# A Study of Interface Design for Engagement and Learning with Educational Simulations.

**W. K. Adams, S. Reid, R. LeMaster, S. B. McKagan, K. K. Perkins and C. E. Wieman**

**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. Here we present results from research on the design and use of such simulations conducted as part of 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. The development of these simulations included over 200 individual student interviews during which the students described what they were thinking as they interacted with the simulations. These interviews are a rich source of information about how students interact with computer simulations and what makes an educationally effective simulation. In this paper we present a summary of findings from these interviews and guidelines for developing simulations based on these findings. We have observed that simulations can be highly engaging and educationally effective. Here we describe the layout, tool use, help, representations, and effective features for engaging students in educationally productive interactions.*

## 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. Desirable features – those that are found to be important for encouraging students to discover and understand physical relationships – include the simulation layout; the simulation start-up mode; multiple significant aspects of representations; types of controls that are intuitive for the student to use and why intuitive use is so important; tool design, placement and identification; "help" characteristics; the importance of encouraging exploration; the impacts of even small amounts of irrelevant information; and methods to provide engaging ways to help students to 'discover' the desired learning goals of the simulation.

## Background

The context of this research is the PhET (Perkins et al., 2006; The PhET Team, 2006a) project, 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.  We use a research-based approach – incorporating findings from physics education and cognitive science – to design simulations that will both engage a broad spectrum of students in the learning of science and develop their understanding of scientific concepts.  Currently there are about 60 PhET simulations. Most of these simulations cover introductory physics and chemistry, but there is a growing set covering more-advanced topics in modern physics.

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 in use in many high school classes as well as some middle school classes. 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.  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 starts with the content and student interface experts creating a detailed initial layout for the simulation.  This initial layout is given to the programmer who begins writing code.  The team members communicate regularly to make any needed adjustments as the simulation takes shape. The simulation can be posted to our website and is labeled as "under construction" after extensive use by the team members and all members feel it's clear, accurate and engaging.  Student interviews are conducted at this stage.  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.  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 posted as a "beta" version on the website. To be considered complete and receive the "star" label, a simulation must also be 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 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 student interview results; the rare exceptions are noted in the appropriate sections below.

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 play with 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 play. Then, after, or

3

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 student's play 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. Appendix A contains a short section of an interview transcript and Appendix B has an individual summary for the same interview. 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 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 essentially increased to 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.

## Simulation Design Guidelines

The simulation design guidelines are a detailed description of the PhET Look and Feel (Adams & Wieman, 2006) including specific details of supporting interviews. First we describe the underlying principles which support our findings and then present the design guidelines that were determined from interview results.

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. A detailed analysis of how and why simulations result in such learning will be the focus of future work. However, 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 are noted below in the relevant sections. However, in this paper 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.

### PhET Look and Feel

As described in the *Simulation Design Process* section above, our design process is iterative in nature and has been informed by extensive simulation interviews. From these interviews we created the "PhET Look and Feel" (Adams & Wieman, 2006), which the design teams now follow while creating a new simulation. During the first

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.



5
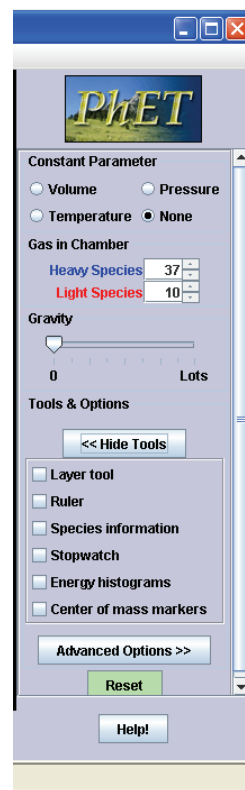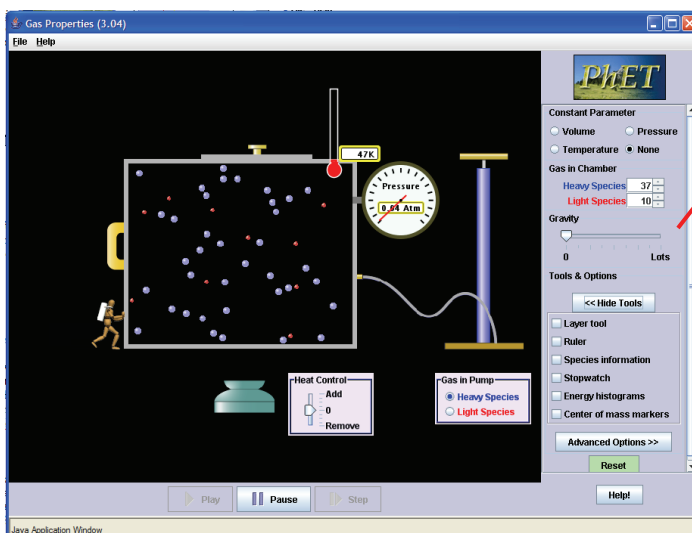
year of interviews, when the look and feel was still in the early development stages, student difficulties ranged from simulation usability to conceptual problems. These difficulties included problems such as interface design, help functions, tool placement, effective types of representations, and what 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. As discussed below, 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 finally 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 guidelines derived from our interview studies[4]. 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.

Here we use the 'PhET Look and Feel' as a structure for the presentation of our interview results regarding simulation design and refer to specific interview results where applicable. These results draw largely from the interview summaries described above. The 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 this paper when the interviews merely confirmed the previously observed results. All general conclusions presented here have been confirmed with interviews on at least several simulations.

**Underlying Principles**

Three major principles support nearly all of the desirable design features identified through our interview studies. These include *Engaged Exploration,* the *Coherence Principle* (Clark & Mayer, 2003) and *Consistency*. In this section we provide a brief introduction to these principles.

***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 with a variety of 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.  However, experienced users were bothered by seemingly minor inconsistencies from one simulation to the next, even if the subject of the simulation was quite different.

## I. Encourage Exploration
Engaging students in thoughtful exploration of the simulation is necessary for improving students' understanding of the concepts. In this section we focus on the design 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 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 coursework.

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. This can be done with either of two types of applications: "toys" or "tools". "Toys" are challenging to use while "tools" are easy to use and help the user attain an outside challenge. 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 is 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 that of being able to understand the phenomenon portrayed by the simulation. We believe 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. 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 often 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. However, that should not be interpreted to mean that such goals are not important. For examples of activities created by teachers for use with the PhET simulations please see the PhET Activity Database (The PhET Team, 2006b).

## 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.*

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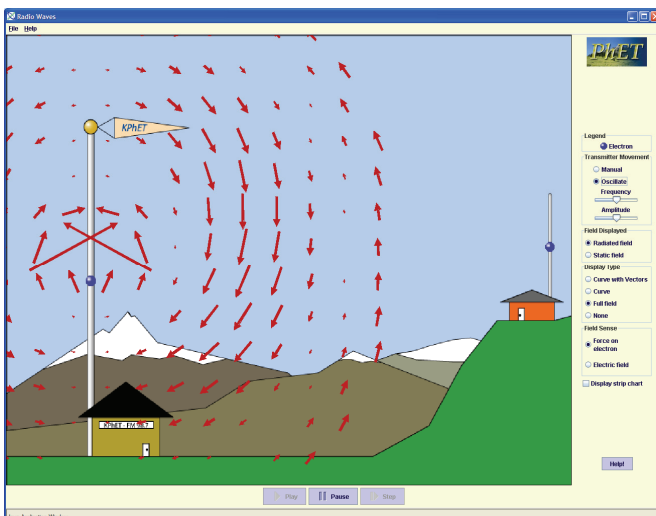
Figure II – An early version of 'Radio Waves'. When the simulation first opens, the transmitting electron moves up and down along the antenna producing an electromagnetic wave that radiates out filling the screen with oscillating red arrows.

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 II). 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, 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 II. 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. However, 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.

**B. 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 playing 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 play, 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 playing with 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 II)

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 below, 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.

**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 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 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 V). 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.

**D. 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.

### E. 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 before this interview, 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 Wave' 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.

## II. 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 provide distraction 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.

### A. Click and Drag Interface

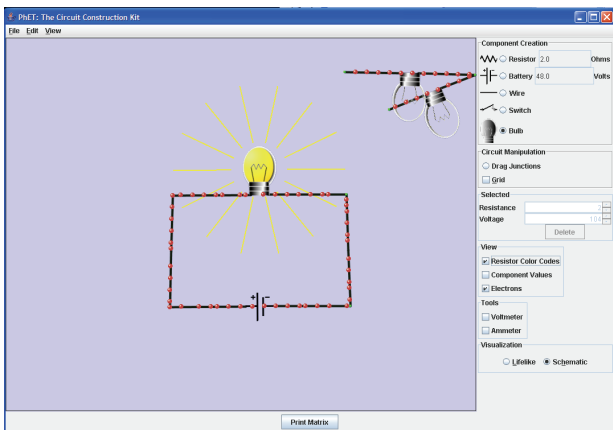- *Click and drag is the most natural motion for students.*

Figure III 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.
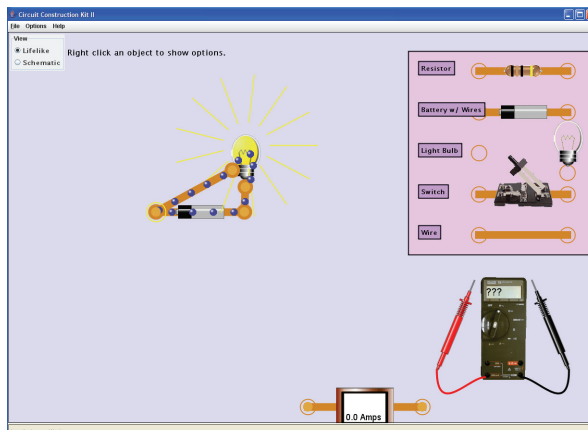


Figure III b – 'CCK' Version II. This new version uses the more intuitive 'click-and-drag' style interface.

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 IIIa) 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.

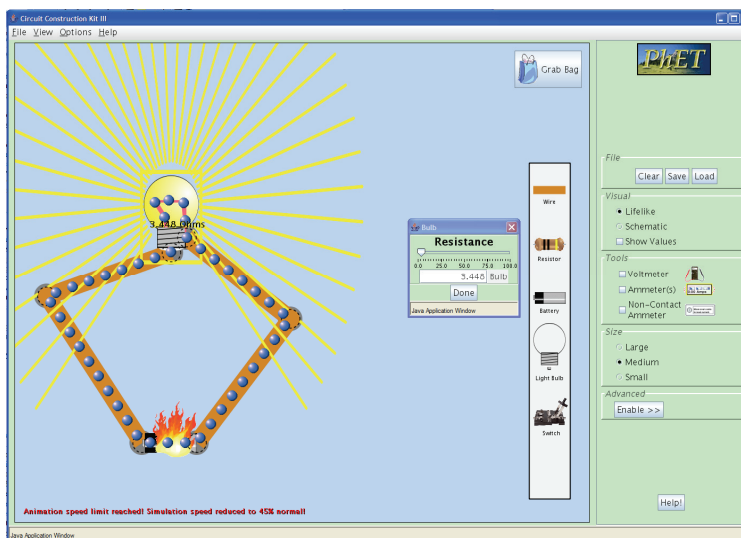Since demonstration by interviewer or in class demonstration was quite adequate for most students



Figure IV – 'CCK' Version 3. Right-clicking on a component brings up controls for that object such as the lightbulb as shown.

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 IIIb).

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 IV) 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.

## B. Grabbable Objects

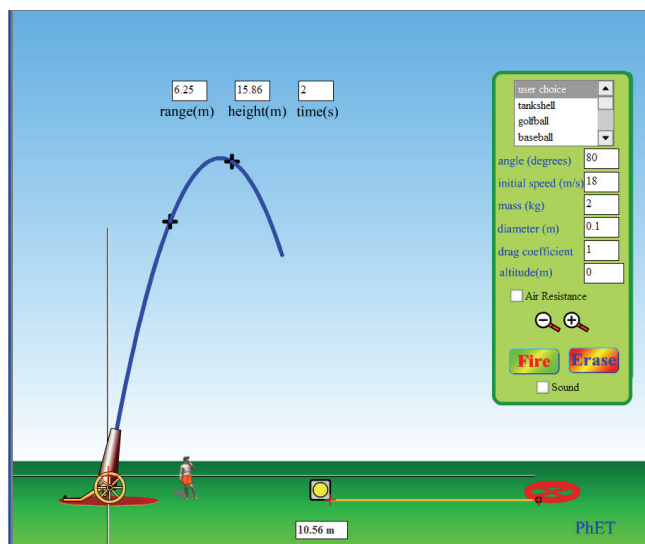■ *Students try to move anything that looks useful.*



Figure V – '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.

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

## C. 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 don't 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 start 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 IV.

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.

**D. 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.

## III. 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.

## A. 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, 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.

## B. 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'. As mentioned earlier our start-up settings for 'Radio Waves' (Figure II) were initially chosen to showcase the simulation's most impressive capabilities. The simulation started up in full field and the electron was 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.*"



Figure VI – 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.

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 VI) 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
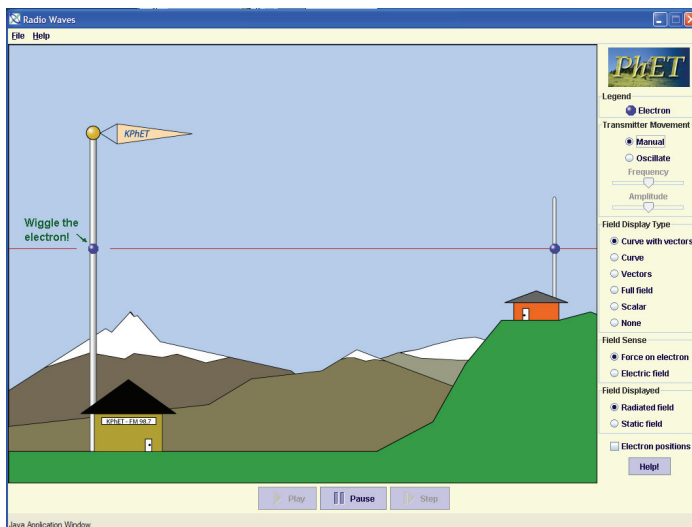
prevalent danger in simulation design; what looks good to an expert may be frightening and overwhelmingly complex for a novice and not result in useful learning.

## 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.*

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 IV. 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. Section **I. C.** above includes more details on simulations where such elements were so much "fun" that they interfered with learning.

**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.*

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 IIIa).  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 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.

**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.*

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.

## IV. 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 IIIa). 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.

## 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.*

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. 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 due to difficulties locating 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 VI). 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 section **I. B.** above.

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 section II.C. 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.

## 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.*

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 be more like physical items, the control panel size is increased and the empty space in the play area has been reduced (Figure VII). These changes brought more attention to the control panel, clarifying the distinction between play area and control panel and
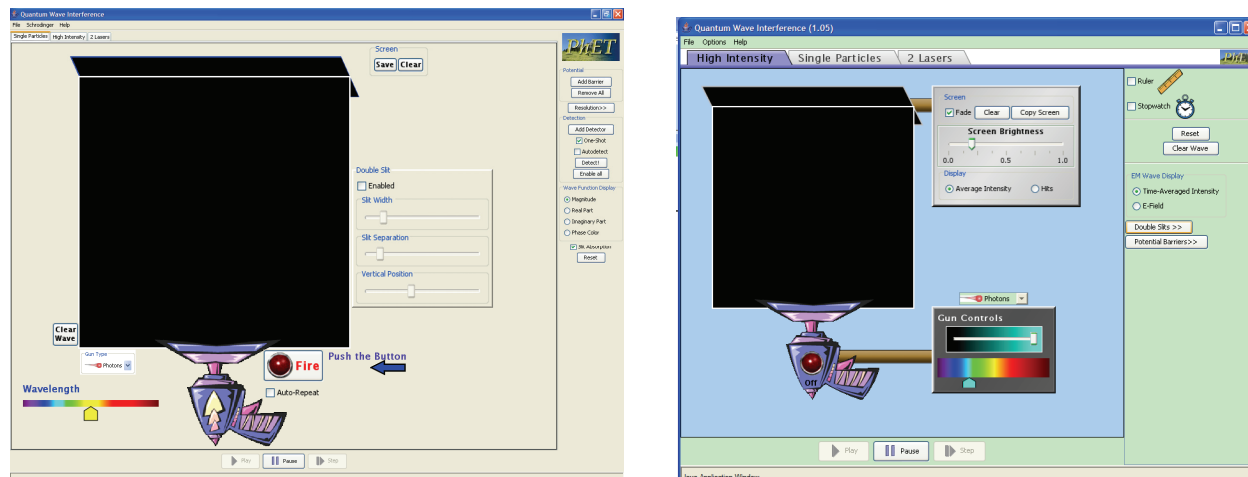


Figure VII – 'QWI' has a large number of controls in the play area for producing photons, electrons, neutrons and alpha particles at various energies. The screen that the particles hit also has user adjustable functionality. Within the Control Panel the user can add double slits and/or potential barriers 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.

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 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' in section **V. B.** 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* 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.

## C. 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 VI) 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.

## D. 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 1 in 10 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 VII illustrates the difference between everyday application tabs and the larger more prominent tabs we've found successful.

## E. 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.

## V. 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.

### 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.*
- *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 VI). During interviews we found that starting the simulation with the electron oscillating on its own was overwhelming to students as discussed in the *Start-up Settings* section II.B. 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.

**B.** *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) as described above:  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 above.  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 clicked 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.

**C. 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.

# 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 the sound waves simulation to understand the Radio Waves simulation. 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 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 gestures can be a useful tool for analyzing student interactions with simulations, and how they are using simulation 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 listed here. This work also 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

# 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 | Mmhmm | |
| 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 | Uhhuh |
| 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 seee 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… |

## Appendix B – 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.

# References

Adams, W.K., (2004) Gesture with Interactive Computer Simulations. [On-line] Available: http://phet.colorado.edu/web-pages/publications/Gesture.pdf

Adams, W.K., Wieman, C.E., (2006). *PhET Look and Feel* Retrieved November 23, 2006, from University of Colorado, Physics Education Technology Web site: http://phet.colorado.edu/web-pages/publications/PhET Look and Feel.pdf

Christian, W. and Belloni, M., (2001). *Physlets:  Teaching Physics with Interative Curricular Material.* New Jersey: Prentice Hall, Inc.

Chi, M. T. H. , Feltovich, P. J., & Glaser, R., (1981).  Categorization and representation of physics problems by experts and novices.  *Cognitive Science, 5,* 121-152.

Clark, C. and Mayer, R., (2003).  *E-learning and the Science of Instruction* (pp 111-129). San Francisco, California: Pfeiffer.

Dweck, C., (1989). Motivation. In Lesgold, A. and Glaser, R. (Eds.), *Foundations for a Psychology of Education* (pp 87-136). New Jersey: Lawrence Erlbaum Associates.

Finkelstein, N., Adams, W., Keller, C., Perkins, K., Wieman, C. and the PhET Team, (2006). High-Tech Tools for Teaching Physics: the Physics Education Technology Project. *Journal of Online Learning and Teaching, 2,* 109-121.

Finkelstein, N. D., Perkins, K., Adams, W. Keller, K, Kohl, P., Podolefsky, N., Reid, S. and LeMaster, R., (2005).  When learning about the real world is better done virtually: a study of substituting computer simulations for laboratory equipment. *Physical Review, Special Topics: Physics Education Research, 1,* 010103.

Finkelstein, N.D., Perkins, K. K., Adams, W., Kohl, P., Podolefsky, N., (2005) Can Computer Simulations Replace Real Lab Equipment? In Heron, P., Marx J. and Franklin, S. (Eds.), *2004 Physics Education Research Conference* (pp 101-104). New York: American Institute of Physics Conference Proceedings.

Malone, T., (1981). Toward a Theory of Intrinsically Motivating Instruction. *Cognitive Science 4,* 333-369.

Minstrell, J. and Kraus, P., (2005). Guided Inquiry in the Science Classroom. In Donovan, M. S. and Bransford, J. D. (Eds.), *How Students Learn: History, Mathematics, and Science in the Classroom* (pp 475-513). Washington, D.C.: The National Academies Press.

Perkins, K. K., Adams, W., Finkelstein, N. D., Dubson, M., LeMaster, R., Reid, S. and Wieman, C.E., (2006). PhET:  Interactive Simulations for Teaching and Learning Physics. *The Physics Teacher 44,* 18-23.

Perkins, K.P., Adams, W.K., Finkelstein, N.D., and Wieman, C.E., (2004). Learning Physics with Simulations:  The Role of Interactivity, Animation and Context. *American Association of Physics Teachers Summer Meeting:  Sacramento, CA.* Retrieved November 23, 2006, from University of Colorado, Physics Education Technology Web site: http://phet.colorado.edu/web-pages/research.html

The PhET Team, (2006a). PhET Interactive Computer Simulations [Computer software] Available at: http://phet.colorado.edu Colorado: Physics Education Technology Project.

The PhET Team, (2006b). PhET Activity Database [Computer database] Available at: http://phetdb.colorado.edu/ Colorado: Physics Education Technology Project.

Podolefsky, N. S. and Finkelstein, N. D., (2006). Use of analogy in learning physics: The role of representations. *Physical Review, Special Topics:  Physics Education Research.* 2, 020101