they don't know. Typically when this happens, students play with the control that is labeled with the unknown word and subsequently create a working definition for the word. Frequency and amplitude were words students were unable to clearly describe before exploring the ‘Sound Waves’ simulation. After playing with the simulation, students correctly described the meaning of these words using visuals from the simulation. A few weeks later, during interviews on ‘Radio Waves’, the same students used the visual descriptions from ‘Sound Waves’ to describe frequency and amplitude. These non-science majors then used ‘Radio Waves’ to create an accurate working definition of an electric field. (See Figure III)

When using ‘Nuclear Physics’, students did not know what the abbreviations on the nuclei such as ^{235}U meant. In response, a small legend that included a thumbnail of the nuclei with the label Uranium 235 beside it was added to the top of the control panel. After this simple addition, further interviews with new students were conducted. All of these new students found the legend and used the correct terms to describe the nuclei from that point forward. In ‘Signal Circuit’ interviews, students were asked what was moving around the circuit. Only one student correctly identified the little blue dots as electrons. Once the other three students discovered that un-checking a box that said “show electrons” made the blue dots disappear, they corrected their responses given about 10 to 15 minutes earlier, to identity that it was electrons that were moving around the circuit. In each of these examples the text is very limited. We’ve found, as described in the *Help* section found in Part II, that legends and control labels can become useless if they contain too many words.

Multiple representations that can be clearly and easily switched between, are also an effective way to get the students to ask questions about what they are seeing and to interact with the simulation. For example, in ‘Color Vision’ both beam view and photon view are offered for the light going from a lamp to Howie Hue’s eye. During interviews, students were unsure about the photon view until they switched to beam view. Once they explored these two views, all students stated with confidence that they are the same thing. A student exploring these views for the white light said: “*One just shows the tiny little photons so you can see the separate colors.”*

Although encouraging exploration is necessary for learning, it is also possible to create features in the simulations that encourage exploration and student thought that is not productive. As an example, in an earlier version of ‘Color Vision’ a pulsing brain inside of Howie Hue’s head was used to represent that Howie’s brain was interpreting colors that entered his eyes. This was displayed when a “Show Inside” checkbox was checked. Every student who was interviewed on this simulation spent a fair amount of time playing with the check box and looking at the brain carefully while changing the other parameters of the simulation. All students were looking for some feature of the pulsing brain to change if the appropriate parameters were selected. Some students quickly determined that there was no conceptual value to the pulsing brain feature *“Obviously this guy has a brain.”,* and others had to be told by the interviewer that there was no significance to the brain *"K, the, well the brain doesn't seem to be doing anything when I show the color, so I don't know if….really why it's there"*. This pulsing brain feature encouraged exploration and thought from all students interviewed; however, no further understanding of the concepts was garnered from this exploration.

Fun

- *When the simulations are fun, students enjoy playing with them. The Flash simulations, and Java simulations with similar characteristics, draw students to them.*
- *When simulations look boring or intimidating, students are not drawn to playing or they are afraid they will break them.*
- *Features can be so much fun to play with that students are distracted from learning.*

To engage students in exploration, students should want to play with the simulations. Every feature adds to a student's cognitive load and so needs to have educational purpose. The example of the pulsing brain is one of a number of examples we have seen where features violated this rule. This point must also be considered in how one designs fun into simulations. If a feature is fun, it must also create learning. There seem to be two levels of fun. The first level is the surface appearance; if the simulation is fun-looking (game like, colorful and cartoon-like, interesting graphics, non-threatening…) students want to try it out. When student users browse the PhET website, they consistently choose Flash simulations over Java simulations. Extensive discussions with users have provided vague answers such as, *"they look more fun"*. We hypothesize that the bright colors, 3-d look of the controls, and simple cartoon-like features are what attract users to the Flash simulations. Too crude and simplistic graphics, or an overly complex appearance, are both perceived as less fun. We've seen a positive response to subsequent Java simulations that incorporate many of the same characteristics of the Flash simulations, supporting our hypothesis.

We've also seen in interviews that when a simulation is first opened up, if it appears too complicated or has unfamiliar features, students are less likely to engage without interviewer intervention. If the simulation has the look of a lab workbook – meaning lots of numbers and detail such as closely spaced graph lines and abstract representations of the physical features – then students are not only less interested but actually uncomfortable about using such simulations. They are afraid they will break them and make comments about "…*[not knowing] how to use stuff like that*." If they don't know what physical item is being depicted on the screen, they are very uncomfortable manipulating that item.

The next level of fun moves beyond merely stimulating initial interest to repeated voluntary use of the simulation. There are several simulations that students regularly say they play with during their leisure time, including 'Electric Field Hockey', 'Circuit Construction Kit (CCK)', 'The Maze Game', 'Travoltage', 'Energy Skate Park' and 'Ramps'. In each of these simulations we've

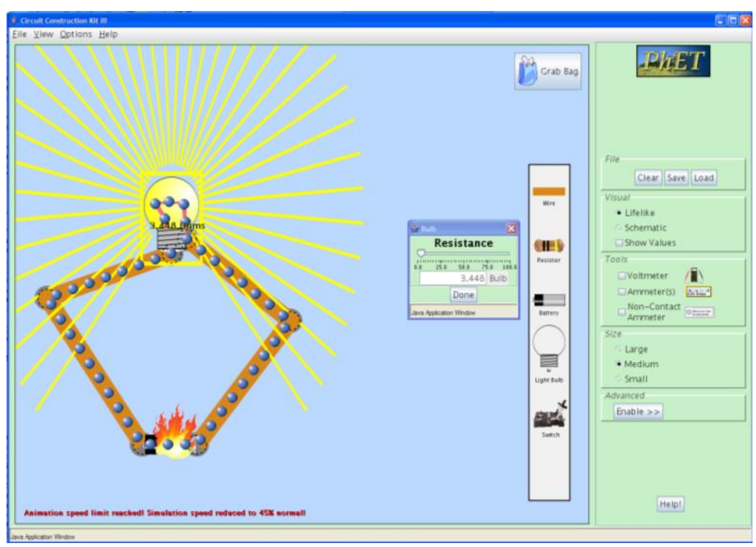


Figure IV – 'CCK'. Fun engaging features are included such as the brightness of the bulb changes as students adjust resistance and voltage or the battery can catch on fire.

worked to successfully add game-like features that create a fun environment for exploration. Interviews show that the addictive features of these simulations now focus on the central physics concept of the simulation. For example in 'CCK' as current is increased through a light bulb, it becomes brighter and when too much current runs through a battery, it catches on fire (Figure IV). In 'The Maze Game' a student can adjust one of three parameters (position, velocity or acceleration) while attempting to direct a ball through a maze. An annoying pop sounds if a barrier is hit and a satisfying music clip is played when the goal is reached. These little features create environments where students spend their free time becoming familiar with the concept of electric charge or the differences between velocity and acceleration.

However, there is a fine line between a fun simulation that stimulates learning and fun features of a simulation that distract the student from learning. 'Ramps' provided an example of the latter. In this simulation, bar graphs represent different forms of energy including kinetic, potential and thermal. With continued friction, the thermal energy bar increases and eventually extends off the screen. For this reason, we added a way to reset the thermal energy. When the user clicks "Cool Ramp" a firefighting dog comes out and sprays water from a fire hose on the ramp to cool it off. Originally, each time the button was clicked, a new dog appeared. Students reacted by seeing how many firefighting dogs can fit on their screen at once – a fun, but unproductive, game. Even teachers who were in a workshop learning about the simulations engaged in the same unproductive behavior of adding as many firefighting dogs as possible. Interviews showed that a suitable balance was achieved by allowing only a single dog to appear. This approach preserved the pedagogical value of using the firefighting dog to stimulate the students to think about how the ramp was heating up and connect that to the physics of the conversion of mechanical energy to thermal energy, while avoiding the danger that simply creating more firefighting dogs became the focus of attention.

Credibility of Simulations

- *For engaged exploration to occur, students must believe the simulation.*
- *Student's level of skepticism is related to their level in school.*

One important question is: How skeptical are students about the correctness of the simulations? The answer is particularly relevant when the simulation gives results that students do not expect and hence have the most to learn from. We have found students to be quite trusting of the simulations, e.g. *"These are really smart people. I'm sure they don't make mistakes."* However, our observations have found that students' level of skepticism is related to their level in school. Non-science majors are very trusting while students in quantum mechanics are quite skeptical. There have been a few cases where the quantum mechanics instructor points out a bug in the simulation during class. Afterwards students were observed to typically take the simulation less seriously. Similar reactions were encountered during quantum mechanics interviews. If the interviewer said that a simulation was still under development or might have bugs, students were much more likely to attribute what they did not understand to programming bugs. On the other hand, introductory students have been disturbingly trusting of simulations, even to the point of attributing significance to behaviors observed under conditions where they were explicitly told the simulation did not function properly.

This high level of trust is demonstrated by a task associated with the first version of 'Energy Skate Park' (formally 'Energy Conservation Kit'). During the first semester of physics for non-science majors, we added short simulation questions to the end of the student's weekly homework assignments. The questions covered material that the students had not yet been introduced to in class. One such task asked the students "If a person wanted to lift a 1 kg rock to a height of 20 meters on Earth or to the same height on the moon, will it require more work (Energy input) on the moon or on Earth? 91% of students correctly predicted that it requires more work to lift the rock on the Earth. After playing with the simulation only 17% of the students believed it took more work on the Earth. Upon close inspection of the simulation we discovered that the default mass for the object on Earth was 1 kg and on the moon it was 1650 kg. After finding the opposite result from what they expected, students trusted the simulation (or at least believed this was the answer we were looking for) and answered accordingly.

Performance Mode

- *Students who do not believe they already know the relevant ideas, are more likely to explore a simulation and use it to learn. Students who think they should understand the topic of a simulation often use it much less effectively and learn much less from it.*

The profound effect of students' self-expectations is illustrated by the multiple interviews that have been done on the 'Radio Waves' simulation. This topic is not important for simulation design, but it is very important for simulation use and testing. These and similar interviews revealed that if students think they understand material prior to the interview and in this case, have previous experience with the simulation, they lapse into what we call "performance mode" – equivalent to behavior associated with performance goals as described by Dweck (1989). In this mode students have difficulty exploring and learning effectively from the simulation. They try to recall what they know and make excuses for their lack of answers. Students who have not covered the simulation in class have very different expectations and are much better at exploring the simulation to develop understanding.

In the fall of 2003, we conducted two sets of interviews on 'Radio Waves' with four students from the first semester of physics for non-science majors. The following semester, we interviewed on 'Radio Waves' again using students enrolled in the second half of this two course sequence. Three of the spring interviewees had taken the first semester of the sequence (one had also been interviewed in the fall), while the fourth student had enrolled in the second semester of the sequence without taking the first semester. The first set of interviews in the fall showed the simulation to be quite successful. These non-science majors gained an impressive conceptual understanding of an electric field from the simulation, before they had ever encountered the term "electric field" in class. Later in the fall semester the concept of an electric field and the 'Radio Waves' simulation were covered as part of the course.

During the spring interviews, a very different pattern was observed. Three of the students interviewed struggled with the simulation, rushed through it, and never really effectively engaged in learning from the simulation. The two students who had taken the first semester course but had not participated in the fall interviews reacted similarly to the 'Radio Waves' simulation. In one case, once the interviewer started asking questions about radio waves, the student quickly decided he didn't understand, and rather than exploring with the simulation to find answers, he responded that he'd aced the homework in the fall and couldn't understand why he didn't get it now. In the other case, as soon as the student was asked the first question, she responded that she had missed a lot of class during this section. Every time she was asked a question, she said, "*I haven't had lecture on this*". When asked further questions, she simply said, "*I just don't understand this stuff*". She kept apologizing, gave fast answers, and the interviewer was quite unsuccessful getting her to look at the simulation and think about what it was depicting. When talking about other simulations in previous interviews, this student appeared to be one of the most intelligent and resourceful.

The third student was an interview subject both during the fall and spring semesters. She was able to work out a reasonable definition of an electric field during her fall interview, but in the spring she responded differently. When the spring interview began, she said she liked this simulation and that it was one of her favorites as she opened it. By the end she said she didn't like it anymore. She was confused and couldn't believe she didn't remember all of it. When attempts were made to guide her, she'd just say, *"I should know this*" and didn't appear to really think it through. She just kept trying to remember and became increasingly frustrated. At times during the interviews, these three students would begin to engage with the simulation, but as soon as they'd make a connection with something in their memory, they'd slip back into unproductive *performance mode*.

In contrast, the fourth interview student in the spring, who had appeared to be the weakest during all previous interviews that semester, performed as well or better than the students had in the fall 'Radio Waves' interviews. This student had not taken the first semester of the course sequence, and so had never seen the 'Radio Waves' simulation nor had formal instruction on electric fields. This student began by saying he knew nothing about radio waves and was more relaxed than the others. When he started with the simulation he wiggled the electron and said "*it appears to be some sort of wave simulation but I haven't had lecture on this stuff so don't understand it*". He proceeded to carefully explore the simulation with only very minor encouragement from the interviewer. In fact, this interview was the first where he actually slowed down and explored. In prior interviews on other simulations, if he'd used the ideas in homework, he would generally rush through the simulation. It typically required a lot of intervention from the interviewer to get him to slow down, reflect, and explain in these previous interviews. When he didn't know something previously, he had tended to become frustrated and annoyed (more so than the other three). However, now working with 'Radio Waves' he took his time, didn't seem bothered if he didn't know something, and worked through most of the concepts very successfully. This level of engagement and learning was similar to the 'Radio Waves' interviews during the previous fall semester, before students had seen the topic in class.

Students often begin any interview that involves some familiar ideas in *performance mode*, explaining what they know. The more the students believe they know, the less they engage with the simulation and the greater their tendency to become tense and frustrated when asked questions they don't quite understand. When in *performance mode,* they move too quickly through the simulation for it to help them clarify their thoughts. The above 'Radio Waves' interviews are an extreme example of this problem since not only had the students had instruction on this topic; but, they also had experience with this simulation and thought they should know everything. They did remember a lot of useful information, but anything that was not completely clear frustrated them, and they were reluctant to slow down and learn from the simulation. In all other simulation interviews, it took only a short amount of time and occasionally a little prompting before students started exploring the simulation and making sense of the presentation provided by the simulation. During the quantum mechanics interviews with upper-level students, this transition into engaged exploration occurred quickly and without prompting. These students seem to realize that they are far from mastering quantum mechanics and in general have stronger meta-cognitive skills than the non-science majors who typically interview on the introductory simulations.

Discussion

In these interviews we find that nearly all the simulations, after suitable testing and revision, consistently result in a high level of learning in our diverse group of interview subjects. After a simulation interview, most students understand the concepts covered in the simulation well enough to explain them accurately and to use them to make accurate predictions about behaviors in the simulation. Students also often volunteer correct predictions or explanations about related real world phenomena. This level of understanding is far beyond what we have observed is typically obtained from the coverage of these concepts in a physics course. There are some reasons why simulations help student learning that are very obvious from our interviews and so shape our design characteristics – e.g. the ability to provide visual models. These reasons were described above or can be found in Part II, in the relevant sections. However, in this work we primarily focus on the somewhat simpler problem, namely *what* characteristics a simulation should have to achieve this impressive level of learning that we have observed. A detailed analysis of how and why simulations result in such learning will be the focus of future work.

The PhET Look and Feel

From these interviews we created the "PhET Look and Feel" (Appendix B), which the design teams now follow while creating a new simulation. During the first year of interviews, when the look and feel was still in the early development stages, student difficulties ranged from simulation usability to conceptual problems. These difficulties included problems such as interface design, help functions, tool placement, effective types of representations, and what types of features encouraged students to interact with and think about the simulation. Many interface problems and successes were found to be consistent from simulation to simulation, and thus informed our simulation design guidelines contained in the PhET Look and Feel. We would typically research particular aspects of the interface design in depth using multiple versions of the same simulation, and then utilize those results in designing subsequent simulations. Results from interviews on the subsequent simulations would then confirm or refine the design guidelines.

Interviews have also revealed three different levels of usability:

1. Non-intuitive –difficult to use even with instruction.
2. Semi-intuitive – easy to use after instruction and demonstration; and
3. Intuitive – easy to use with no instruction.

It is relatively easy to create a simulation that will be easy for a student to use after observing a demonstration. It is more difficult to create an intuitive simulation that requires no instructions; but, we have found that an intuitive simulation can be designed rather routinely (even for rather complex simulations) by following the now highly-refined PhET Look and Feel guidelines derived from our interview studies. Thus, our new simulations rarely have usability issues, and our current interviews focus primarily on a simulation's ability to engage the student and achieve the desired learning goals.

In this paper we described the *Encourage Exploration* section of the PhET Look and Feel, while the second paper, Part II, contains the larger part of the PhET Look and Feel that focuses on the features we have found to be successful at creating an *intuitive* interface as defined above. This second paper also contains extensive interview results to support each feature of the PhET Look and Feel.

Underlying Principles

Three major principles support nearly all of the desirable design features identified through our interview studies and are consistent with the literature. These include *Engaged Exploration,* the *Coherence Principle* (Clark & Mayer, 2003) and *Consistency*.

Engaged Exploration

- *When in engaged exploration, students are actively working to make sense of the information before them.*
- *Students are more easily engaged in the exploration of topics that include relatively unfamiliar science.*

We have found it particularly important to get the students involved in what we have labeled as *engaged exploration*. When in *engaged exploration*, students are posing questions and seeking answers by observing the results of their own interactions with the simulation and making sense of what they see. We have seen various reasons for students not to engage in exploring a simulation. A short, but far from exhaustive list includes: they have been interacting with the simulation for a very short time; they are unable to successfully figure out how to use the simulation; they are overwhelmed by the simulation and do not know where to start; or they believe that they are familiar with the content and attempt to quickly explain the scientific concepts to the interviewer simply using the simulation as a demonstration tool, rather than as a learning tool. The idea of *engaged exploration* is consistent with work by Minstrell and Kraus (2005) and Dweck (1989).

Coherence Principle

- *Adding interesting but unnecessary material to simulations can harm the learning process in several ways.*

Clark and Mayer's (2003) Coherence principle describes many of the simulation features that our interviews have shown are important. The empirically-based Coherence principle emphasizes the importance of having all elements (controls and visual cues) directly related to the learning goals of the simulation and excluding extraneous information. Clark and Mayer (2003) discuss how unnecessary information can interfere with learning in three ways: *"distraction* – by guiding the learner's limited attention away from the relevant material and towards the irrelevant material; *disruption* – by preventing the learner from building appropriate links among pieces of relevant material because pieces of irrelevant material are in the way; *seduction* – by priming inappropriate existing knowledge (suggested by added visual cues, sounds, or words), which is then used to organize the incoming material." Our research has repeatedly confirmed the need to limit simulation features to only those items that are directly necessary to convey the learning goals of the simulation.

Consistency

- *Users' interpretation and use of simulations depends heavily on their prior experiences.*

As described in the *Interview Methodology* section, interviews were conducted with students who had various levels of experience with PhET simulations. Users experienced with one or more simulations were able to start using a new simulation more quickly than completely inexperienced users. Experienced PhET users also ‘know’ what a particular representation should look like and bring what they’ve discovered from one simulation to the next. However, experienced users were bothered by seemingly minor inconsistencies between simulations, even if the subject of the simulation was quite different.

Further Work

The PhET interviews have provided a rich source of ideas for further studies of student thinking and learning with interactive simulations. We see students clearly achieving impressive levels of mastery on a variety of difficult topics in physics. It will be interesting to study in more detail what are the topic specific questions they formulate in working with the simulations, how do students address these questions, and how does that result in their understanding? By exploring these issues with a number of students, it will provide a greater understanding of topic specific learning and how better to teach these subjects, with or without the use of simulations. A second area of potential research is based on the observations of how students used the ideas they developed using ‘Sound Waves’ to understand ‘Radio Waves’. We are currently building on this to explore the broader issue of analogical scaffolding in creating understanding (Podolefsky & Finkelstein, 2006). A third interesting area is the use of gesture by the students while using and discussing simulations. The use of gesture while interacting with simulations was analyzed and coded in order to help interpret the interviews (Adams, 2004). It was seen that there was a decrease in rate of gesture while using simulations, and that students generally use deictic gesture (indicating an object or person by pointing to where they are or have been) while using the simulations. Instances where students use lexical forms of gesture (smooth, continuous shapes in space indicating places, objects or ideas) are indicative of either students drawing on prior knowledge, or if the gesture mimics the simulation, the simulation is not quick enough in demonstrating the necessary animation. These observations support the notion that the simulations can be considered an extension of gesture, and suggest that analysis of gesture can be a useful tool for analyzing student interactions with simulations, and how they are using simulations to construct meaning.

Conclusion

We have carried out extensive interview studies on the student use and learning from interactive simulations for teaching physics. We find overwhelming evidence that simulations that suitably incorporate interactivity, animation, and context can provide a powerful learning environment where the students productively engage with and master physics content. However, we find that this can only be achieved by following an extensive set of principles for design and layout as contained in the PhET Look and Feel. Here we have included only one section of the PhET Look and Feel, *Encourage Exploration*, while the sequel to this paper contains the detailed specific design guidelines along with relevant interview results for creating an intuitive simulation including layout, representations, tool use and help functions. This work reveals many design pitfalls that can result in simulations not achieving the desired educational effectiveness. Finally, this work demonstrates the importance of testing educational simulations carefully with the desired target users.

Acknowledgements

We would like to thank Danielle Harlow, Noah Podolefsky, and Stephanie Fonda who conducted some of the interviews whose results are incorporated in this paper. We also thank Noah Finkelstein and the other members of the Colorado Physics Education Research group for many useful discussions. We are pleased to acknowledge support of this work by the University of Colorado, the National Science Foundation, the Kavli Operating Institute, and the Hewlett Foundation.

A Study of Educational Simulations Part II –

Interface Design

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Abstract

Interactive computer simulations with complex representations and sophisticated graphics are a relatively new addition to the classroom, and research in this area is limited. We have conducted over 200 individual student interviews during which the students described what they were thinking as they interacted with simulations. These interviews were conducted as part of the research and design of simulations for the Physics Education Technology (PhET) project. PhET is an ongoing project that has developed over 60 simulations for use in teaching physics, chemistry, and physical science. These interviews are a rich source of information about how students interact with computer simulations and what makes an educationally effective simulation. The interviews demonstrate that the simulation must function intuitively or the student's attention is focused on how to use the simulation rather than on the topic presented. Here we provide guidelines for intuitive interface design developed by this research. These cover layout, tool use, help and representations that we use to create a simulation. We give examples from interviews which demonstrate the effectiveness of each guideline for engaging students in educationally productive interactions.

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Introduction

Computer animations and interactive simulations are commonly found in today's classroom and have been integrated in a variety of ways. This popularity is partly due to the fact that simulations are quite easy to introduce into a curriculum. Textbooks now regularly include DVDs or a URL to websites with a library of various simulations. While many educators (Christian & Belloni, 2001) find it appealing to use simulations in their classroom, very little research has been done to determine if simulations improve a student's understanding of or enthusiasm for science and how simulations can be designed and used most effectively. Available simulations use a wide variety of appearances, controls, graphics, interactivity, and design principles, often guided only by the designers' preferences or ease of coding. Little is known, however, about design principles and features that are important for optimal student use and understanding (Viadero, 2007).[1]

[1] For a more extensive discussion of the history of simulation design please see Part I.

An extensive analysis of student use of simulations, including comparisons of multiple incarnations of a single simulation using different interface design features has been done as a part of the Physics Education Technology (PhET)[2] Project (Perkins et al., 2006; The PhET Team, 2006a). This analysis has led to an empirically determined and tested set of design principles based on our observations of student use. This research focuses on identifying which characteristics make a simulation effective or ineffective through the use of extensive think-aloud student interviews using simulations. This paper is Part II of a two part series. Part I (Adams, Reid, LeMaster, McKagan, Perkins and Wieman, 2007), focuses on the general features of a simulation that are most important for achieving engagement and learning. Here specific details on interface design that are important for supporting these general features are described, including characteristics that make a simulation engaging and easy to use, types of controls that are intuitive for the student, effective use of representations, the impact of different types of *help* and the impact of even small amounts of irrelevant information.

Background

Part I focuses on the simulation design process, examining those features that encourage students to explore and understand physical relationships and engage them in the process of 'discovering' the desired learning goals of the simulation. We also discussed the interview research methodology and protocol, and surprising degree of consistency in responses. Here we will only give a brief description of our interview

[2] PhET is an ongoing program to develop an extensive suite of freely available online simulations for teaching and learning physic, chemistry and physical science.

methodology and how our design guidelines were created. For a more in depth discussion of this and other research and the theoretical principles which support our guidelines, please see Part I.

Interview Methodology

Over the past three years we have video-taped more than 200 simulation interviews with 89 different students covering 52 of 60 simulations. Student interviewees are volunteers that are typically non-science majors who have typically not yet received formal instruction on the ideas covered by the simulation. For the more advanced quantum simulations, we also interview physics majors. For each simulation, we typically interview a diverse group of four to six students.

Our standard interview protocol includes the following: in the first interview with a particular student, the interviewer begins by getting to know the student, asking about their background, career and major choices, and courses. Once the student relaxes, and in all subsequent interviews with that student, the simulations are explored in a think-aloud style format. With this approach, the students are asked to talk out-loud while they investigate the simulation. The simulation explorations are structured one of two ways: 1) The student is asked prediction-type conceptual questions (where the student describes their understanding of an idea/concept before seeing the simulation) to guide their interactions. Then, after, or more often while, interacting with the simulation, they are allowed to revise their answer; or 2) The student is simply asked to explore the simulation freely without a guiding question.

The PhET Look and Feel

The summary of this research on interface design is embodied in the "PhET Look and Feel" (Appendix B), which the design teams now follow while creating a new simulation. During the first year of interviews, when the look and feel was still in the early development stages, student difficulties ranged from simulation usability to conceptual problems. These difficulties included problems such as interface design, help functions, tool placement, effective types of representations, and what types of features encouraged students to interact with and think about the simulation (Figure I). Many interface problems and successes were found to be consistent from simulation to simulation, and thus informed our simulation design guidelines contained in the PhET Look and Feel. We would typically research particular aspects of the interface design in depth using multiple versions of the same simulation, and then utilize those results in designing subsequent simulations. Results from interviews on the subsequent simulations would then confirm or refine the design guidelines.

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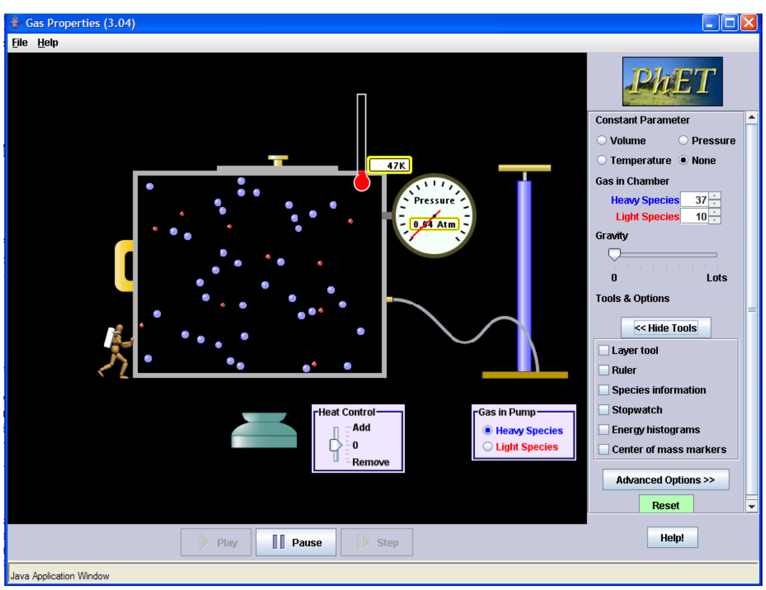
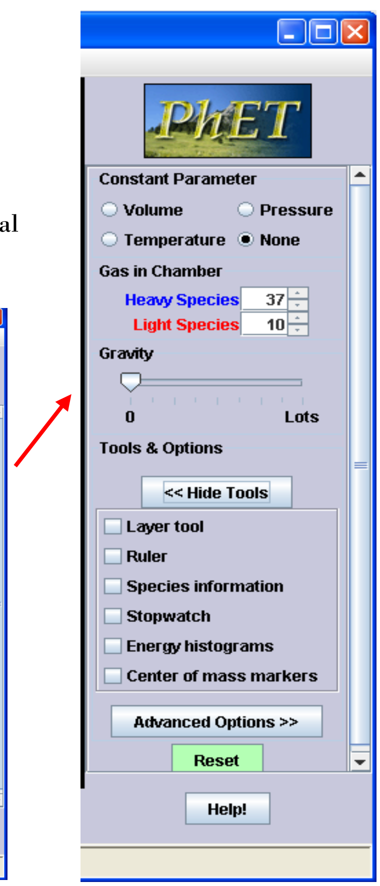
In this paper we present the interview results which led to the larger part of the PhET Look and Feel that focuses on the features we have found to be successful at creating an *intuitive* interface while the first paper, Part I, contains the *Encourage*

Figure I – Interface Design: The black region is the play area containing the representations of physical objects that students can manipulate themselves and observe the effects of their actions instantly. The grey area on the right is the control panel which contains radio buttons, sliders and text boxes for adjusting various parameters and in the lower half of the control panel there are several tools for the students to use while working in the play area.





Exploration section of the PhET Look and Feel.

Interview Results

The following discussions of design features focus on the specific simulations and interviews where the problems were discovered, the potential solutions were explored, and the desirable design features first confirmed. We have checked the validity of these design features and principles in subsequent interviews with new simulations; however, in the interest of brevity, discussions of these follow up interviews will not usually be provided in these papers when the interviews merely confirmed the previously observed results. All general conclusions presented here have been confirmed with interviews on at least several simulations.

Intuitive Controls

Engaging students in exploration of the simulation can only happen if they can readily use the simulation. If simulation controls are difficult to master, students' attention is focused on the use of the simulation rather than on the exploration of scientific concepts. In this section we focus on controls which are intuitive for users and don't distract from the learning goals.

- *Interviews showed that certain types of controls are intuitive for users. These types of controls are independent of the content of the simulation.*
- *If highly non-intuitive controls are used, even with 'help' in the simulation or tutoring from the interviewer, many students still cannot use the simulation.*

Analysis of the first year of interviews consistently revealed that particular types of controls are intuitive to students while other types of controls prove more difficult to master regardless of the concept being addressed by the simulation. Much of the study of different control use was carried out using various versions of ‘CCK’. This simulation underwent several rounds of interviews and extensive rewrites until it reached its present form.

The effectiveness of user interface items revealed by the study of this specific simulation, such as *grabbable objects, sliders* with immediate response for adjusting numerical values, and *radio buttons* for turning things on and off, has proven to be quite general. Many subsequent interviews with a variety of simulations have shown these to be consistently intuitive, independent of the simulation content. Student’s desire to grab objects with the mouse and their ability to readily use these controls is suggestive that controls are more intuitive when they most resemble using the mouse as a simple extension of direct manipulations by hand.

Click and Drag Interface

- *Click and drag is the most natural motion for students.*

The first version of ‘CCK’ used ‘mode-switching’ – similar to a paint program. When the user clicked on a battery in the tool box, the mouse became a battery tool and would create a battery in the play area each time the user clicked in the play area. This battery could then be manipulated within the play area along with other components such as wires, resistors, light bulbs and switches to create a circuit. (See Figure IIa) With this user interface, none of the four students interviewed figured out how to build a circuit on their own, although one did figure out how to get components into the play area but could not connect them. In the end, three of the students were able to readily build circuits after it was explained and demonstrated for them. The fourth never mastered it and quit in frustration. She kept performing common mouse motions that she knew by instinct such as double clicking or dragging from the tool bar even after being shown by the interviewer how to use the simulation. She became frustrated and said "*here, you do it!*" so the interview could build circuits for her to use.

Before interviewing on this simulation, we were aware that some instruction was required before students could use the simulation to do their homework. However, once instructed they used it easily in small groups. As a result, the extent of its difficulties went unnoticed until interviews were conducted. This example emphasizes how easily one can be misled into creating simulations that the first time user will find difficult or impossible to use.

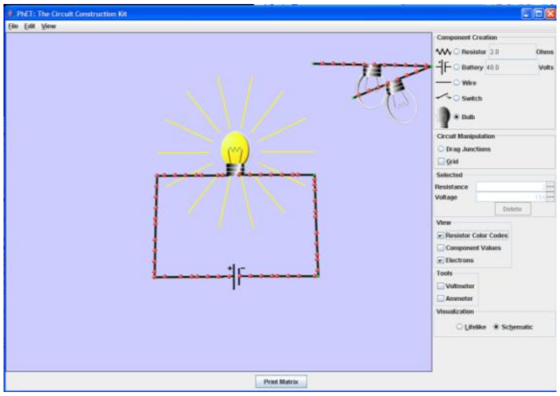


Figure II a – ‘CCK’ Version I. The ‘mode-switching’ interface changed mouse function. In the above case the mouse was set to create light bulbs. When the user tried to drag a battery from the tool box, they ended up with light bulbs hanging out of the tool box.

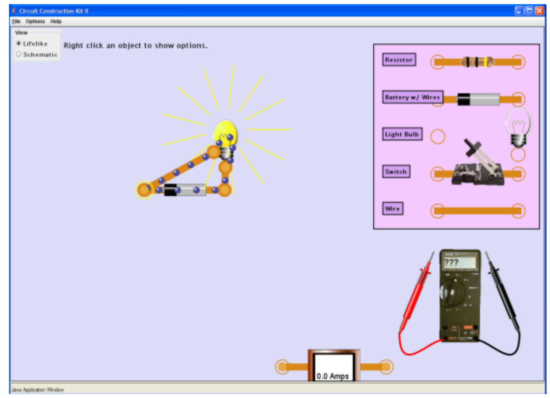


Figure II b – ‘CCK’ Version II. This new version uses the more intuitive ‘click-and-drag’ style interface.

Since demonstration by interviewer or in class demonstration was quite adequate for most students with this type of interface, we tried adding help to the simulation as a substitute for personal demonstration; however, adding help was unsuccessful. (See the section below on *Help!* for more detail.) To solve this interface problem, ‘CCK’ was completely rewritten with a click and drag interface based on the interview students’ instincts which were to click and drag from the tool box (Figure IIb).

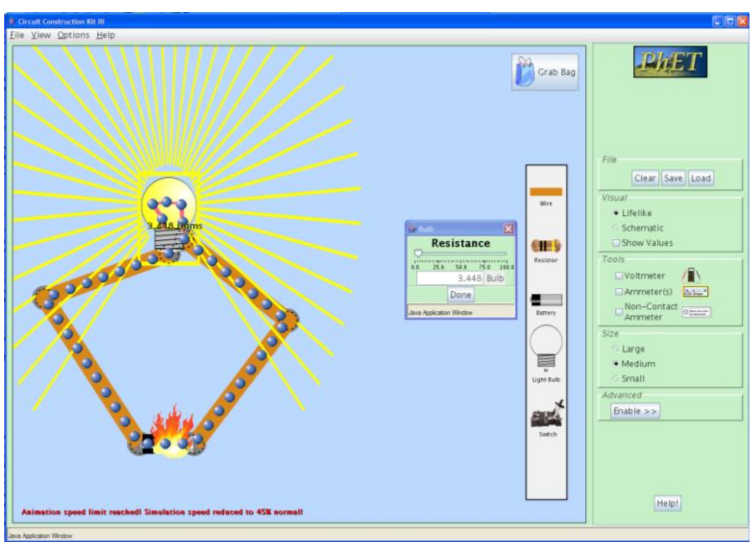


Figure III – ‘CCK’ Version 3. Right-clicking on a component brings up controls for that object such as the light bulb as shown.

After the rewrite was complete, five students were interviewed (three new ones plus two from the first set of interviews). During this series of interviews, the major difficulties were gone and students had limited, but consistent, problems with the interface that were connected with representations. Four of the five students had difficulty determining that a connection had been created. The ends of two components had to be placed nearly on top of one another before a connection was established. A red circle around a junction indicated no connection; however, the students did not pick up on this cue. Another problem that surfaced with four of the five subjects was finding that the light bulb connects at the bottom and then only on the left side of the bulb. Students would try the right hand side first at times never finding the connection on the left. In addition, batteries came with wires attached and students wanted to make new connections directly to the battery terminals. To deal with the problems with all junction connections, we decided to change the representations to make all junctions more obvious and another total rewrite took place that provided a somewhat less realistic representation. (see Figure III) This included loosening the tolerance for connection so a connection was established quite easily. Later interviews, using the final version of 'CCK', did not reveal interface difficulties with the exception of one user who did not know he could right click on a component to access further controls. This series of interviews and rewrites illustrates the coupling of visual representation and interface issues, as well as illustrating the need for using representations that emphasize important features beyond what appears necessary to someone already expert in the topic.

Grabbable Objects

- *Students try to move anything that looks useful.*

Our interviews have shown that it is particularly effective to have objects in the play area (Figure I) that can be directly manipulated by the students. This approach gives them direct control over the physical situation, and they can test out various setups within the simulation. With all simulations we observe that the students first click on the objects in the play area and try to manipulate them, before looking to the control panel for other controls. The instinct to manipulate objects in the play area first is closely related to the click and drag interface. Users first try direct manipulation of objects; as in the real world. The set of 'Projectile Motion' interviews is one of many examples that demonstrate this point. All students began interacting with the simulation by clicking on the canon in an attempt to ascertain its functionality. They quickly discovered that they could change the angle of the cannon (Figure IV). Three of the four students then tried to grab David, who stands by the cannon (for the purpose of scale). Two of the students also moved the target around a bit. Once students had played with all movable objects in the play area, they then used the fire button. It wasn't until the students had played for about 10 minutes that they started to explore the radio buttons and adjustable

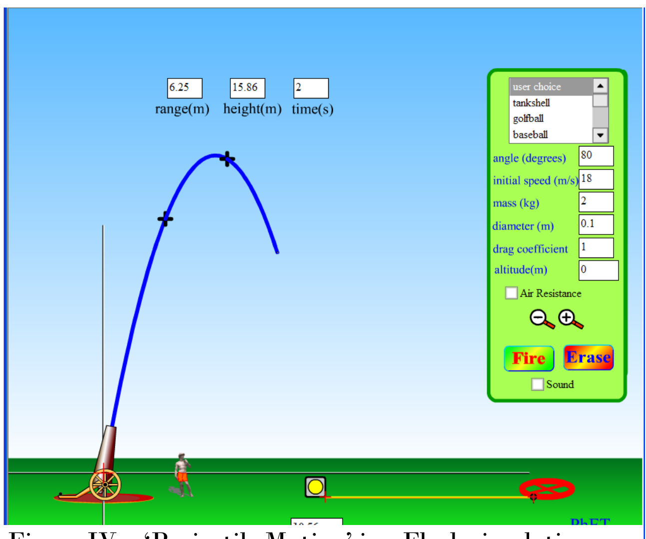


Figure IV – 'Projectile Motion' is a Flash simulation that traces the path of a projectile as it is shot out of a cannon. A target and tape measure are available in the play area if needed.

controls in the control panel. This sort of exploration, where items in the play area are manipulated before looking to the control panel, is common in all interviews.

Sliders, Radio Buttons and Checkboxes.

- *Students are familiar with the functionality of radio buttons and sliders.*
- *Students use sliders when they first explore a simulation and then turn to the digital input when completing a specific task such as homework or lab.*
- *Students turn things on with a checkbox but seldom turn things off.*

When a control cannot be placed on a specific item in the play area, we rely on controls in the control panel. For example, if a representation will be changed or the user can change an all encompassing parameter such as which planet the simulation is on, then the control panel is utilized. For example, in ‘Energy Skate Park’ a slider in the control panel adjusts gravity. During interviews students have never required instruction on the use of sliders and radio buttons; however, checkboxes have caused some confusion at times. Students do not have difficulty turning check boxes on; however, quite often they do not think to uncheck the box when they want to turn something off. Their instinct is to choose a new setting which will erase the old setting, similar to the functionality of a radio button. An extreme example comes from ‘Radio Waves’ where a checkbox is used to bring up an additional small window with a strip chart graphing electron positions. This window did not have a red x in the upper right corner to close it; instead the user was required to uncheck the box to remove the chart. During interviews, none of the students turned to un-checking the box to remove the window when they wanted to get rid of it. They either asked for help or moved the window off to the side. The addition of a red x in the upper right-hand corner of pop-up windows or graphs solved this since students are familiar with this type of control to close a window.

When using sliders, we've found it useful to combine them with a digital readout box that allows numbers to be directly typed in. In interviews when a user is first exploring the simulation and starts interacting with the sliders, they tend to use the slider to determine the basic effect: e.g. less gravity lets the speeding skateboarder bounce higher in 'Energy Skate Park'. We have found these sliders (as well as draggable objects) to be more engaging and better at encouraging interaction and exploration than direct number entry. However, when the students are completing a homework assignment or using a simulation in lab where they need to use particular values, they prefer the efficiency and control afforded by a text box that allows them to enter the exact value, e.g. setting the position, velocity and/or acceleration in 'Moving Man' or adjusting the voltage of the battery or the resistance of the light bulb in 'CCK' as shown in Figure III.

There may be other types of intuitive tools beyond what we have listed here. Once we identified this set of intuitive tools, we continued to use them and did not examine other possibilities.

Consistent Set of Tools

- *Experienced PhET users have little difficulty immediately interacting with a new simulation.*

- *Experienced users "know" what something should look like. If the appearance does not match their expectations, it makes it considerably harder for them to figure out what it is.*

We have found it helpful to provide consistent controls and tools (stopwatch, ruler, tape measure). The PhET interviews were often conducted with the same set of students throughout a semester. These students became familiar with the 'PhET look and feel' and were able to immediately begin investigating the physical concepts associated with new simulations presented during the weeks following their initial interviews. There were times that multiple iterations of interviews were required for the same simulation. In these cases, we would bring in additional students and often these students would also be first time PhET users. These 'first timers' take a little more time (around 5 minutes) finding controls or becoming familiar with tools. For example, during the interviews on 'Nuclear Physics', several new students were interviewed. All three of these students took more time to explore the control panel and figure out how the controls worked for adding Uranium, while the experienced PhET users knew how to do this immediately when they first encountered this particular simulation.

On the other hand, when the experienced user thinks they know how something should look/function based on one simulation, and it appears differently in another simulation, they do not recognize the tool's function and quite often spend time trying to determine what is different about its functionality. These differences created difficulties for the experienced PhET users but not for a brand new user. For example, 'CCK' has probes attached to a voltmeter. Students learned how to use the meter and move the probes around without difficulty during interviews. Some of the same students were interviewed on ‘Semiconductors’. In this simulation, similar looking probes are used to show that the energy levels on the side are a measure of what is happening in the semiconductor. These probes do not move. The students who had experience with ‘CCK’ were very bothered by the fact that they could not move the probes to different locations. Interviews were also performed on ‘Semiconductors’ with students who had not previously used ‘CCK’ and they were not concerned that these probes were stationary.

Representations

The obvious benefit of a computer simulation is the animated *visual model* that is provided for the student. It is far simpler and more reliable to show students how something moves rather than telling them about that motion or describing it in written text. With a simulation, behavior can not only be explicitly shown, but the student is able to *interact* with the objects on the screen and determine for themselves what happens as things are changed. Visual representations must be created with care because we observe that when students are learning about the phenomena they will apply equal importance to every feature. We have also found that care must be taken not to overwhelm the students with too much new information at once. Using common *real world* objects gives students a place to begin and facilitates connections with what they already know. It is critical to emphasize the characteristics that convey the learning goals of the simulation; and, our interviews have shown that *consistent representations* between simulations create connections between different phenomena.

Explicit Visual Model

- *Simulations provide a correct visual mental model of the physics.*
- *Such visual models advance discussion and analysis beyond trying to establish a common visualization.*

Our interviews have clearly shown that simulations are a powerful tool for helping students develop an accurate mental model of the physics. At times simulations show something students have already seen such as oscillating springs or projectile motion; however, in a simulation time can be slowed or the path traced. During interviews and lab, students talked about how the trace helped them see the path of the familiar motion of a projectile and connect the pictures in their text with their everyday experience. Other simulations provide a visual model for more abstract concepts, such as current flow. During interviews students regularly refer to the desire to have a visual model of such physics; for example they talk about wanting to see what it 'looks like' inside a wire when a switch in a circuit is opened and closed. The value of providing an explicit visual model has been particularly evident in interviews on quantum mechanics simulations such as 'Quantum Bound States' and 'Quantum Wave Interference (QWI)'. In these interviews, it is clear that many students have constructed incorrect mental models from lecture and text books that are corrected rapidly as they play with the simulation.

Many interviews begin with prediction questions about the phenomena that will be investigated with the simulation. During these discussions, before using the simulation, there are times when the student and/or interviewer is unable to adequately describe his or her personal mental picture to the other and as a result,

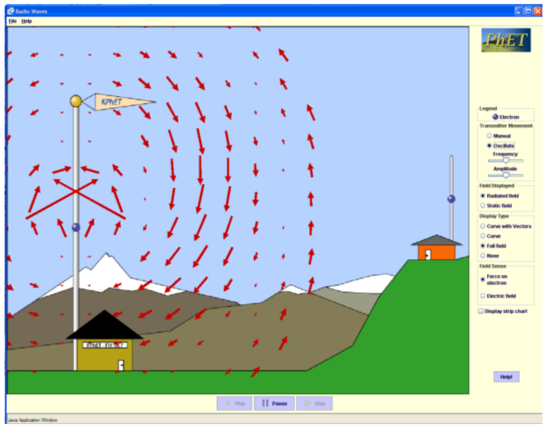


Figure V a – An early version of 'Radio Waves'. When the simulation first opens, the transmitting electron moves up and down along the antenna producing an electromagnetic wave that radiates out filling the screen with oscillating red arrows.

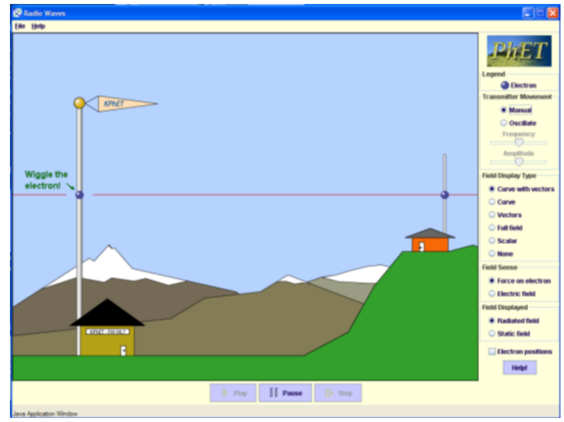


Figure V b – The current version of 'Radio Waves' begins in manual mode with a simple line of text called a wiggle-me that descends onto the screen to let the user know that they can move the electron with the mouse and to identify the blue sphere as an electron.

they are unable to have an effective discussion of the prediction questions. Once the simulation is employed, the students are able to move past describing what they are personally visualizing and begin discussing what is happening and why. In other interviews the simulation is used immediately without prior discussion. In these interviews there is also no clarification or discussion of what the phenomena looks like, the visual model has been provided by the simulation. Interview students become more confident about discussing the reasoning about the phenomena once they know what it looks like. We see the same advances in conversation between students that use simulations during homework sessions.

Start-up Settings

- *To encourage exploration, simulations should start up with very little or no animation.*
- *A "wiggle-me" is an effective way to initiate desired exploration when necessary.*

We've found that the best start-up settings include the least amount of animation and complexity possible. At times a simple cue is needed to focus the user on a moveable object that may not be obviously grabbable. Clark and Mayer's *Coherence Principle* (2003) describe the same characteristics that we have found to be important for the start up settings of a simulation.

Start-up settings were first investigated during the multiple interviews of 'Radio Waves'. Our start-up settings for 'Radio Waves' (Figure V a) were initially chosen to showcase the simulation's most impressive capabilities. The simulation started up in full field view and the transmitting electron oscillating creating an impressive 2-D display of electromagnetic waves radiating out from the transmitting antenna. Physicists and teachers were very impressed with the appearance of this simulation when it started up. Students on the other hand were overwhelmed and stared without speaking for extended periods of time. The interviews for this simulation were done with guiding questions. With this simulation students would often try to answer the questions based on watching the start-up screen, rather than by playing with the simulation on their own. In addition, once students became experienced 'Radio Waves' users, they would open it up and immediately change to a simpler view without exception, while making comments such as "*this is too confusing*", or "*I like the curve better, it makes more sense to me.*"

An additional problem that surfaced during these interviews was that students didn't try the manual mode on their own. In this mode, the electron on the transmitting antenna is grabbable and will not move unless moved by the user. Only one student clicked on the manual button but never figured out that the electron was grabbable. Other students assured the interviewer that they had tried everything in the control panel after trying all tools except the manual mode. Once it was pointed out to them, and they switched to manual mode, they still did not figure out that the electron could be manipulated with the mouse. Only after students were prompted to play with the electron did they discover that the creation of radio waves is linked to the motion of the electron.

For these reasons we tried changing the start-up setting to manual mode (Figure V b) with the simplest display format (wave represented as a curve w/ vectors). When the simulation screen first appears, a line of text "wiggle the electron" slowly descends on the screen with no other animation. New interviews were performed with these revised start-up settings. All the students that were interviewed immediately began investigating the simulation and talking about it. They were then able to explore and reason out the answer to the question that the interviewer had posed to them before playing.

We have repeatedly seen that simulations that start-up with things moving, draw the user's attention to the movement and can easily prove overwhelming. If all their attention is focused on the movement, students do not think about how to manipulate the simulation. This reaction is consistent with the cognitive load principle; there is too much to process and the students get overwhelmed. We find it more effective to design the simulation so that students are first exposed to and can master the simple cases. They can then build up complexity at their own pace. Also, we observe that if the simulation already has things moving when it opens, students do not play and some express nervousness about trying things on their own, asking if it's ok before making each change. This reaction is never observed when the activity in the simulation is initiated by the actions of the student. The observed difference between physics teacher reaction and student reaction to the elaborate initial display of 'Radio Waves' illustrates a prevalent danger in simulation design; what looks good to an expert may be frightening and overwhelmingly complex for a novice and not result in useful learning.

Real World Connections

- *Simulations showing familiar everyday objects encourage exploration and encourage understanding.*
- *Cartoon-like features are an effective way to emphasize important features while avoiding misleading literal interpretations.*
- *Students test the limits of the simulations looking for realistic reactions. Simulations need to 'break' in a meaningful way when pushed to extremes.*

During interviews and observations of users, real life objects are where the user first begins manipulating the simulation. For example, in 'Gas Properties' (formerly 'Ideal Gas') (Figure I) users immediately pump the handle on the bicycle pump to see what will happen. Not only is the function of this object familiar but the connection between air and a bicycle pump already exists in their minds so all students recognize that it is air that they are putting into the box when they pump the handle. When a student is learning about an unfamiliar concept or idea, there is a lot of information to process and it's sometimes difficult to tie the new information in with current knowledge. For this reason, we find it effective to include visual features that a student will have encountered in their everyday life. Other examples of objects that students have immediately recognized and connected with their everyday experience include: Faucets to supply water in both ‘Faraday’s – Electromagnetic Lab’ and ‘Wave Interference’; light bulbs and batteries in ‘Circuit Construction Kit’ (see Figure IV); speakers to generate sound in ‘Sound Waves’ and ‘Wave Interference’ and theater lamps to supply light in ‘Color Vision’, ‘Wave Interference’ and ‘Lasers’.

However, it is undesirable and impossible to depict everything realistically. For example, the earlier versions of ‘CCK’ were written with relatively realistic looking wiring; however, several students had trouble identifying the junctions. A third rewrite was done changing the look to the current very cartoon-like version seen in Figure III. We have found the larger, not-to-scale, representations of wires and junctions to be more effective by emphasizing the characteristics we want the students to notice, such as the junctions. Fortunately we have also found that when the scale is completely off such as for these features and the size of the electrons in ‘CCK’, students recognize the scale as unrealistic and don’t attempt to attribute meaning to the relative size of these objects. Similar large cartoon-like features can be found with the water molecules in ‘Microwaves’. During interviews, students immediately recognized that far more than six water molecules exist in a cup of coffee, but that the behavior of these molecules had the general characteristics shown and that this was the most important feature of the simulation. This large cartoon type of representation can focus the student's attention where it is pedagogically most effective. Students also appear to be attracted to cartoon-like appearances. When students look at the PhET web page, they nearly always choose the more cartoon-like simulations to play with first.

During interviews and observations, both students and teachers regularly explore the limits of the simulation behavior by setting parameters to extremes, and they are disappointed if there is not a physically meaningful response. For example in ‘Gas Properties’ users cool the molecules to absolute zero to see if the molecules stop moving completely, and then they heat the molecules up enormously to see what happens. Users were disappointed that the temperature could reach thousands of degrees and the box remained intact, so we added a feature where the lid flies off under extreme conditions. Now users are more satisfied. We have found, however, that there is a fine line between enabling the simulation to break in a meaningful way and in the breaking creating a distraction. Part I includes more details on simulations where such elements were so much “fun” that they interfered with learning.

Visual Cues - Everything Matters.

- *Students look at all visual cues equally, if they do not understand a concept. It is important to emphasize items that are pedagogically important and eliminate all potential distractions.*
- *Color is an important visual cue.*

The interviews consistently show that when students are attempting to make sense of a phenomenaon they look at everything. If they do not understand a concept, they’ll attribute equal importance to all cues; including features that experts often do not even notice. Thus any irrelevant visual feature results in increased cognitive load and potential confusion for the student. For example, in both ‘Signal Circuit’ and ‘CCK’, electrons are shown flowing inside the wires of an electric circuit. In ‘Signal Circuit’ the electrons would bunch up at the light switch just after it was turned off. In the first two versions of ‘CCK’ a different density of electrons was depicted due to the branching of circuits (see Figure II a). These small effects were inadvertent features of the simulation code which experts often did not notice. During interviews with both simulations, students spent considerable time trying to make sense out of these small changes in the electron spacing. In both cases students used this cue to create an incorrect understanding of current flow and electron movement. We saw the same type of problem in an earlier version of ‘QWI’. There was one extra pixel on the right hand side of the box that created a slight asymmetry in the interference pattern. During interviews students were extremely troubled by this asymmetry, believing it to be caused by some physics principle that they didn’t understand.

Interviews have shown that color and other visual cues are a much more powerful cue than text labels. Several simulations use colored arrows to depict different types of forces. The same simulations will have graphs that depict the forces and different types of energy. We’ve found that students look to the color coding to match up forces or to match different types of energy to forces. Students who used ‘Forces 1-D’ became accustomed to a green arrow depicting total force and red denoting friction. When a different color scheme was used a few weeks later in a new simulation, students thought the green arrow represented the total force, even though it had a label on it saying “gravity”. We consistently observe that students believe the simulations and work hard to incorporate all the visual cues into a coherent understanding. While this reaction is highly desirable, it emphasizes the need to take care in the design of simulations and to test them adequately with non-experts, since experts can easily overlook irrelevant but misleading visual cues.

Consistent Representations

- *When an object is represented differently from simulation to simulation, students perceive it as two different objects, and when objects are represented in a similar fashion they are perceived as the same, even though they may be completely unrelated.*

Several unrelated simulations ('Greenhouse Effect', 'Lasers', and 'Color Vision') were developed independently and used different representations for photons. Photons are a unique challenge because of their wave particle duality. In this case, the representation chosen for each simulation was effective within that particular simulation and elicited accurate understandings of the core concepts. However, when users were asked to compare the little objects in the different simulations (all of which were representations of photons), two out of four students believed them to be fundamentally different objects.

Students had less difficulty with the simulations where they were presented with consistent wave representations. For example, 'Radio Waves' had three possible views of electromagnetic waves; two of which were quite similar to those used in the microwaves simulation. When students were asked to compare these views in 'Radio Waves', the question elicited thought and their answers indicated greater understanding of electromagnetic waves and their applications. This response occurred with all four students. When these same students used ‘Microwaves’, they brought the ideas they had developed with ‘Radio Waves’ to ‘Microwaves’.

After these observations, we removed the inconsistencies between the simulations that use a photon view of light, and we added functionality to many of these simulations, such as ‘Lasers’ and ‘Color Vision’ so the student can explicitly move from one representation to another (e.g. switch between wave view and particle view) for the photons. Subsequent interviews showed that adding this capability not only elicited an understanding amongst the students that they had the same type of object in each simulation, but was also effective at encouraging sense-making of the wave/particle duality of electromagnetic radiation.

Another example of the importance of consistent representations between simulations was seen with ‘Gas Properties’ and ‘Reversible Reactions’. In this case, the same representation was used for fundamentally different objects. Users brought what they had learned in ‘Gas Properties’ about little blue and red spheres to the ‘Reversible Reactions’ simulation. ‘Gas Properties’ uses little red and blue spheres to denote heavy and light gas atoms. When ‘Reversible Reactions’ was written, very similar little spheres were used to denote molecules where the sphere’s color changed to represent a change in molecular structure. When this simulation was used in the context of a chemistry course, where there was instructor guidance, it worked well; however, experienced ‘Gas Properties’ users (including teachers) had a completely different response. Teachers were confident that they fully understood the representation, but came away from the simulation with a complete misunderstanding believing the spheres to be individual atoms, as in gas properties, and thus the simulation must be demonstrating kinetics rather than reversible reactions.

It is important to use a consistent representation for objects that appear in more than one simulation such as photons, EM waves, electrons and light bulbs. When a veteran user encounters a familiar appearing object in a new simulation, they have strong ideas about what that object is and how it behaves based on their previous simulation experiences.

Layout

Using results from many interviews, we have created a basic set of guidelines for laying out a simulation; however, it is something that cannot be rigidly dictated. Each simulation has a special set of characteristics that require a certain amount of flexibility in the layout. We do try to be consistent in as many ways as possible and follow a general outline which provides consistency between the simulations and a framework from which to start for each simulation. This basic layout was adopted after a number of interviews, and it seemed to work for subsequent simulations. Therefore, we have not explored possible alternatives.

Each simulation has the same basic layout consisting of the play area on the left dominating the screen and a control panel on the right. The play area contains animated objects that can be directly manipulated while the control panel contains global controls. In the original 'CCK' students did not see the distinction between the tool box which was located in the control panel and the play area. They became frustrated when they could not drag tools from the tool box into the play area (See Figure II a). We found that a clear division between the play area and control panel can be created by the use of different color backgrounds. Students quickly see that "clicking and dragging" works only in the play area and that extended controls can be found in the different color control panel.

The general features of the layout are described in the following sections. These features include: controls that are placed in the play area on or near the object they control, when possible; VCR type 'Play, Pause, Step' buttons that are placed along the bottom of the play area; large, prominent tabs that are placed, when necessary, in the upper left hand corner; and a Help! button that is placed at the bottom of the control panel. When rearranging is necessary due to unique aspects of a simulation, we try to keep all controls in the same basic area of the simulation (e.g. the right-hand side), otherwise users focus on one area and completely miss the rest of the controls. This approach follows Clark and Mayer's *Contiguity Principle* (2003) which states that people learn more readily when corresponding printed words and graphics are placed close to one another on the screen. Below we discuss how specific aspects of the layout arose from interview results.

Control Panel

- *Limiting the number of tools/controls and arranging them in small groups makes it easier to identify what is available and makes the simulation less intimidating.*
- *Students become familiar with the layout.*
- *Limited text*
    - *Students only read text that is attached to a control*
    - *Abbreviations are not understood by most students.*

• *Text strings of one to three words work best.*

Interviews showed that students are hesitant to begin playing with simulations that have lots of tools/controls (more than three groups of about three similar items). Once they turn from direct manipulation in the play area to using the control panel, most users investigate one set of controls at a time, usually beginning with the most inviting, such as a simple slider. They will then quickly become immersed in exploring the simulation. If a simulation has too many controls or a poorly laid out control panel, when asked if they've tried everything, students will often say yes, without realizing that they have not, and several prompts from the interviewer are required before the user will try every control. After the interviewer points out a specific control, then the student realizes she missed something. Experienced users also become frustrated with simulations that have an extensive number of controls because it is difficult to locate previously used controls. To reduce this problem we have limited the number of controls and grouped them according to functionality.

We find it most effective to allow students to manipulate all relevant parameters. However, this can at times be overwhelming and requires a large number of controls in the control panel. When this happens we have found it useful to hide some of the controls and allow access through an advanced button, such as in 'CCK', where the control panel initially allows them to adjust basic parameters such as "life-like" or "schematic" [view] and access to basic tools such as a voltmeter and an ammeter. The advanced features, accessible by clicking on the advanced button, add in such elements as the resistance of wires and the option to show equations.

Interviews reveal that students read as little as possible when using simulations. Once students turn their attention to the control panel, students nearly always first begin using the controls that have the shortest simplest descriptions. For example, in 'Radio Waves', all users explored the set of controls that had the brief labels "Full Field", "Curve" and "Curve w/Vectors", before turning to controls that had longer labels (Figure V). We've also observed that students read one to three words at a time and glance past strings of text. For example, in 'Radio Waves', after encouragement from the interviewer, users would click the "Show strip chart" check box. Users indicated that they had no idea what they would see based on the control label. When the box is checked, a pop-up window appears where an active graph is plotting the transmitting and receiving electrons' positions. At the top of the window there is a label that says "Electron Positions". After watching these graphs for awhile, three out of four students could not figure what the graphs were depicting until the interviewer pointed out the very clear label at the top that says "Electron Positions". Once they read these two words, they made sense of the graphs without any sort of explanation from the interviewer. Similar results are seen where students consistently overlook the labels within the control panel that are not directly attached to a control. We've also found that students are not familiar with abbreviations, so it is best to use complete words or add a legend to define the abbreviation as we described for 'Nuclear Physics' in Part I.

Additional characteristics for the control panel were not based explicitly on interview results; however, they have had positive reactions during interviews. The tools that are placed in the control panel have a 3-D look about them and are limited to items such as sliders, radio buttons and check boxes. Students are familiar with the functionality of these basic control types as described in *Sliders, Radio Buttons and Checkboxes* above. Based on the preferences students showed for the Flash simulations compared to the early Java simulations, we concluded that the 3-D look (which is built into Flash tools) is seen as friendlier and more inviting. Finally, the Help! button is consistently placed at the bottom of the control panel and experienced PhET users know where to find it.

Play Area

- *The play area must be distinct from the control panel in look and functionality. Objects in the play area are grabble and animated.*
- *When too many tools are in the play area, the control panel is overlooked.*
- *Text is a distraction in the play area.*

The play area contains the physical objects that the user is investigating. We find that students always begin by attempting to manipulate these objects before turning to the control panel. For this reason it is best to allow manipulation of play area objects directly with the mouse as much as possible. If it's not possible to manipulate all the features of the object with the mouse, it is best to have an attached control adjacent to the object to make the connection between the control and the object clear. Under these circumstances we see that students do not have difficulty finding the control. For example the gun in 'QWI' or the light sources in 'Photoelectric Effect' have wavelength and intensity sliders in a control box attached to the gun/light. Students quickly use these controls and understand their function. This result is consistent with Clark and Mayer's *Contiguity Principle* (2003) that students’ cognitive load is reduced if the connection is physical rather than a verbal description in the control panel.

However, placing controls in the play area has to be done carefully. The initial ‘QWI’ had a large number of controls in the play area that looked and behaved the same as controls in the control panel. During interviews students successfully used these controls but never noticed the control panel. In the current version, the look of the controls in the play area have been grouped and the look changed to be more like physical items, the control panel size is increased and the empty space in the play area has been reduced (Figure VI). These changes brought more attention to the control panel, clarifying the distinction between play area and control panel and made the simulation look more fun. After these changes, students now see and use the control panel.

As described above in the *Control Panel* section, students rarely read. We’ve found that when the text is in the play area, students are actually more likely to read it; but, it often distracts them from engagement. For example, in the original version

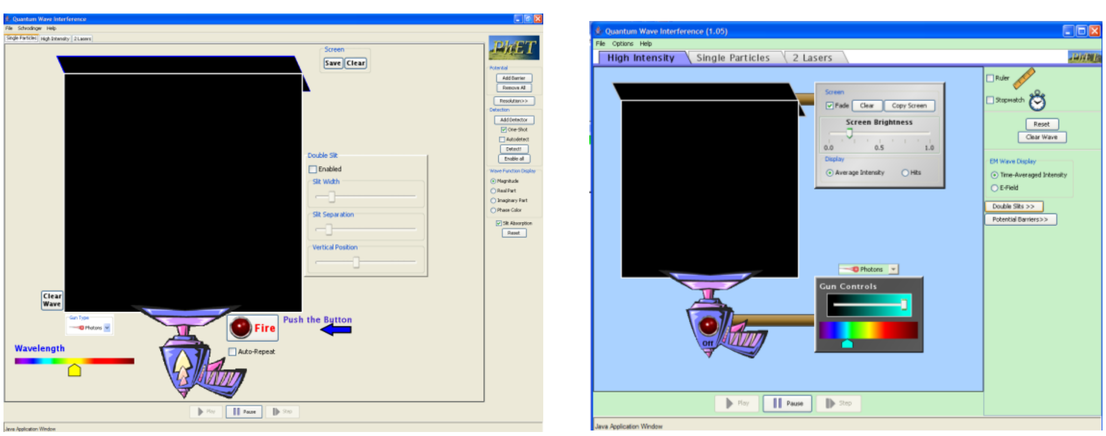


Figure VI – ‘QWI’ has a large number of controls in the play area for producing photons, electrons, neutrons and alpha particles at various energies. The screen that the particles hit also has user adjustable functionality. Within the Control Panel the user can add double slits and/or potential barriers as well as find some helpful tools. The screen shot on the left shows the first version of this simulation and the right shows the current. revised interface.

of CCK there were strings of text in the play area describing what to do. Students would read the text before playing, but then their interaction was limited to the one action or object being described by the text. The students did not explore on their own after following the text directive. Furthermore, most students misunderstood the text and became frustrated after being mistaken about what would happen. However, one word labels that are included on an object or as part of a control have been correctly interpreted and useful without unduly guiding students in their exploration. Very short sentences or phrases in the *Help!*, as described for 'Sound Waves' below, is effective at guiding student actions and getting them engaged; however, students' exploration was then scaffolded by these directions rather than their own questioning. Since such text seldom encourages the student-driven *engaged exploration,* as described in Part I, that we see is most pedagogically effective, we believe that an important property of a good simulation is to provide a clear and friendly environment that does not require written explanation to initiate exploration.

Backgrounds

- *Backgrounds, pictures in the play area, can serve as a useful visual cue, but it is important that the main objects in the play area can be easily distinguished from the background.*

We have found that backgrounds (e.g. pictures depicting location) can serve a useful function, but they must not be distracting. In some initial designs, we found the backgrounds were competing with the central features of the simulation for the user's attention. For example, in 'Radio Waves' (Figure V) the important features were cartoon-like and the background consisted of a cartoon-like picture of mountains. Both the background and features were of the same character and novice users would miss the receiving antenna and other important features. (This fits with differences in novice and expert perceptions (Chi, Feltovich and Glaser, 1981).) An effective background is distinct from the features of the simulation. For example, the first version of 'Energy Skate Park' had a very distinct photo of the mountains behind Boulder, Colorado in the "earth" setting, but the simulation features were all quite cartoon-like so were easily distinguishable from this background. Interviews revealed that the background provided a useful cue as to when the simulation was portraying the earth, moon, or outer space. When this background was reduced to a solid color so that the user only had the slider as an indication of gravity's setting or a drop down menu with the planet name, we found that quite often the user would forget they had adjusted the gravity or planet parameter and would get confused as to the behavior of their skater. When the background depicting their location was restored, this confusion did not recur.

Tabs

- *Students notice large, bright tabs. When tabs are small and professional looking, they go unnoticed.*

Multiple panels are used in PhET simulations that have many levels of sophistication or show several connected ideas. We use file-folder like tabs in the upper left corner to allow users to switch between these panels. One might think that students have been trained by everyday applications to look for controls in the upper left hand corner; however, our interviews and observations of students in classes have found less than one in ten students would click on standard program menus or typical tabs. Typical looking controls or tabs, which are commonly overlooked, are those of the same size font as the labels in the control panel and with a grey background. However, when these tabs are large, contain larger fonts and are colored to be more prominent, most students find them. Figure VI illustrates the difference between everyday application tabs and the larger more prominent tabs we've found successful.

Play Buttons

- *Students do not find play/pause buttons, but students will use these buttons as needed, including in new simulations, once they have been shown to them.*

Centered along the bottom of the play area we locate various VCR type buttons such as play, pause, record, step etc. There have only been five interviewees, most of whom were engineering and physics majors using advanced simulations, out of approximately 80 students, who have found these buttons without help from the interviewer. We were unable to find a location that was obvious to all students. During interviews, many students asked if they could replay something or more often if they could slow it down, but they only recognized and used the buttons after the interviewer pointed them out. Once students became familiar with the location of the play/pause buttons, they used them to investigate phenomena in all future simulations.

Help

- *In a good simulation explanation is not necessary to stimulate learning.*
- *Verbose help can be a deterrent to exploration.*

PhET simulations can have up to three levels of help. The first is named a "wiggle-me". A wiggle-me is a short snippet of text that makes a slow, relaxed entrance into the simulation when the simulation is first opened. The next level is called "Help!" and usually consists of about four short strings of text explaining important but not obvious functions of the simulation. The most complete form of help is "Megahelp". It is a still graphic of the simulation with a description of nearly every object on the screen.

Wiggle-Me

- *When the most important object in the play area is not obviously grabbable, a wiggle-me is useful for telling the user where to start.*
- *The wiggle-me should draw attention to itself; however, it should not distract the user from the rest of the simulation.*

The wiggle-me was first created for the 'Radio Waves' simulation (Figure V b). During interviews we found that starting the simulation with the electron oscillating on its own was overwhelming to students as discussed in *Start-up Settings* above. We also found that when the simulation was in manual mode, students had no idea they could move the little blue dot, or for that matter, what the little blue dot represented. Both of these problems were solved with the addition of the wiggle-me. The simulation's start-up was changed to the manual mode where the user must grab the blue dot - that is, the electron - in the antenna and move it up and down to create a radio wave. The wiggle-me text says "wiggle the electron," both identifying the little blue dot and describing its functionality. We have since found wiggle-mes to be an effective way to begin many simulations.

Wiggle-mes are always a short bit of text used to give the user an invitation to begin exploring in the play area. Once the user clicks the mouse anywhere, the wiggle-me disappears. For a number of simulations, the entrance of the wiggle-me is the only movement on the screen when the simulation begins. Wiggle-mes are particularly successful when they swoop or descend in to the play area, grabbing the user's initial attention, and then sit stationary until the user clicks in the play area. By making the wiggle-me stationary and having it disappear once the user starts interacting with anything, the user has a chance to become familiar with the simulation environment and to start interacting with it however they wish. Other designs, such as wiggle-mes that always remain on the screen or move continuously until the user interacts as directed, are annoying and distracting to the user; they draw the user's attention from the rest of the simulation and essentially force them to follow the directive even when they have not had a chance to look over the rest of the simulation, or they intended to investigate something else first. For the reasons discussed above, we only introduce a wiggle-me when attempts to make grabble objects obvious without text fail.

Help!

- *Must be clear, concise strings of text.*
- *If it is too prominent, then it gets followed like a command and the user is unlikely to explore on their own.*
- *Needs to be able to remain on screen as continual reference while the user explores the simulation. For this reason it must be located so that it does not interfere with manipulation of the simulation.*

We investigated several forms of Help! and found that most hinder a student's ability to learn from the simulation. This result is consistent with Clark and Mayer's *Coherence Principle* (2003): No extraneous, pictures, words, help etc. should be included. What is perhaps not so obvious is that help that provides useful guidance can still be distracting. The most important thing we learned from these investigations was that avoiding the need for help clearly works the best. When help is absolutely necessary, it must include: minimal reading – conversational style rather than formal; minimal guidance – directions/help severely limits student's natural curiosity and exploration; no distractions – if it stands out, students will <u>only</u> follow it's directives; no science explanations – only cues on how to make the simulation function; and good location – placed right beside the item as described by Clark and Mayer's *Contiguity Principle* (2003) defined in the *Underlying Principles* section of Part I. We provide samples of the data below that support these conclusions.

One form that failed was "help bubbles". When attempting to create an intuitive environment with 'CCK', we tried using help bubbles. The original interface of the 'CCK' simulation was found to be impossible for first time users, as discussed above, but it was easily used by most students after some instruction. For this reason, we first thought that a few written directions would be adequate to clarify the interface. Help was implemented by making it so that when the user clicked on various question marks that were placed in the play area, a help bubble appeared containing a sentence describing how to build a circuit. We found that some sentences contained words students were not familiar with such as "tool box" or "construction area", and/or were too complicated. Users tended to read these sentences quickly and were in a hurry to do what they said, which increases the opportunities for confusion. Quick reading, coupled with the sentences not remaining on the screen at all times, caused students to go back and forth between trying to play and reading the help. One student tried to use the help as the tool itself, dragging the circuit components onto the question marks. The students were not able to use the simulation following this help until the interviewer took the mouse and demonstrated how to use the tool box and construction (play) area. After demonstration, all but one student could manipulate the simulation perfectly.

Interviews revealed another problem with the Help!. Once Help! was available, most of the students interviewed would limit their play to following the Help! directions and refrained from trying anything else. For example, when interviews were performed with the first version of ‘Energy Skate Park’ (formally ‘Energy Conservation Kit’), the help that was provided consisted of a few sentences that appeared on top of the play area when first starting up the simulation. The large bright lettering with three different sets of instructions would disappear once the student would clicke in the play area. After the students tried one of the things that the help text told them to do, they were unsure what to do next because their instructions were gone, and they focused their exploration on how to get the help back. When used in lab, once students could not find a way to bring the help back, every group asked for instructor assistance. When these same lab students used other PhET simulations that start-up without any text, the students did not request assistance and began interacting immediately.

The Help! in 'Sound Waves' proved successful. It consisted of clear simple sentences near relevant objects that would remain on the screen and were not distracting, e.g. "listener can be moved left and right". In interviews students would follow what one help indicator said and then play further on their own, forgetting about the help. When they were done exploring, they looked to the help to see if they had tried each indicated feature. This type of help design provides useful guidance, but does not seem to dominate students' actions. With this type of help, student's explorations were still somewhat directed by the sentences rather than their own questioning, so we believe it is better to only have help appear upon request.

After implementing this type of simple help on request, we have found users usually only look for Help! now when in search of quick answers to explain the physics. Once they see that Help! merely describes the simulation's functionality, they quickly close it and begin exploring the simulation in search of understanding. Hopefully, this is at least partly due to the effort we have put into making the simulations intuitively clear.

Extensive Help.

- *Users do not use detailed extensive help.*

In early tests, after Help! had been selected, two buttons appear – "Hide Help" and "Megahelp". Clicking Megahelp brings up a screenshot of each pane of the simulation with a bubble describing each item. The descriptions include any relevant and not obvious actions the object can perform, for instance a description may need to include the fact that an object can be moved and thus are quite extensive. In a year of interviews, we only had one interviewee look at Megahelp. This person was of a different generation than the traditional student. It is our belief that this extensive help only provides an efficient reference guide for teachers to quickly view all the features a simulation has to offer.

Conclusion

We have carried out extensive interview studies on the student use and learning from interactive simulations for teaching physics. We find overwhelming evidence that simulations that suitably incorporate interactivity, animation, and context can provide a powerful learning environment where the students productively engage with and master physics content. However, we find that this can only be achieved by following an extensive set of principles for design and layout as contained in the PhET Look and Feel. Here we have detailed specific design guidelines along with relevant interview results for creating an intuitive simulation including layout, representations, tool use and help functions. The findings presented here include the interface design features of the PhET Look and Feel for creating intuitive simulations. Details of the *Encourage Exploration* section and a more extensive discussion of engagement and learning with simulations can be found in Part I. This work reveals many design pitfalls that can result in simulations not achieving the desired educational effectiveness. Finally, this work demonstrates the importance of testing educational simulations carefully with the desired target users.

Acknowledgements

We would like to thank Danielle Harlow, Noah Podolefsky, and Stephanie Fonda who conducted some of the interviews whose results are incorporated in this paper. We also thank Noah Finkelstein and the other members of the Colorado Physics Education Research group for many useful discussions. We are pleased to acknowledge support of this work by the University of Colorado, the National Science Foundation, the Kavli Operating Institute, and the Hewlett Foundation.

Simulation Use Out-of-Class (First-Contacts)

Arguably students spend the bulk of their time associated with a course outside the classroom walls (at least such is the expectation of most college and university instructors). Homework, review of materials (traditionally reading), and preparing for exams are anticipated to comprise two to three times the amount of time spent in lecture. I have been exploring what roles computer simulations might play in student learning of physics concepts in these less structured environments.

In a study designed to observe the utility of simulations in less structured environments and to compare the effects of using a simulation to that of the canonical task of reading, I compare students' conceptual mastery after they have read with student conceptual performance after playing with a simulation in out-of-class settings. Students from two different courses, one a calculus-based physics course for majors and one a class for non-science majors were asked to participate in these *first-contact studies*. The first-contacts were designed to be the student's first formal discussion of the concept presented (at least for this course); i.e. these studies took place before homework or lecture on a particular topic. Students were assigned to one of three groups: i) a group that read a relevant text passage and was asked a question (*read*), ii) a group that played with the simulation and then was asked a question (*play first*), and iii) a group that was asked a question as a prediction, played with the simulation and then asked the same question again (*predict and play*). The calculus based course only included the *read* and *predict and play* conditions.

These studies indicate that some simulations are better suited for this outside-of-class scenario than others. We see that the more sophisticated the simulation, the necessity for a more structured environment to encourage learning. An example of a straight forward simulation which is quite effective in our first contact studies is *Balloons and Static Electricity* shown in Figure 1. The control group read a passage from Serway and Faughn text (2000) on charge transfer by rubbing differing materials together. Figure 2a and 2b display a question and percentage of student answers that are correct before treatment (prediction) and for each of the three treatment groups. This particular concept of charge transfer was better understood by both the *play first* and the *predict and play* groups than the

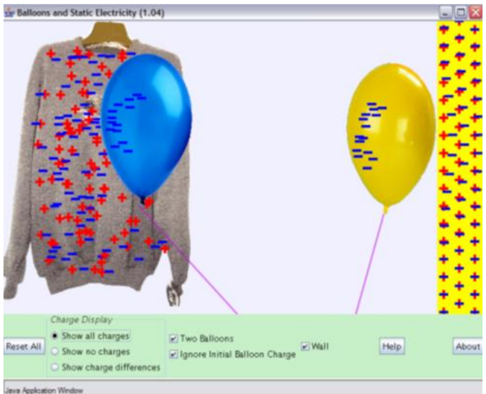


Figure 1 – Balloons and Static Electricity

When an object becomes charged by rubbing it with another object,

a) protons are created by rubbing if it becomes positively charged or electrons are created if it becomes negatively charged.
b) either protons or electrons transfer to/from the object. Whether it is protons or electrons that transfer depends on whether the object becomes positively or negatively charged.
c) only protons transfer to or from the object. The direction depends on whether the object becomes positively or negatively charged.
d) only electrons transfer to or from the object. The direction depends on whether the object becomes positively or negatively charged.
e) both protons and electrons transfer. Protons transfer to the object and electrons from the object if it becomes positively charged. Vice versa if it becomes negatively charged.

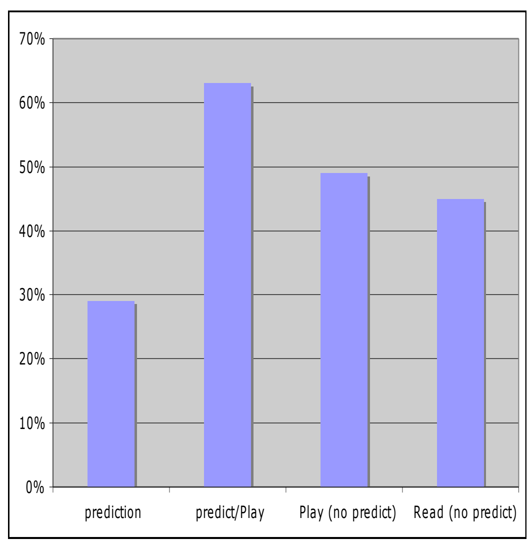
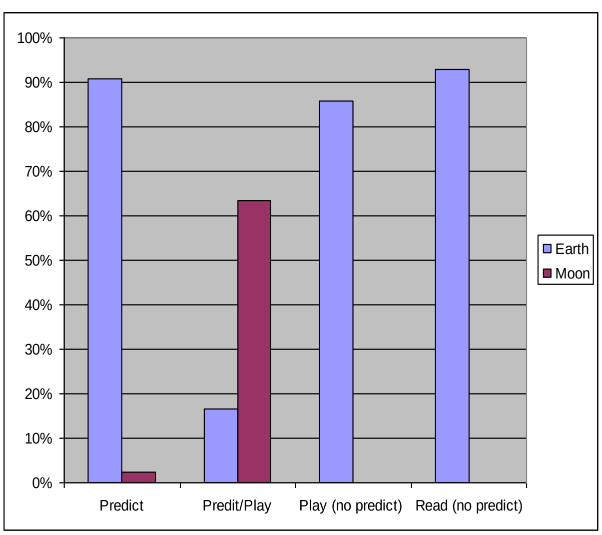


Figure 2a question **and 2b** correct student responses for students learning about charge transfer from reading or using a simulation.

students who read a three page excerpt from the text with pictures and demonstrations that specifically stated the answer to the question.

Another example of an effective simulation is *Energy Conservation Kit*; however, in this case the effect was not exactly what we hoped. Figure 3a and 3b list the question and the percentage of student responses to a question about the work required to lift identical objects on the Earth and on the Moon. From the prediction we see that 91% of students came in knowing that it requires more work on the Earth. For the group that saw the question first and then played with the simulation only 17% of the students believed it took more work on the Earth after playing with the simulation. Upon close inspection of the simulation we discovered that the default mass for the object on Earth was 1 kg and for the moon was 1650 kg. These results clearly indicate that most of the students are not only using the simulation in an attempt to answer the question but they also had to open up the energy graph to do this. After finding the opposite result from what they expected, students trusted the



If a person wanted to lift a 1 kg rock to a height of 20 meters on Earth or to the same height on the moon, will it require more work (Energy input) on the moon or on Earth?

a) On the moon.
b) On Earth.
c) The same amount of work.
d) Depends on where you are on Earth (ie. On top of a mountain, sea level, etc..).

Figure 3a question **and 3b** correct student responses for students learning about work to lift an object from reading or using a simulation.

simulation (or at least believed this was the answer we were looking for) and answered accordingly.

In the course for non-science majors, across twelve different conceptual questions spanning seven different simulations, with all but two questions, simulations are more productive than reading a passage on a related topic. Priming students with a question, predict and play, appears to further improve the simulation experience. In examining particular concepts, we observe that some concepts and questions are better addressed by these simulations than reading. In the calculus based physics course, for majors, I studied three different simulations and five different conceptual assessments. Students using the simulation perform indistinguishably from their counterparts who read in lieu of using the simulation.

I believe these variations to be indications of the manner in which the simulations are used and the particular concepts that are addressed. That is, particular questions and concepts (e.g. on the microscopic nature of charge) are better facilitated by a simulation which makes explicit use of this microscopic model. Furthermore, some simulations are better suited for scaffolded student learning (e.g. Ideal Gas where students can learn about Boltzmann statistics through carefully designed exercises); whereas, other simulations easily demonstrate the learning goals without significant scaffolding (e.g. Balloons, where students learn about charge transfer by manipulating a balloon as they would in real life.)

Figure 4 below contains the questions and results for the first contact questions.

Springs and Masses

Question

The fruit and vegetable scale at the grocery story is simply a tray hanging from a spring. If you put a pineapple on the tray, the tray hangs lower by say one inch. If you put **two** pineapples on a different scale, that has a spring that is only half as stiff, the new tray will hang about

a) 1/4 of an inch lower than when empty.

b) 1/2 of an inch lower than when empty.

c) one inch lower than when empty.

d) two inches lower than when empty.

e) four inches lower than when empty.

Answer	**Correct**					
	e)	a)	b)	c)	d)	Total responses
Prediction	48%	0%	20%	17%	13%	46
After playing	40%	3%	20%	20%	7%	30
Play First	41%	0%	14%	12%	33%	49
Read	60%	2%	6%	14%	19%	52

Energy Conservation

Questions

1. If a person wanted to lift a 1 kg rock to a height of 20 meters on Earth or to the same height on the moon, will it require more work (Energy input) on the moon or on Earth?

On the moon.

On Earth.

The same amount of work.

Depends on where you are on Earth (ie. on top of a mountain, sea level, etc..).

not answered

2. Does the total energy of a rock increase as it falls?

Yes

No

Depends on what planet you're on.

not answered

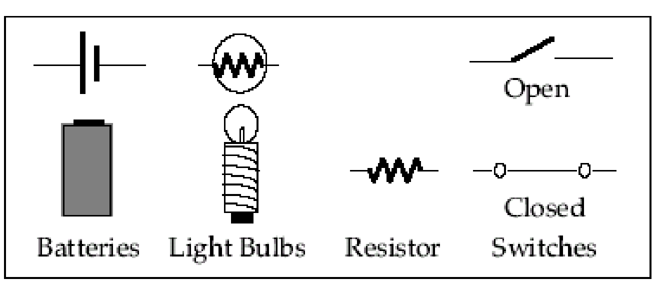
Answer	Correct				
	1. b)	1. a)	1. c)	1. d)	Total responses
Prediction	91%	2%	7%	0%	45
After playing	17%	63%	17%	0%	30
Play First	86%	0%	10%	5%	42
Read	93%	0%	7%	0%	43

The default mass of the vehicle on the moon was 1000 times that on Earth

Answer	Correct			
	2. b)	2. a)	2. c)	Total responses
Prediction	56%	30%	14%	45
After playing	77%	7%	3%	30
Play First	43%	41%	14%	42
Read	49%	42%	9%	43

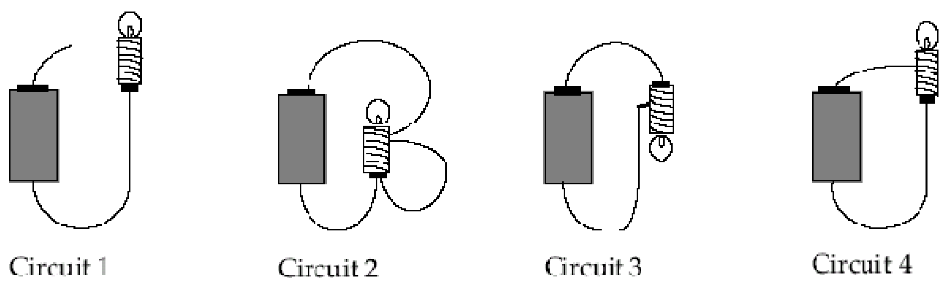
CCK

All light bulbs, resistors, and batteries are identical unless you are told otherwise. The battery is ideal, that is to say, the internal resistance of the battery is negligible. In addition, the wires have negligible resistance.



Question

Which circuit(s) will light the bulb?



- Circuit 1
- Circuit 2
- Circuit 4
- Circuits 2 and 4
- Circuits 1 and 3

Answer	**Correct**					
	c)	1. a)	1. b).	1. d)	1. e)	Total responses
Prediction	45%	0%	5%	45%	4%	22
After playing	50%	0%	0%	45%	5%	21
Play First	33%	0%	4%	56%	4%	27
Read	38%	0%	3%	56%	3%	32

Simulation helped a little maybe, mostly shows some rather inconsistent resuts. This was the version of CCK which had the 'tool' format like a paint program. Maybe poor response on Play first because frustrated and pissed off? Note: This one was given as extra credit rather than part of the homework, there are only about half participating also. I this was given towards the end of the semester at an awkward time.

Radio Waves

Questions

1. What effect does an electric field have on an electron?

   ○ Electric fields do not affect electrons.

   ○ An electric field causes an electron to accelerate in the direction of the electric field.

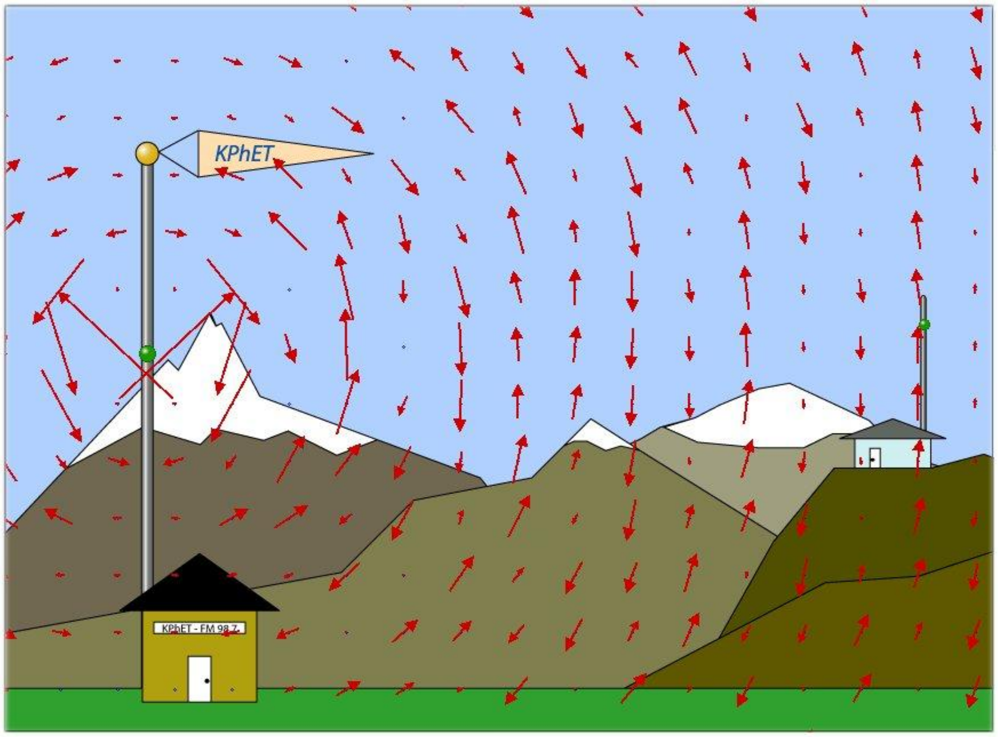
   ○ An electric field causes an electron to accelerate in the opposite direction of the electric field.

   ○ An electric field causes an electron to accelerate perpendicular to the direction of the electric field.

   ○ An electric field causes an electron to move in a circular motion.

   ◉ not answered

2. The radio transmitter for station KPhET is setup as shown below. The little house to the right on the mountain has a receiving antenna standing upright on the roof. Which orentation of the receiving antenna will pick up the signal?



a) As shown. Oreinted up and down.

b) Oriented on its side front to back.

c) Oriented on its side right to left.

- a) only
- b) only
- c) only
- only a) or b)
- only a) or c)
- only b) or c)
- any of the above a), b) or c)

Answer	**Correct** 1. c)	1. a)	1. b)	1. d)	1. e)	Total responses
Prediction	38%				14%	34
After playing	38%				26%	34
Play First	50%				8%	43
Read	54%				23%	34

Wrong answer more prevalent for simulation due to start up mode being in full field view which appears to move in circular motion.

Answer	**Correct** 2. a)	2. b)	2. c)	2. Only a) or b)	2. Only a) or c)	2. Only b) or c)	2. Any of the aove a), b) or c)	Total responses
Prediction	18%							34
After playing	41%							34
Play First	28%							43
Read	40%							34

Signal Circuit

Why do the filaments in your lights at home start heating almost instantly when you turn on the switch?

- When the circuit is completed, there is a rapid rearrangement of surface charges in the circuit.

- Charges store energy. When the circuit is completed, the energy is released.

- Electrons in the wire travel very fast.

- The circuits in a home are wired in parallel. Thus, a current is already flowing.

○ Electrons in the wire are like marbles in a tube. When the circuit is completed, the electrons push each other through the wire

Predict	**After Play**	Play first	Read	
34%	**68%**	43%	31%	Correct
31	**31**	37	38	

The Use of Metaphor in Computer Simulations

Noah Podolefsky and Wendy Adams

Human Learning Term Paper

March 11, 2004

Introduction

In 1911, Earnest Rutherford proposed the planetary model of the atom (Taylor et al. [2003]). This model described the atom as a tiny planetary system with negatively charged electrons orbiting a central positive nucleus. This description of the atom is analogous to a system that most people are familiar with: the solar system (Fig. 1). The nucleus corresponds to the sun; the electrons to the planets. The gravitational force holding the planets to the sun corresponds to the electric force holding the electrons to the nucleus. This is a familiar example of what Lakoff and Nunez [2000] describe as an *inference preserving conceptual metaphor*. It is a conceptual metaphor in that the grounded concepts in a source domain (i.e. the solar system) are mapped to abstract concepts in a target domain (i.e. the atom). It is inference preserving because certain inferences, or properties, of the solar system carry directly via the metaphor to the atom. Of course, physicists today do not believe this is the correct model of the atom. In determining that the planetary model is inference preserving, we are not concerned with whether the model, or target domain, is entirely correct. Rather, we are interested in whether the inferences of the source domain transfer to the chosen model in the target domain. Even expert physicists often use incomplete models. However, somehow they know when these incomplete models are useful in understanding the concepts and when they are detrimental

(Reiner et al. [2000]). In this paper we will describe situations in which inference is not entirely preserved and how this affects student learning of physics concepts.

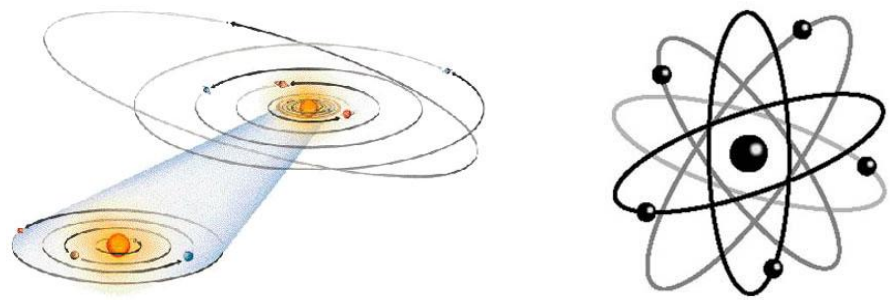


Figure 1. The solar system (left) is used as a model for the atom (right). (Clipart from Dorling Kimberly Limited)

Our work is based on the Physics Education Technology (PhET) computer simulations. The PhET simulations are more than simple animations that a student can view on a computer screen. They are highly interactive *microworlds*. According to Rieber [1996], “A microworld is a small, but complete, version of some domain of interest. People do not merely study a domain in a microworld, they ‘live’ the domain, similar to the idea that the best way to learn Spanish is to go and live in Spain.” Rieber contrasts a general microworld, which could be a child’s sandbox, to an *artificial* microworld, which is a model of some system or domain. The PhET simulations do more than simply model a physics laboratory. They include visual information that is not, and could not, be available in the real world.

Here is where the use of metaphor is key. By using certain visual information to depict a physical situation, we are making implicit use of a visual metaphor. The particular metaphorical mapping turns out to depend on the knowledge base of the person using the simulation. Students in a physics class may preserve certain inferences that an expert physicist would not. Reiner et al. [2000] proposed that physics novices use an existing knowledge base that they have derived from everyday experience. They claim that this knowledge is *substance-based*, i.e. based on material objects. When this knowledge base is used to understand concepts such as heat or light, novices cling to this substance-based knowledge and therefore attribute material-like properties to heat and light. Likewise, novices may preserve the inferences from a source domain such as water waves to the target domain of sound waves. This can cause difficulty in their understanding of the physics concepts. However, the material view may sometimes be helpful in teaching certain concepts. Thus we must be careful about when to avoid the material view and when to take advantage of it.

In Part I of this paper, we explore the implications of this theory for the PhET simulations. Students are first exposed to the Sound Waves simulation, where they learn about the concepts of frequency, wavelength, and amplitude. Later in the course, they use the Radio Waves simulation to learn about electron-magnetic waves. We have developed a theory of how students use metaphors to understand the concepts in Sound Waves, then transfer these concepts to Radio Waves. In Part II, we present results of interviews with students who have used the PhET simulations. With this information in hand, we can build a more robust theory of the use of metaphor in computer simulations. This has been a sort of feedback process. Our initial theory had to be rethought and adapted to fit what students were actually saying. The result of this process is the matter of this paper.

Part I

Sound Waves

Who has ever actually seen a sound wave? In our everyday experience, if a bell rings from a tower across campus, the tone seems to "magically" end up at our ears. There are no visual clues that anything is going on in between. The Sound Waves simulation attempts to put a face to sound waves (Fig. 2).

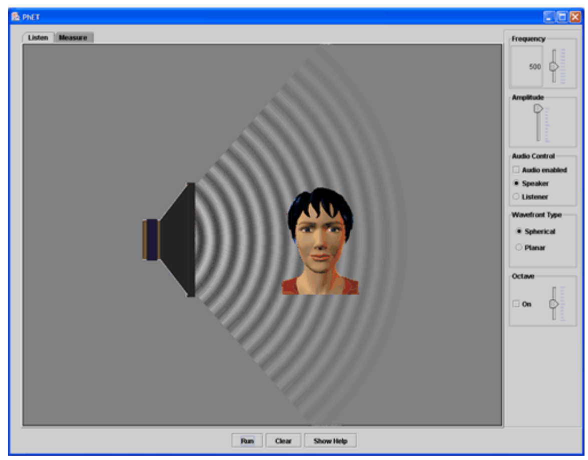


Figure 2. The PhET Sound Waves Simulation

What visual information is presented in this simulation? Most of the pictures on the screen look like the objects they portray (e.g. the speaker and listener). If you were looking down on an actual room, these two objects would look more or less the same. Interpreting these visuals does not require abstraction. Thus, they are not really conceptual metaphors, but could fall into the category of *literal* concepts (Lakoff [1992]). The thing you would not see in the room is the large pattern of light and dark circles surrounding the speaker. There is another situation in nature where you might look down and see this pattern. Imagine your self standing on a bridge over a pond and dropping a stone into the water. After a splash, waves would travel out in circles and would look very much like those in the Sound Waves simulation. In fact, we find that in describing the physical phenomena associated with sound waves, students make use of the water waves metaphor. The metaphorical mapping looks something like this:

The Water Waves are Sound Waves Metaphor

Source	Target
Waves on water	Waves in air
Water waves travel out in circles	Sound waves travel out in circles
Particles of water move up and down	Particles of air move up and down

Here we have an example of a metaphor that does not preserve inference. In a sound wave, the particles of air do not move up and down like water waves. Rather, the air particles move in and out along the direction of the wave, compressing at one point and spreading out at another. Where they compress the pressure is high, where they spread the pressure is low. The mapping should be more like this:

A More Correct Water Waves are Sound Waves Metaphor

Source	Target
Waves on water	Waves in air
Water waves travel out in circles	Sound waves travel out in circles
Particles of water move up and down	Pressure of sound goes up and down

In going from the source to target in the last line, we have skipped a crucial step. Particles are a substance-based concept, while pressure is abstract. Pressure describes the state of a substance – it is not a substance itself. We need a metaphor from the abstract concept of pressure to the substance-based concept of particle motion.

Pressure is Particle Motion Metaphor

Source	Target
Higher pressure	Particles are compressed
Lower pressure	Particles spread out

We need one more metaphor to complete our picture. The concept of pressure must be associated with wave height. This is a familiar metaphor of a graph where the horizontal axis is distance and the vertical axis is pressure (bottom plot in Fig. 3). The metaphor for this is straightforward.

Wave Height is Pressure Metaphor

Source	Target
Higher wave	Higher pressure
Lower wave	Lower pressure

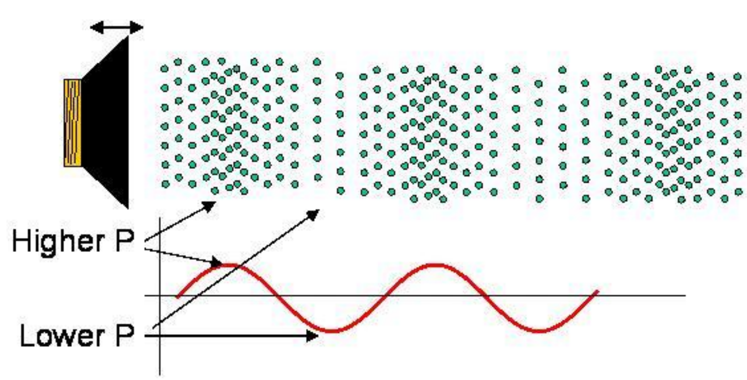


Figure 3. The motion of air particles is related to a pressure wave.
(In lecture notes of a physics course at the University of Colorado,
with permission from Kathy Perkins)

Metaphors can be *blended* together to form new metaphors (Lakoff and Nunez [2000]). As a final step in our analysis, the Pressure is Particle Motion metaphor is blended with Wave Height is Pressure to form a *complex* metaphorical blend. This is the picture of how the correct concepts for sound waves are understood in terms of the Sound Waves simulation.

The Complex Sound Waves Blend

Visual on screen	Water waves	Pressure	Sound waves
Bright circle	Crest of wave	Higher pressure	Air particles compressed
Dark circle	Trough of wave	Lower Pressure	Air particles spread out

Now we must ask the question: how do we get students to realize the correct concept? Answer: *we have to tell them*. There is no conceivable way to get the concept of pressure as particle density from the simulation alone. This is not just a misunderstanding. If we assume that before using the simulation that the student did not have any model in mind, then we can conclude that the simulation would cause them to come up with the *incorrect* model. The correct model was introduced in class as shown in Fig. 3. Here, a wave is plotted below a representation of air particles. This is how students got the idea for the Pressure is Particle Motion metaphor.

There are several concepts that are important in the Sound Waves simulation beside the motion of the particles. We would like students to learn about frequency, wavelength, and amplitude. These concepts have their own metaphorical mapping:

Source – Visual on Screen	Target – Concepts
Distance between adjacent dark (or light) circles	Wavelength
Number of dark (or light) circles passing a point in 1 second	Frequency

Number of times speaker moves back and forth in 1 second	Frequency
Pitch of sound	Frequency
Apparent height of wave (from shading)	Amplitude
Distance speaker moves back and forth	Amplitude
Volume of sound	Amplitude

Notice that for frequency and wavelength, there are three possible sources. This is one difficulty in producing a robust theory of metaphor. Students may use any or several of these sources to understand the target domain. In two cases, there is a mapping from audio (rather than visual) information to the abstract concept. Using the computer's speakers, the student can actually hear the volume change as the volume is changed in the simulation, or as the listener is moved around. This is coupled to the visual information about amplitude (i.e. the height of the wave). The mapping from wave height to an abstract quantity is important in our discussion of radio waves next.

Radio Waves

Implicit in the Water Waves are Sound Waves metaphor is that we live in three-dimensional space. We know from experience that water waves, when viewed from the side, go up and down. This is why the Sound Waves Blend in the last section worked. The two-dimensional image in the simulation was mapped onto a three-dimensional substance in the real world. Imagine that you rotated the wave in Sound Waves so

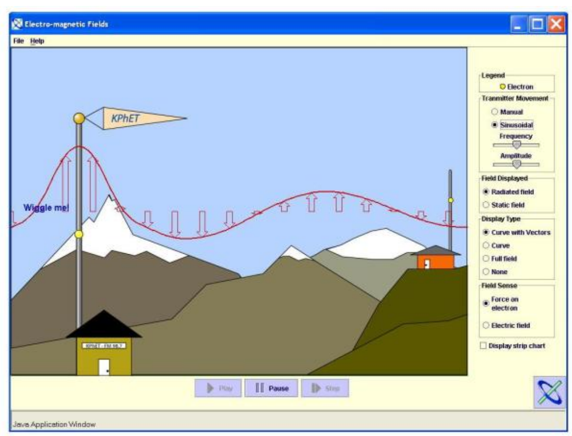


Figure 4. The PhET Radio Waves simulation.

that you were looking at it from the side. You would have something like what is seen in the Radio Waves simulation (Fig. 4).

Why have we followed Sound Waves with Radio Waves? It seems arbitrary. After all, one could have started with Radio Waves, or some other simulation involving a side view of waves, like those on a vibrating string. We are doing it this way because the students that were interviewed experienced the simulations in this order. Thus, we would like to build our theory based on their specific experiences.

In Radio Waves, a transmitting tower on the left broadcasts a radio wave to a receiving tower on the right. Given what we know about Sound Waves, what is the metaphor for Radio Waves? Following Lakoff and Nunez [2000], we suggest that it is a *linking* metaphor from the Sound Waves Blend to Radio Waves.

The Radio Waves Linking Metaphor

Source – Sound Waves	Target – Radio Waves
Distance between dark (or light) circles is wavelength	Distance between crests is wavelength
Number of dark (or light) circles passing a point in 1 second	Number of crests passing a point in 1 second
Wave height is pressure	Wave height is force on an electron

First, notice that this is a set of mappings of metaphors to metaphors. It is a linking metaphor from one simulation to another. It maps the metaphors used in Sound Waves to the metaphors necessary to understand Radio Waves. The first two mappings work because we can imagine rotations in three-dimensional space. The last mapping works because we now understand the abstract concept of pressure in terms of wave height. So it maps an abstract concept to another abstract concept (just replace *pressure* with *force*).

Bridge

Again, we must keep in mind that this is all highly speculative. There are other interpretations of the visual information in addition to the several we have already pointed out. For example, if air particles are darker than the background, the dark circles in the Sound Waves simulation could represent a high density, and the white circles could represent an absence (or it could be the reverse!). In the next section we will discuss the results of student interviews and show how their thoughts helped shape our theoretical model.

Part II

While interviewing six physical science students about the Sound simulation (Fig. 2) it was striking how well they understood frequency, wavelength and amplitude. It was even more impressive four weeks later while interviewing the same students about the Radio Waves simulation that they all, without exception, still understood these concepts quite well and related the ideas back to the Sound simulation while describing the ideas. In addition they moved from one representation of a wave to another with ease.

I [Wendy Adams] have taught the concepts of frequency, wavelength and amplitude in both physical science classes and algebra based physics classes. In every case, many students remain confused about the terms physicist use when describing wave behavior. Especially frequency. Students have a very hard time grasping frequency and often confuse the idea with time or wave speed. They especially have trouble seeing the relationship between frequency and wavelength and quite often fall back on the formula $v = \lambda f$ to figure out whether frequency and wavelength are proportional or inversely proportional. Similarly many cannot discern the difference between the position of the mass or point on a string and the amplitude. They also see different representations of waves as completely separate things and have a very difficult time transferring ideas from one representation to the other. These problems continue after having a standing waves lab, springs lab, lecture and wave table demonstrations in class.

The six interview students were of varying ability and all were quite comfortable explaining the ideas of frequency, wavelength and amplitude four weeks later while seeing a completely different representation of a wave. These students who had only seen the Sound simulation and heard lecture were much more capable of explaining the concept than students who had spent a week and a half on waves and springs and another week on sound. What makes the simulation so much more effective than other teaching methods?

When teaching from a textbook and in lecture, one is limited to static diagrams or simply words. Many textbooks do not make use of a diagram when describing frequency. Others show diagrams similar to figure 5. To understand frequency from this diagram the student must visualize the motion of the wave. With only a static picture to go on, the student is required to map frequency to distance. They have to first identify wave fronts, then while picturing the wave moving across the page, vary the number of wave fronts passing per unit time to see the difference between different frequencies. When picturing different frequencies, it is very difficult to do so with a constant wave speed. It's no wonder students have a terrible time keeping frequency, wavelength and wave speed straight! The number of metaphors and conceptual blends required can easily be overwhelming. In addition, if they want to understand how frequency effects what they hear, they can only read that it is proportional to pitch.

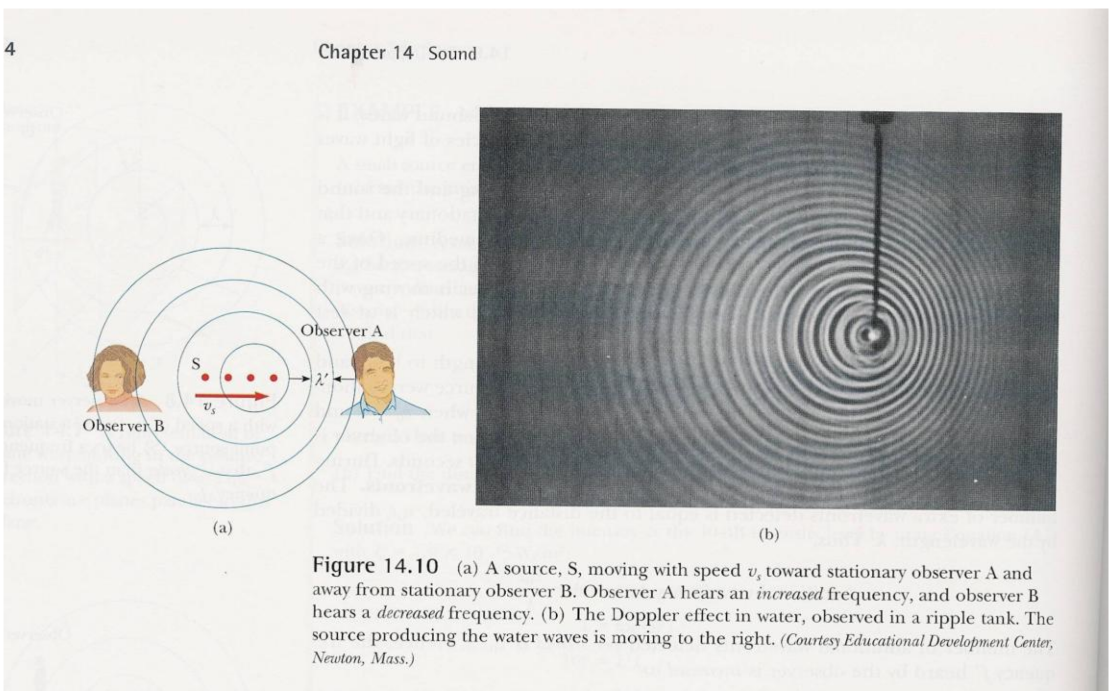


Figure 14.10 (a) A source, S, moving with speed v_s toward stationary observer A and away from stationary observer B. Observer A hears an *increased* frequency, and observer B hears a *decreased* frequency. (b) The Doppler effect in water, observed in a ripple tank. The source producing the water waves is moving to the right. *(Courtesy Educational Development Center, Newton, Mass.)*

Figure 5. Depiction of variation in frequency heard by two different people due to the Doppler effect. (Serway and Faughn (2001), *College Physics*, (Fifth Edition), Harcourt)

To understand amplitude the text may use a picture such as seen in Figure 6. Here closely spaced lines indicate higher points in the wave. This can easily be confused with the pictures used to indicate increased frequency. An oscilloscope is also included to connect the representation of a transverse wave with the wave fronts produced by the speaker. It is much easier to define amplitude with this representation; however, the student must make the connection between the wave fronts and the transverse wave shown by the scope.

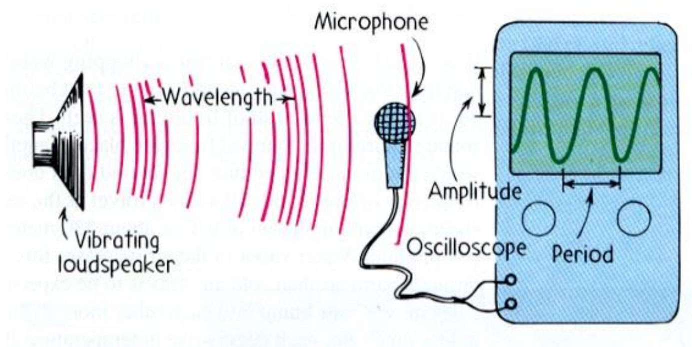


Figure 6. Depiction of sound as wave fronts including an oscilloscope showing a transverse wave to define amplitude. http://sol.sci.uop.edu/~jfalward/physics17/chapter10/chapter10.html

With many concepts, the ideas can be clarified with a lab. Watching the actual object in action is immensely useful. Students observe standing waves in a lab that uses a vibrating source with a string attached. In this lab the students can see the waves travel along the string and the vibrations of the source; however, the frequencies are so high that the string appears to be in two places at once and the observer certainly can't discern the movement of the source, it's just a blur. Although, this lab does give the student a chance to hear the pitch of the source change as they change the frequency.

Sound is something you can't see. Part of the standing wave lab has the students place a tuning fork above a tube of variable length. They identify the lengths of the tube that allow standing waves to be set up. With these tools they can figure out the wavelength of sound. Again, you can't see the sound and you have to do several trials and some calculations to learn about the wave's characteristics. The frequency of the tuning fork is too high for the eye to discern the movements of the fork and the students simply take the value off of a stamp on the fork. The student cannot "see" anything for themselves. They must map what they've learned in class about waves with their observations and take what is given to them on faith.

Frequency is not only something that can't be depicted directly with a diagram but it's commonly taught with objects outside of students' experiences. The standing waves lab could be easily connected to musical instruments, the string behaving as stringed instruments would and the variable length tubes modeling the wind instruments. However, these connections are rarely made explicit. The connections may be obvious to a physicist but for the student they are not. Not only are we trying to teach abstract ideas about waves, we are doing it with objects that are outside of the students' realm of experience.

The idea behind a lab is to remove the need for metaphor. Labs put the objects in the hands of the students who can then observe the objects' behavior. However, many labs, such as the standing waves lab described above, use equipment that is foreign to students. In these labs students can observe the phenomena their instructors want them to but it doesn't become much, if any, more grounded than hearing the idea presented by their instructor or reading it in a book because they are still left with the challenge of linking it to their life experience. This is consistent with Otero's [2003a] theory that student's must bridge their spontaneous concepts (intuitive knowledge stemming from real life experiences) with their scientific concepts (academic or instructed knowledge) before they can develop conceptual understanding. When using lab equipment that is unfamiliar to the student, the entire lab experience falls in the category of scientific concepts. The ideas are abstract and the student is left with a rather large gap to bridge on their own between the foundation of knowledge they entered the class with and the scientific concepts the instructor has presented them with. If lab equipment were familiar to the student, it would allow the student to make use of their spontaneous concepts while "trying on" the scientific concepts their instructor and/or textbook has presented them with.

The simulation addresses many of the problems stated above. It uses speakers, which all students have had experience with, shows the sound that we can't see and allows one to slow it to a speed that is observable. Then the students can change frequency and amplitude to see how that changes the speaker's movements, the sound wave itself and the sound the student hears. The simulation assures that the instructor and the student share the same base visualization, and gives the student two ways to see frequency in addition to hearing it. This means the student is interested, they have experience with the objects involved and they only have to map the visualization given for the wave with their experiences with waves on water. This requires a very minimal cognitive load for the student in contrast with the common methods of instruction mentioned above where the student must hold many complex metaphors and ideas in their head while attempting to visualize sound and, at the same time, understand the new physics concepts they're being presented with.

The interviews were done in a predominantly think-aloud style with simulations. During the interviews involving the Sound simulation, students were asked to play with the simulation while verbalizing all of their thoughts. The interviewer simply encourages them to talk if they are silent for more than a few seconds. The interviews for the Sound simulation were after lecture, but before the students had completed their homework.

While playing with the simulation, the students would describe what was happening as they changed the frequency or amplitude. There were two types of explanations coming from the students. One used the speaker as the visual and the other used the sound waves. When using the speaker for their visual, the student might say “a higher frequency is when the speaker moves faster.” If the student used sound waves, they would say something to the effect of “A higher frequency means wave fronts come by more often which shortens the wave length.” Notice with the second type of explanation nearly every student volunteered the information about the wavelength. With the students who used the speaker as their visual, a follow up question was asked about wavelength. They would think a bit and then give the correct answer after switching to the sound waves for the visualization behind their explanation. The follow up question was necessary with one student who had used the sound waves as their visualization while describing frequency. They immediately answered and were then concerned that they were missing some important part of the question because the relationship between frequency and wavelength was so obvious to them it didn’t seem necessary to state it. Quite a difference from my students in the past who never quite got a grasp on the relationship between these two ideas.

After playing with the simulation, the students were asked what the air particles were doing. For example, does an air particle move from the speaker to the person's ear at which time they hear the sound the speaker was making when that particle left the speaker? The students all disagreed with this idea and explained that the particles would move back and forth in a confined region as the sound wave traveled past. "It's like a cork on water. As a wave passes the cork moves back and forth a little but doesn't move along with the wave." Comments such as these are evidence that the students are mapping sound with water waves. One of the instructors of the course told us that during homework sessions some of the students made the comment that having dark regions represent high density air and light regions represent low density was counterintuitive. Again, leading us to believe the students are using water waves as part of their metaphor to understand sound. It is interesting to note that water waves were never used in lecture to describe sound or the Sound simulation, only higher and lower density of air.

Four weeks after the interviews about the Sound simulation students were interviewed about the Radio Waves simulation (Fig. 4). This set of interviews happened before the topic was covered in lecture. These were think-aloud type interviews again. While playing with the simulation, the first student volunteered definitions of frequency and amplitude while playing with the sliders for each. "Let's see, frequency is the number of wave fronts that go by each second so, let's see, yes, that makes sense. I increase the frequency and I can see more waves between the two antennas. It's just like the Sound simulation except this wave is like you turned the sound wave or like a ripple on the water on its side." This student is keeping the inference from water, that we do not want, believing that sound waves are transverse, however, she does a beautiful job of explaining frequency and then amplitude while referring back to the Sound simulation from four weeks prior without any other cue to the Sound simulation. Incidentally, we had interviewed two weeks before about a completely different simulation so the Sound simulation was not the last thing she had interviewed about.

After this first interview, the decision was made to prompt the other students for definitions of amplitude and frequency as soon as they began playing with these two controls. Each one, without exception, used visualizations from the Sound simulation to support their definitions. Some used the movement of the speaker and others used the Sound wave. They would use their hands saying "Remember in Sound how the speaker moves faster with higher frequency?" Each one seemed to have no trouble applying what they knew about waves to this new representation of a wave as transverse rather than wave fronts. We believe the motion that is seen in each simulation is adequate to allow a smooth transition between these normally very difficult to connect representations of a wave.

It is interesting to note that the students who used the speaker movement as the visualization in their descriptions are the same students who throughout the semester of interviews had more difficulty with abstract concepts. We believe this fits well with our theory because the speaker is a *literal* concept (Lakoff [1992]) where as with the sound wave, the student uses The Water Waves are Sound Waves Metaphor described in Part I to understand the abstract concept of sound.

Although students cued on different parts of the Sound simulation to describe the concepts of frequency and amplitude, they were visualizations from the same source that other students or the instructor were familiar with. This common visualization is extremely important. Quite often an instructor and student or two students have a conversation and come away feeling they understood one another when, in fact, they were each visualizing two very different things while using the same words to describe what was going on. Otero [2003b] presents data on students discussing their models of charge transfer without simulations. The students believed they were visualizing the same phenomena; however, interviews by researchers after class probed the students further and found they had quite different models. In later classes the students used a simulation while working on their ideas and discovered their models were not the same. With the use of the simulation as a common visualization to aid in their discussions, the students were able to make better sense of their experiments and come up with a class consensus for charge transfer.

Thinking about these interviews allowed us to see that simulations can be very effective in teaching physics for several reasons. The ideas can either be connected to *literal* concepts or abstracted via a simpler metaphor while the instructor and students are using a common visualization that includes motion. This reduces the cognitive load of the student giving them more to work with while “trying on” the new scientific concepts they have learned in class.

Conclusion

Students often have trouble with basic physics concepts. We have found that students who interact with the PhET simulations grasp these concepts more easily than traditionally taught students. Part of the explanation for this may be in the visual information provided by the simulations. Not only is information provided that is not available in a real laboratory, but the interactive aspects may help learning. We have developed a theory of the metaphors used by students in understanding Sound Waves, and carrying that understanding to Radio Waves. Our theory is built upon results from student interviews. However, we have found that different students take different cues from the simulations to understand the concepts. Thus, a single theory can only go so far in describing the way a particular student thinks.

Our perspective has been that the use of metaphor is central to students' understanding of physics concepts. The particular metaphors that students use may shed light on where their misconceptions come from, and how we might be able to overcome them. What is important to realize is that metaphors work because they link knowledge that students have from everyday experience to more abstract concepts. Thus, in crafting simulations, we should attempt to build into them objects that students can relate to their everyday lives.

Gesture With Interactive Computer Simulations

Abstract

This paper explores student gesture while using interactive, animated computer simulations. First I will carefully analyze the rate and type of gesture used with the Nuclear Physics simulation created by the Physics Education Technology Project. This analysis can be viewed with two lenses. The first being simulation use as an extension of gesture. The other is to evaluate through gesture, how the simulations are used to support student understanding. ***This paper is simply a taste of what can be understood through analysis of gesture. Future work is identified.***

Introduction

The use of gesture has been carefully studied with student's scientific talk. Researchers have found that the students' gestures change in several ways while explaining a topic they "understand" versus talking while constructing meaning. Gestures differ with the two types of talk temporally, in rate of gesture and in types of gesture used. More broadly, research, including the above, supports the claim that gesture is *necessary* for meaning construction. Crowder (1996) found students' gesture less often and that their gestures coincide with the words they use while 'explaining their ideas'. In fact she goes as far as to describe this type of gesture as redundant. In contrast she describes the type of gesture used while students are constructing meaning as preceding verbalization or even providing information their words do not convey. Additionally, the rate of this type of gesture is also higher. Another difference Crowder found with the two types of talk are what she describes as inside and outside gestures. The students, who are constructing understanding, step inside of the gesture space indicating they are using the gestures for their own understanding rather than as a communication tool. This can be observed by watching a student's eyes. When explaining a topic they understand, students look at the audience and not at their hands.

Roth and Welzel (2001) observed similar behaviors with their German students during scientific talk. There studies were slightly different in that they studied the students while doing hands on activities. They classified manipulation of the objects as part of gesture. Their observations brought them to three conclusions: (1) Students use gesture to take the place of words that they are unfamiliar with. (2) Gesture provides the necessary glue for students to construct complete conceptual understanding. (3) They found changes in type, rate and timing of gesture as students became more comfortable with their explanations. Both (1) and (3) are consistent with Crowder's work described above. The second conclusion adds an additional dimension in part due to the use of objects. Roth and Welzel found that gesture and the objects were necessary items for the students to construct understanding. In order to understand the scientific topics at hand students are required to layer conceptual understanding onto the phenomena they observed in lab. Roth and Welzel state that there are more representational layers possible when objects or gesture can be used during speech. Without the use of gesture or objects the demands on memory capacity would be tremendous.

In support of Roth and Welzel's hypothesis that gesture and objects allow the students to construct meaning are studies done such as those by Glenberg and

Robertson (1999), Rime, Schiaratura, Hupet and Ghysselinckx (1984) and Alibali, Kita, Bigelow, Wolfman and Klein (2001). Rime et al and Alibali et al both did studies with gesture and spatial information. Rime et al found adults' descriptions contained a greater degree of imagery when they were allowed to gesture than when their appendages were restricted. Alibali et al studied children's descriptions and found more perceptual-based explanation when they were allowed to gesture than when they weren't. Even closer related to Roth and Welzel's claims, Glenberg and Robertson argue indexing, that is, linking words and phrases to real-world objects , is required for comprehension. They studied adults attempting to follow directions. Some were given directions while seeing a compass and watching an actor's hand point to the compass's arrows and turn its dial at the appropriate moments. Others simply heard the directions. The adults who were given the visual cues had a much deeper and more usable understanding of the directions than those who simply heard the verbal transcript.

In order to understand students' sense making while using simulations, it is necessary to study students' gesture while using the simulations. In this paper I study two roles of gesture with simulations. First I will look at the rate and type of gesture used while exploring simulations and second I will observe students' gestures while describing a phenomena related to the simulations and evaluate, through gesture, how the simulation can be used in their descriptions.

To answer the above questions think-aloud style interviews were conducted with students while using simulations that are part of the Physics Education

Technology Project (PhET)[3]. These simulations are of a highly interactive, animated nature. Thirteen different students were interviewed about various simulations. The students consisted of volunteers from introductory physics courses at the University of Colorado, Boulder. There were six students from a first semester non-science majors course, four from the second semester of the non-science majors course and three student's who were taking the second semester of algebra based introductory physics. All students exhibited the same general trends in gesture while playing with the simulations.

Rate of Gesture during simulation interviews

While using these simulations students predominantly use the mouse, watch the simulation and gesture sparingly. The mouse becomes an extension of their hand and is continuously used to change parameters or move objects on the screen. It's also used to point or show motion on the screen in conjunction with student's verbalization. In the extreme cases students do not gesture at all while using the simulation or others may gesture with an average rate of one gesture every 15 seconds. The highest rate observed is still much lower than during typical speech or science talk and was punctuated with intervals up to two minutes where the student relied solely on mouse movements to supplement her speech.

The following examples were taken from a set of interviews with a simulation called Nuclear Physics[4]. This simulation has three panels that can be explored

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[3] http://www.colorado.edu/physics/phet

[4] http://www.colorado.edu/physics/phet/simulations/nuclearphysics/nukes.jnlp

demonstrating alpha decay, nuclear fission and chain reactions. Some of the students had already seen the simulation used in class, others had never seen it before nor had any instruction on the topic. The use of gesture by these two categories of students was comparable once the students stopped trying to explain what they remembered and began playing with the simulation in earnest.

Gordon, a rather talented second semester non-science major, used three gestures during a 30 minute interview (Figure 1). When words were not adequate, he reached for the mouse. This is a student who's gestures are never grand; however, while explaining his major and employment he gestured 23 times in two minutes. Granted this is not the same type of science talk; however, it was in the same setting with the same interviewer in an interview that occurred before the above mentioned interview with simulations.

Serena, a B- student from the algebra based physics course, happily had no instruction on nuclear physics. She spent more time with the simulation than the other students, approximately 40 minutes, while constructing her understanding of what the simulation was demonstrating[5], she gestured at a higher rate than the other students studied. During an eleven minute segment, Serena gestured 40 times while using the simulation (Figure 2). This included briefs periods of time where she answered related questions by the interviewer that could not be answered directly by the simulation. During these episodes, Serena gestured continuously without any discernable break until she'd finished answering the question.

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[5] Serena did construct a nearly complete understanding of the Nuclear Physics simulation during the interview by simply playing with the simulation, talking and being asked only a couple of probing questions by the interviewer. No instruction was given and Serena's questions were not answered by the interviewer.

Sally and Larissa were both from the same second semester non-science majors course as Gordon. They gestured in a similar fashion to one another. Larissa is a stronger student than Sally in many ways. Sally gestured eight times during the first ten minute interval of the 28 minutes that she explored the Nuclear Physics simulation (Figure 3). Similarly Larissa gestured ten times during the first 13 minutes of the 17 that she needed to thoroughly explore the same simulation (Figure 4).

As with the Nuclear Physics simulation, all of the interviews show a very low rate of gesture while students are using simulations. In fact, Nuclear Physics actually has a higher rate of gesture than most of the other simulations. One may argue that the mouse is inhibiting the students ability to gesture; however, I do not believe this is the case. Evidence for this opinion comes from a quick look at the transcripts which shows that the students are not gesturing with their left hand, which is free to move. Additionally, the students are extensively using the mouse to animate the simulation or point to objects or motions on the screen.

Type of Gesture during simulation interviews

In addition to the rate of gesture during simulation use being dramatically lower than in typical science talk settings, the type of gesture was also affected by the simulations. I have classified types of gesture using three categories as defined by Krauss, Chen and Gottesman (2000). Lexical, deictic and motor are as follows: Lexical is a broad category that includes objects or people in space, shapes of objects or people and smooth, continuous motions or a set of discrete movements that represent change over a series of steps. Deictic gestures always indicate objects or people such as pointing to where an object or person is or was. Finally motor gestures beat with the rhythmical pulsation of speech.

Gestures used by students while playing with the simulations are predominantly deictic in nature and are directed at the screen. I have identified three reasons for gesture that is not deictic in nature during the interviews with the simulations. First, when students are answering a question from the interviewer to clarify a term or concept that they had used, they look away from the simulation and use more traditional gesticulation. Second, when the student's metaphor for understanding differs from the visualization provided by the simulation. Finally when the student is unable to quickly cause the simulation to provide the visualization they need to support their speech. In this section I will look at both Larissa and Serena's type of gesture; however, the other students also fit into the scheme indicated above.

Larissa gestures very little. Near the beginning of the interview, 5:07, she uses a lexical gesture to help her describe what she thinks will happen. She is on the alpha decay page and at that moment the simulation has not yet emitted an alpha particle. She is trying to remember what she saw the simulation do during class and incorrectly defines alpha decay as fission. At 5:20 she follows the curve of the graph on the screen (Graphing addressed shortly). At 6:14 she gestures while describing fission again, even after watching the alpha decay occur on the screen[6]. The next time she gestures is over three minutes later at 9:30. Here she is describing chain

[6] Larissa, after watching fission in the fission panel around ten minutes into the interview, smoothly transitions into the correct descriptions of alpha decay and fission as if she'd been explaining them correctly the entire time.

reactions, again remembering what she's seen in class, while looking at the fission panel. Up to this point her gesture has been very limited and used when she's thinking about something the simulation is not showing her. During the next episode of gesticulation, 14:46-15:10, she is answering a question by the interviewer about the yellow circle that appears briefly around the nucleus at the instant it undergoes fission. This requires her to visualize a phenomena which the simulation merely represents as a yellow circle.

The last series of gestures, 16:30-18:00, occur while she is describing the potential energy curve shown in the bottom half of the play area. There was also a gesture early on, 5:20, where she indicated the shape of the curve. Every student using the Nuclear Physics simulation, except Gordon, gestures in this way when describing the curve. During the interviews several students did not construct sufficient descriptions of the potential energy curve. After coding the interviews for gesture, I saw that all students, except Gordon, used many lexical gestures while answering the question, "what does the potential energy curve mean?". I interpret this as an indication that the simulation is not providing the animation necessary to convey understanding of the curve. In any case, it was clear that the potential energy graph is something the simulation did not adequately address for the students.

A course look at Serena, my high rate gesturer reveals that she predominantly points at the screen either indicating an object or motion that is occurring or has recently occurred on the screen. On occasion she uses a lexical type gesture to indicate an event that recently occurred such as fission of the nucleus. The only time she averts her gaze from the simulation and makes use of gestures that do not refer to or mimic the simulation, she is answering a question posed by the interviewer. For example at the time stamp 21:38 she has recently used the term radioactive and the interviewer asks her to define radioactive. In this case she looks away from the screen and for a little over 30 seconds does her best to define radioactive while gesturing continuously. She then looks to the simulation to help her with her definition, points to the screen and then takes up playing again.

By looking closely at lexical gesture I have stumbled across a very valuable aspect of coding gesture use with simulations. When students' gestures are not deictic in nature or mimicking the simulation, it's an indication that either the simulation cannot keep up with their description or, more importantly, the students are drawing on other resources to understand or describe the concept at hand. This can be a very useful research tool for simulation design. When there is a point in a simulation that requires supplementary gesture, it is an indication for the developers that students must draw on other resources to explain or understand the concept.

Two Lenses

I would like to analyze the above rate and type of gesture use with simulations using two lenses. The first being simulation use as an extension of gesture. The other is to evaluate through gesture, how the simulations are used to support student understanding.

With all of the students, their rate of gesture in the above analysis appears to be extremely low. I argue that this actually is not the case. To thoroughly analyze gesture when using simulations, I believe it may be useful, as Roth and Welzel did with objects, to include the use of the simulation as part of gesture. The mouse becomes an extension of the student's hand. Mouse movements combined with the animation of the simulation take the place of gesture. If one were to include the use of the simulation as gesture, the rate of gesture would be comparable to these students' rate of gesture while talking without simulations. Further support of this idea comes from instances where students resort to gesture, with their hands, in the case where it takes to much time to make the simulation animate their thoughts.

Another useful facet of gesture analysis is that one can see evidence that the simulations are supporting student understanding. After using the simulations, students' descriptions of various physical phenomena are supported by gestures that clearly mimic a simulation they have used in the past. A review of the interviews and conversations with the instructor of the non-science majors course reveal many examples of this occurring. To pull an example from the above transcripts, Larissa mimics what she has seen happen in the Nuclear Physics simulation a few days before during a lecture demonstration. She uses gestures that match the visuals from the simulation to support her description of fission and chain reactions before she makes the simulation demonstrate either of these phenomena during the interview.

Future Work

In this paper I have only looked closely at the Nuclear Physics simulation. A quick look at interviews with the same students using different simulations has elicited some very tantalizing ideas about the potential analysis of simulations. One possibility would be to look closely at the other interviews to see if the rate of gesture correlates with the level of interactivity for all simulations. Another intriguing possibility is to follow the line of research sited at the beginning of this paper attempting to differentiate explanation of concepts versus constructing meaning during simulation use.

Preliminary analysis shows that the Nuclear Physics simulation elicits a slightly higher rate of gesture and type of gesture than many of the other simulations. I hypothesize that the nature of the Nuclear Physics simulation, it is animated however not as interactive as some, is the cause of this difference in gesture. There are fewer options for the student to choose; however, the major difference is that it takes from five seconds to two minutes to see the complete result of an option change. Many other simulations show an immediate change when an option is selected or an object in the play area is moved. This makes the predominant role of the student in the Nuclear Physics simulation that of setting up the simulation and watching what happens. I believe this elicits a greater number of gestures, most of which are deictic in nature, because it’s easier and faster for the user to gesture than to get the simulation to show the supporting visual to their verbalization.

A supporting example of this is seen in the gesture where both hands move apart to indicate the results of a nucleus undergoing fission. While on the fission panel, the simulation shows a single fission. If the user would like to see it again, they must reset and fire another neutron. In this case, while discussing what is happening the students use their hands rather than wait for a reset and new fission. If the student is on the Chain Reaction Panel and has the correct combination of nuclei, they may have the good fortune of watching many fission events over a period of at least a minute. While watching the chain reaction screen and talking about fission, students do not use the fission gesture described above during an event where the simulation is continually showing nuclei fission. Some students do point at the screen while explaining as this occurs because the chain reaction does not require user control.

A set of interviews with a slightly different use of the simulations appears to support this hypothesis as well. During these interviews, students were asked to think about all the simulations they'd used in the past and pick their favorites in two categories: 1) how much fun the simulation is to play with, and; 2) how useful the simulation is for understanding physics. Because of the slightly different situation, the level of interactivity and reaction time of the simulation stands out. Larissa, when explaining the various simulations she had previously used, even when the simulation was running in front of her, tended to describe the simulations using many lexical gestures rather than taking time to demonstrate the simulations' abilities with the simulation. However, when describing Springs and Masses, one of the most interactive simulations in the PhET suite, Larissa only used a couple of motor gestures with her left hand while quickly demonstrating her favorite features of the simulation with the mouse.

Tackling the second question, explanation of concepts versus meaning construction, will be a far greater challenge. A first step will be to use the interviews mentioned above where students are describing previously used simulations. It appears that a transition can be seen in these interviews from explanation to construction of meaning. During all of these interviews there comes a point where the student will be in the midst of quickly describing a simulation while playing a bit when they stumble across a feature or behavior of a simulation they can not adequately explain. When this happens their talk becomes slower and disjointed, their focus shifts from a combination of the interviewer and simulation to a solitary focus on the simulation, and their rate of gesture slows dramatically. I believe coding this set of interviews and carefully analyzing the results could possibly bear fruitful information on the very difficult problem of identifying sense making.

Conclusion

Analysis of gesture while using interactive computer simulations can be a very powerful tool for analyzing both the simulations themselves and student understanding through simulations. This paper has shown a decrease in rate of gesture while using simulations and that students generally use deictic gesture while using the simulations. Instances where students use lexical forms of gesture are indicative of students drawing on prior knowledge or if the gesture mimics the simulation, the simulation is not quick enough in demonstrating the necessary animation. These observations support the notion that the simulations can be considered an extension of gesture. It also gives evidence that students use the simulations to support their understanding of concepts. I believe further analysis of gesture will provide many more useful insights for the development of simulations. In addition it may provide a tool for identifying students' construction of meaning.

Time	Gesture	Statement	Commentary
0:10			Began Nukes

3:15	right hand flitters (darts) up and out	"they're not just standing still, they have to be moving. Then when they get shot out, they just go"	On the Alpha Decay Page
23:55	Hands sitting on legs. Right hand lifted slightly off leg on 'looks', 'amount' and barely on 'random'.	"it could could easily just explain this. It looks to me like there's no actual like set amount you need to have to get like a certain percentage or whatever it's just kinda random"	While on the Chain Reaction Page
24:19:00	hand poised above mouse, rolls wrist to the right on probability and a little further on half.	"for there to be like a good enough probability to get like half or more of them hit"	While on the Chain Reaction Page
32:30:00			Switched to Semi Conductors

Figure 1: Complete transcript of Gordon's use of gesture while spending 30 minutes using the Nuclear Physics simulation.

Time	Gesture	Statement	Commentary
17:10			Starts talking about Nukes
17:33	points at legend on screen touches side of computer	"That's a proton"	While Serena thinks about things she asks herself questions and then answers with "I don't know" "I can't figure out this computer program" "I don't really know!". While doing these things she does not move the mouse or gesture. Maybe plays with her hair or shirt. Once she gets a piece of information she pionts with the mouse or gestures.
17:45	Left hand open up moves to the left.	"Biology perspective"	
18:08	Right hand opens towards screen fingers straight. Bounces again on farther away it gets	"Energy is decreasing the farther away it gets."	

18:24	Fingers open up fingers close together then open both hands	"Break atom? Release energy"	
18:39	Right hand waves to right	"That's fine just thinking outloud"	
19:16	points at nucleus as neutron enters then at potential energy curve and then at daughter as it moves off the screen	"So when a neutron enters it the potential energy increases and it splits"	
20:06	Right hand barely open beats twice as moves right (indicating two words)	"It says chain reaction"	
20:08	holds right hand spread out to screen and pulls back and brings fingers in a fist Three times spaced apart by a second or so as she asks	"so what was that burst of light right there? Was that energy? Was that energy…"	
20:16	hands move apart with index fingers pointing	"when the two particles separated"	
21:00	Right hand lifts off the mouse and waves over shoulder to right with arm resting on table.	"maybe this is a chain reaction when…"	Sense making
21:05	points at screen three times puts hand down then up and points again beats twice	"Can't remember what these stand for because I haven't had chemistry in awhile I think this is one of the elements"	
21:29	folds hands together then beats down	" I don't remember for sure Maybe it's a half life.."	Asked what makes it radioactive
21:38	Hands open facing each other and apart as talk move in and back out. Then on half slaps together and apart and almost together and sweeps right hand towards her across palm of left without touching them.	"It just means that umm as time goes on it's going to decrease by half and then keep decaying but it'll never be gone"	These gestures were in response to interviewers questions and she's drawing on previous knowledge

21:55	puts middle fingers to thumbs like holding something and brings them together and apart and then just the right hand this way and then sets them down.	"it's always going to be there. I think that's still radioactive it's usually what they're talking about right?"
22:03	points at the screen	"It is like this element. This chemical they have here like, what is that ura uranium?"
22:30-23:02	hand, plam up, fingers out, in front of her Whole serious of hand waving as she explains rockey flats. Never stops moving them.	"like Rocky flats"
24:55:00	Hand is poised above the mouse then rotates up and to the right.	"releases energy" (pause opens hand) "potential energy I guess."
25:30:00	Points at nucleus and then follows daughter	"Nuetron is fired at it it breaks apart and releases energy"
25:40:00	rotates open right hand up and out to right	"it looks like"
25:50:00	points again at potential energy curve and then to right along curve.	"And it looks like looks like that particle that is split apart goes away from the nucleuses center."
26:08:00	points at PE curve and moves finger along and to the right	"So, so that should I think that should show you that the potentail energy is decreasing the further away it gets from the nucleuses center."
26:50:00	points vaguely at the screen and beats on that, maybe and neutron	"So I'm thinking that maybe when the nuetron hit the uh.."
26:53:00	points at legend on right beats with a little circle on uranium	"that particle uh uranium"
27:00:00	points at a spot on the screen and then back to the mouse	"it causes a chain reaction it says"
27:05:00	points at neutron and follows off the screen	"Maybe these two particles that split off"

27:08:00	hands loosely open facing up moving in and out together.	"Hit other particles and keep releasing more and more energy"	
27:12:00	hands flow out and around down	"or the radiation"	
27:15:00	hands in and out. Left out then fold	"maybe that's what causes what causes decay"	
27:41:00	points at each U238	"1, 2, 3, 4 5, 6 six on the screen"	
27:04:00	lift hand off leg and rolls out to left	"then they split"	
27;50	points loosely at the nuetron coming in.	"I think that … the neutron I keep firing"	
28:01:00	open curved right hand pointing towards the screen and beat on 'something'	"always going to hit something"	
28:10:00	open hands waving together and apart	"because all these particles are gonna be really close together and there's gonna be a lot more of them so it'll cause more a a bigger chain reaction than I'm seeing here."	
28:01:00	hands together	"particles really close together"	
28:06:00	hands come together then pull apart	"bigger chain reaction than what I'm seeing here"	
28:25:00	points at a daughter that moves off the screen	"passed right by it"	
28:29:00	points at one particle and then another	"when this particle broke off it didn't hit this one and cause it to break off as well"	
37:18:00	hands fly around indicating activity	"maybe that's what causes the decay, all that radioactivity"	
41:29:00	hands forming ball	one whole nucleus	
51:15:00			Finishes with Nukes

Figure 2*:* Transcript of an eleven minute excerpt from Serena's use of gesture while using the Nuclear Physics simulation for 40 minutes.

Time	Gesture	Statement	Commentary

0:00:00			Sally actually began nukes a few minutes before the video started.
1:00	left hand opens and moves to right at the same time	"pushed away"	Sally is trying to explain what the graph is representing
1:08	hand forms hitch hike emblem and moves to left with thumb leading	"so increase"	HAND PRECEEDED VERBAL
1:11	hand forms hitch hike emblem and moves to left with thumb leading on sucked away then sits stationary	"but if it's an electron it's being sucked there. So it'll decrease as it gets closer"	
7:00	hands together and then apart	"splitting things apart whereas fusion was crushing them together"	
7:27	hands around making a circle held until statement complete	"whole containing all the same amount of protons and neutrons"	
8:25	right hand barley off mouse fingers curled together and open up as wrist rolls out to right	"broken apart"	
10:10-10:30	Small beat gestures	explaining what radiation is trying to remember	
10:50	rigth wrist rolls hand out to right then fingers seem to grasp and pick out particles.	"waves coming off the explosion. The actual air moving around it the particles"	
29:00:00			Switched to Semi Conductors

Figure 3*:* Transcript of a ten minute excerpt from Sally's use of gesture while using the Nuclear Physics simulation for 28 minutes.

Time	**Gesture**	**Statement**	**Commentary**
1:30			Starts sim on Alpha Decay panel Larissa confidently explains what will happen using the mouse to show it while waiting but nothing is happening. Eyes on sim.

5:07	hands start together and then move out she begins her comment hands clasp on 'fuse together' then pull apart on 'fiss' clap then pull apart and back on 'fissioned'	"Wait, fusion is fusing together fiss fissioned" chuckles "apart" chuckles	
5:20	right hand curves up	potential energy curve starts	
6:14	hands together, folded at knuckles, then hands spray out 4 times to denote energy	Because it's fissi fissioning together part of the energy is going to have to be set out to once it tunnels out.	either mismatch with fission or showing energy going out before she describes it.
8:40			Moves to Fission Panel
9:30	hands start together loosely curved, they move out quickly and then back together. Repeats this 5 times.	"creates two daughter nuclei that and other neutrons that go out and then they split and if it was the chain reaction one then it hits another one and another one and"	
14:46-15:10	Hands spray out twice with energy comes out of it. Then clasp together (fingers intertwine) on 'fuse' then fist into flat hand for neutron fuses. Flat hands facing and move forward and back opposite each others motion on 'get those two confused' Hands pause in mid air until gets to 'energy goes out' simultaneously hands start together and spray out twice. Then arms stretch out in front in circle on 'big huge' then swoops up 'comes back up'	"Just like the energy that comes out of it…" Like once the fuse once the neutron fuses to the I still get those two confused" chuckle "to the U235 it just um shows all the energy that comes out of it so it's kinda like when the nuclear bomb goes off there's like all that stuff that goes out and it comes back up from like the big huge all the energy that comes back up."	In answer to question "what is the yellow circle when a U235 fissions?"
16:10	points at bottom and then curved up like potential and then fingers intertwine on nuclear force	"The proton has to travel up here It has kinetic and then it becomes Electrostatic potential and then it starts to become internuclear force "	Did this because asked her to explain the graph

16:30	hands togther and then apart and then right hand curves up	"To get in there because there's a repelling force from the protons and it has to go and it has to has to have enough potential energy to get to where the nuclues is."	
17:15	fingers together then two hands start intertwined and then move up.	"this short little divit it won't take that much energy for it to get in there but if it has it has a bigger well it takes more energy to get in there."	
17:25	Hand flat up and down beats on overcome and repelling force	"over come that repelling force to get to the nuclear force"	
18:00	lifts slightly off mouse and beats twice	"anyways"	
18:33			Quit Nukes and Started Semi Conductors

Figure 4*:* Transcript of a thirteen minute excerpt from Larissa's use of gesture while using the Nuclear Physics simulation for 17 minutes.

Appendix A

Section of interview coding for 'Radio Waves'.

			Just switched to static field
7:04	Sue	Hmmmm I just showed the static field. It's just showing few of em um but I'm not really sure why. And hide the vectors ok this goes with that	Clicks hide the vectors and then to radiating field
7:32	Sue	I guess I like the radiating field better just cus as it gets further away it starts going just up and down. It seems to make more sense I guess.	Looking at the radiating field on Full field mode
7:43	Wendy	Ok	
7:44	Sue	Ummm Oooh that's a good one. Ummm I'm kinda looking at how this affects the wave and…. I sort of like that. Makes the wave make a little more sense I guess.	Looking and the curve with Vectors mode
8:12	Wendy	Uh huh	
8:12	Sue	To see it like push it push the wave up and down as it goes down it goes across	

8:19	Sue	ummm autoscale.. and let's see….	
8:30	Wendy	Uhhhhh	
8:30	Sue	So that may have frozen it.	
8:32	Wendy	That wasn't your fault	Exits and restarts
8:33	Sue	(unrecognizable)	
8:34	Wendy	Why don't you exit it and go back in.	
8:35	Sue	Ok	
8:36	Wendy	I was noticing that it was complaining about being out of memory in the corner.	
8:39	Sue	Ok	
8:39	Wendy	It never quite recovered	
8:45	Sue	Um… Ok what would be the difference between these two?… I don't really seee…	Checks display strip chart and stares for a few seconds
9:00	Wendy	Move the window around a little bit because there are some lables that are missing. Sometimes they come up without it… Here will it just let you resize it?	
9:07	Sue	This one?	
9:08	Wendy	Yea this No, the little guy.	
9:10	Sue	Noooo it's just got an x... so	
9:20	Wendy	Well it's supposed to say transmitter above the top one and receiver above the bottom one.	
9:25	Sue	Ok, maybe like this.	Sue resizes and two versions of the strip chart show up.
9:27	Wendy	Oh neat! It's really not working!	
9:29	Sue	Laughs	
9:32	Sue	Um, Well mostly I'm just kinda tyring to think…	trys to click x to get rid of the strip chart
9:35	Wendy	The x doesn't do anything	
9:39	Sue	Ummm Go back to this one?	
9:43	Wendy	You'll have to to move the thing out of the way.	She clicks the check box off.
9:44	Sue	This one?	
9:44	Wendy	And um, On the side, where the controls are supposed to be.. Display strip chart. Just take it off.	
9:52	Sue	Ummm,,,, Well I guess I'm just trying to think back to um.. theee question that it had asked me about. I guess it was which way the waves flow?	Stops using mouse and looks at Wendy
10:07	Wendy	Mmmmhmmmm	
10:08	Sue	Sorta Umm I 'm just trying to think	
10:09	Wendy	It just asked you how the what effect the electric field has on and electron and then the other one asked you about the orientation of the antenna to pick up a signal.	

10:17	Sue	Ok So what effect the field has on the electron? So I guess I would want to show the static field and here to figure that out. and ummmm So that's the radiating field. So the static field is just.... along the main pole. I dont' know. Um. Well this is k this is radiating and that's how it would go all the way over here. But if it's static I don't know you would just see… I guess I'm trying to figure out the difference between static and radiating Why static is just stationary like in one area.	Looks back at the computer moves the mouse some and then plays with hair while she thinks and describes. Then uses the mouse to point and try different things.
11:12	Wendy	Have you tried all the controls? All the possible things you can do?	
11:17	Sue	Ummm I haven't tried really like changing this width this static field. But I think I've tried pretty much everything else.... umm Yea, I've tried all these things.	Looking at the screen, clicking around
11:36	Wendy	Did you try manual control?	
11:38	Sue	No. I did not.	
11:41	Sue	Sooo then… Oh so then I would move this here.	
11:45	Wendy	Mm hmmm	
11:47	Wendy	Yea I'm wonder.. Nobody's tried that. and I was wondering what kept you from trying it.	
11:52	Sue	Ummmm. I guess when it says manual control I would I thought that it was kind of maybe talking more about controlling this stuff which I was already doing so I didn't really	
12:02	Wendy	Ahhh Ok.	
12:04	Sue	I guess I didn't really think of moving this myself.	
12:07	Wendy	Ok	
12:09	Sue	Soooo let's see... it matters if I go fast or slow. It matters if I get higher! Maybe.... Well I guess it's... it doesn't really (cleared throat and banged mouse to readjust position on screen). Well I'm seeing obviously that when I move it the um the radiation starts I guess. And when I stop moving it there's nothign going on. So that would mean this would have to be moving for those waves to go out. Um but as far as moving down and then up and then down again I don't really know if there's really a difference between moving up and down other than just to keep it moving basically.	
13:16	Wendy	Mmmmmhhhhn	
13:20	Sue	So… umm	
13:23	Wendy	What were you trying to figure out before you did this?	
13:27	Sue	Ummm I guess just how Going to back to the question of um what effect does the electric field have on the electron.	
13:37	Wendy	Mm hmm	
13:39	Sue	Soooo	
13:41	Wendy	You were looking at the static field and the	

		radiating field?
13:43	Sue	Mmhmm I geuss I was trying to decide what the difference was. So it looks like... the static field um... it seems like it has maybe less effect on this one over here. Maybe just because it's not radiating as far it's not reaching as far. Which is I guess kinda of.. obvious with these because there not floating all the way over here they're just staying in this main range.
14:23	Wendy	Uh huh
14:24	Sue	And static usually means to stay still doesn't it?
14:27	Wendy	Yep
14:29	Sue	Sooooo... This just doesn't show the arrows. I'm more drawn to the radiating field because I can see it reaches the other side. It makes more sense that way. So um. I guess I'm trying to figure out how the electric field... um works with the electron. I don't know I guess I don't really see like where the electron like an electron would be in this other than maybe the green dots.
15:13	Wendy	Ok
15:15	Sue	So if I said the green dots were the actual electron and the arrows represent the field um…

Sample Interview Summary

Questions asked:

1. How does the signal transfer from a radio station to your home?

2. How does an electric field affect electrons?

3. Show three orientations of an antenna and ask which will pick up a radio signal.

Radio Wave Sim: Before simulation said she thinks an electric field is a wall of electrons but it could be passed through. Said radio waves could travel anywhere including space but didn't understand why. Answered questions correctly. Did sim and figured out electric field and electrons without prompting. Worked just about everything out. Said she liked radiating view better than static view. Actually saw them as different representations of the same thing rather than different things. I asked if she'd played with everything and she said yea. So I asked if she'd played with manual control and she said no. Played with it and I had to prompt her that she'd been working on static versus radiated. I don't think she ever noticed radiated view only created a field when the electron was moving and static view all the time. She said both things but not in the same thought. Went to the questions and answered and explained them very well. Said it'd help if the antenna on the house were easier to see and the effects of the electric field on the electron in the antenna were more obvious because that is the point isn't it? She had even noticed that one electron (transmitting antenna) produced the field and the other one was affected by it. Attitude: Have to make sense to use equations right. In calc never had time half the time. This is much better. At first with Electric force didn't understand the equation but now she does. Was bothered by that until she got it.

Previously I wondered how she could be a high performer because she couldn't connect her everyday experiences to the physics. She excelled at this abstract stuff because you don't need to use your everyday experiences!

Class seating arrangement negatively affected her because she's in the back now. She has to focus more to concentrate. There is more whispering and snickering which really annoys her. She can't see the demos well but the screen is fine.

Appendix B

PhET Look and Feel

Underlying Ideas

There are three themes which support the PhET Look and Feel guidelines that have come from interviews. These include: the importance of engaging the students in exploration of the simulation as discussed in section V. below; the *Coherence Principle*; and *Consistency* from simulation to simulation.

Coherence Principle (Clark and Mayer, 2003)

- Adding interesting but unnecessary material to simulations can harm the learning process in several ways.
    - It can distract the user from relevant material.
    - It can disrupt the learner's processes of making sense of important information because unnecessary information is in the way.
    - It can prime inappropriate bits of knowledge.

Consistency (Clark and Mayer, 2003)

- Users' interpretation and use of simulations depends heavily on their prior experiences. If inconsistent representations or layout is used, students may spend extra time on unnecessary information or may incorrectly bring ideas from one simulation to another.

I. Layout

- Below is a basic set of layout guidelines; however, this is something, due to special characteristics of each simulation, that cannot be rigidly dictated.

A. *Control panel*

- Limiting the number of tools/controls and arranging them in small groups makes it easier to identify what is available and makes the simulation less intimidating.
- Students become familiar with the layout.
- Limited text
    - Students only read text that is attached to a control
    - Abbreviations are not understood by most students.
    - Text strings of one to three words work best.

B. *Play area*

- The play area must be distinct from the control panel in look and functionality. Objects in the play area are grabble and animated.
- When too many tools are in the play area, the control panel is overlooked.
- Text is a distraction in the play area.

C. *Backgrounds*

- Can serve as a visual cue to remind the user of the setting that they are currently exploring such as the Moon versus the Earth.
- Backgrounds should not distract the user from the important features of the simulation. Separation between the features of the simulation and the background is what is important.

D. *Tabs*

- Students notice large, cartoon-like tabs. When tabs are small and professional looking, they go unnoticed.

E. ***Play buttons***

- Students do not find play/pause buttons on their own.
- Once these buttons are shown to the user, they get used as needed by the experienced users.

II. Intuitive Controls

- Interviews showed that certain types of controls are intuitive for users. If different controls are used, even with 'help' or tutoring from the interviewer, many students still cannot use the simulation and the student's focus is on learning how to manipulate the simulation rather than on the concepts.
- Fortunately the types of controls that work for users are independent of the content of the simulation.

A. ***Click and drag interface***

- Click and drag is the most natural motion for students.

B. ***Grabbable objects***

- Students try to move anything that looks useful.

C. ***Sliders, radio buttons, checkboxes*****.**

- In interviews students are familiar with the functionality of radio buttons and sliders.
- Students use the sliders when they first explore a simulation and then turn to the digital input when completing a specific task such as homework or lab.

- Students use checkboxes to turn things on but rarely use them to turn things off.

D. ***Consistent set of tools***

- Students 'know' what something should look like. If it does not match their expectations, it makes it much harder for them to figure it out.

III. Representations

A. ***Common picture***

- Simulations explicitly provide a visual mental model. Advanced simulations in particular corrected incorrect pictures that students had constructed from readings and lecture.
- Simulations provide a common picture for discussion. Discussion before simulation use typically starts with a fairly long conversation about what the phenomena looks like before students can begin discussing the concept – with simulations, this part is unnecessary and students are more confident about what they are discussing.

B. ***Start up settings***

- To encourage exploration, simulations should start up with very little or no animation.
- Using only a "wiggle-me", that comes in and stops, is an effective way to initiate desired exploration.

C. ***Real world connections***

- Simulations showing familiar everyday objects encourage exploration and encourage understanding.
- Cartoon-like features are an effective way to emphasize important features while avoiding misleading literal interpretations.
- Students test the limits of the simulations looking for realistic reactions. Simulations need to ‘break’ in a meaningful way when pushed to extremes. However, care must be taken that the ‘breaking’ is not too exciting or it can easily become the focus of the simulation.

D. Visual cues – everything matters.

- Students look at all visual cues equally, if they do not understand a concept. It is important to emphasize items that are pedagogically important and eliminate all potential distractions.
- Color is an important visual cue. Students expect it to be consistent not only within a particular simulation but from one simulation to another.

E. *Consistent representations*

- When an object is represented differently from simulation to simulation, students perceive it as two different objects, and when objects are represented in a similar fashion they are perceived as the same, even though they may be completely unrelated.

IV. Help

- In a good simulation, help is not necessary to stimulate learning.
- Too many words of help can be a deterrent to learning.

A. *Wiggle- me*

- When the most important object in the play area is not obviously grabbable, a wiggle-me is useful for telling the user where to start.
- Consists of a very short, clearly written directive (eg. Wiggle the electron) with an optional arrow pointing toward the object it refers to.
- The wiggle-me should draw attention to itself; however, it should not distract the user from the rest of the simulation.
    - It should swoop in from the side and then remain stationary until the object it is referring to has been manipulated.

B. *Help!*

- Must be clear, concise strings of text.
- If it's prominent, then it gets followed like a command and the user is unlikely to explore on their own.
- Help! should not appear unless it is requested by the user.
- Once invoked it needs to remain on screen as continual reference while the user plays. For this reason it must sit somewhere that it can stay up and not be in the way while manipulating the simulation.

C. *Extensive help*

- Users do not use extensive help

V. Encourage Exploration

A. *Animation and interactivity*

- Students notice animated features first; however, students do not ask questions and make new connections when only observing and not interacting.
- User control of every perceived potentially significant parameter is valuable.
- Limiting students control over certain items must be done carefully.

B. ***Little puzzles/clues (Questions that stimulate student to figure things out)***

- When students encounter small features that they do not understand, they will explore how the feature changes the simulation until they can create a working definition of the feature.
- Legends and control labels tell the student what a particular feature controls and then when they play, they learn a working definition of the control..
- Multiple Representations - Simulations that have multiple views of the same idea such as beam view and photon view facilitate further understanding and connections about the idea.
- Exploration is not always productive – Features which encourage exploration in unproductive directions must be avoided.

C. ***Fun***

- When the simulations are fun, students enjoy playing with them. The Flash simulations and JAVA simulations, with similar characteristics, draw students to them.

- When simulations look boring or intimidating, students are not drawn to playing or they're afraid they'll break them.
- Danger of being so much fun students may be distracted from learning.

D. Credibility of simulations

- For engaged exploration to occur, students must believe the simulation.
- Student's level of skepticism is directly related to their level in school.

E. Performance mode

- Students who do not think they know the relevant ideas will comfortably explore a simulation and will try to use it to learn; however, students who think they should understand the topic of a simulation use it much less effectively and learn much less from it.

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