MS #06-020

High-Tech Tools for Teaching Physics: the Physics Education Technology Project

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to appear in
the Journal of Online Teaching and Learning
September 15, 2006

MERLOT

Journal of Online Learning and Teaching

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Abstract

This paper introduces a new suite of computer simulations from the Physics Education Technology (PhET) project, identifies features of these educational tools, and demonstrates their utility. We compare the use of PhET simulations to the use of more traditional educational resources in lecture, laboratory, recitation and informal settings of introductory college physics. In each case we demonstrate that simulations are as productive, or more productive, for developing student conceptual understanding as real equipment, reading resources, or chalk-talk lectures. We further identify six key characteristic features of these simulations that begin to delineate why these are productive tools. The simulations: support an interactive approach, employ dynamic feedback, follow a constructivist approach, provide a creative workplace, make explicit otherwise inaccessible models or phenomena, and constrain students productively.

Introduction

While computer simulations have become relatively widespread in college education (CERI, 2005; MERLOT, n.d.), the evaluation and framing of their utility has been less prevalent. This paper introduces the Physics Education Technology (PhET) project (PhET, 2006), identifies some of the key features of these educational tools, demonstrates their utility, and examine why these are useful. Because it is difficult (and, in this case, unproductive) to separate a tool from its particular use, we examine the use of the interactive PhET simulations in a variety of educational environments typical of introductory college physics. At present, comprehensive and well-controlled studies of the utility of computer simulations in real educational environments remain relatively sparse, particularly at the college level. This paper summarizes the use of the PhET tools in lecture, laboratory, recitation, and informal environments for a broad range of students (from physics majors to non-science majors with little or no background in science). We document some of the features of the simulations (e.g., the critical role of direct and dynamic feedback for students) and how these design features are used (e.g., the particular tasks assigned to students). We find, for a wide variety of environments and uses surveyed, PhET simulations are as productive or more productive than traditional educational tools, whether these are physical equipment or textbooks.

Research and Design of PhET Simulations

The Physics Education Technology project at the University of Colorado has developed a suite of physics simulations that take advantage of the opportunities of computer technology while addressing some of the limitations of these tools. The suite includes over 50 research-based simulations that span the curriculum of introductory physics as well as sample topics from advanced physics and chemistry (PhET, 2006; Perkins et al., 2006; Wieman & Perkins, 2006). All simulations are free, and can be run from the internet or downloaded for off-line use. The simulations are designed to be highly interactive, engaging, and open learning environments that provide animated feedback to the user. The simulations are physically accurate, and provide highly visual, dynamic representations of physics principles. Simultaneously, the simulations seek to build explicit bridges between students' everyday understanding of the world and the underlying physical principles, often by making the physical models (such as current flow or electric field lines) explicit. For instance, a student learning about electromagnetic radiation starts with a radio station transmitter and an antenna at a nearby house, shown in Figure 1. Students can force an electron to oscillate up and down at the transmission station, and observe the propagation of the electric field and the resulting motion of an electron at the receiving antenna. A variety of virtual observation and measurement tools are provided to encourage students to explore properties of this micro-world (diSessa, 2000) and allow quantitative analysis.

We employ a research-based approach in our design – incorporating findings from prior research on student understanding (Bransford, Brown, & Cocking, 2002; Redish 2003), simulation design (Clark & Mayer, 2003), and our own testing – to create simulations that support student engagement with and understanding of physics concepts. A typical development team is composed of a programmer, a content expert, and an education specialist. The iterative design cycle begins by delineating the learning goals associated with the simulation and constructing a storyboard around these goals. The underpinning design builds on the idea that students will discover the principles, concepts and relations associated with the simulation through exploration and play. For this approach to be effective, careful choices must be made as to which variables and behaviors are apparent to and controllable by ~~to~~ the user, and which are not. After a preliminary version of the simulation is created, it is tested and presented to the larger PhET team to discuss. Particular concerns, bugs, and design features are addressed, as well as elements that need to be identified by users (e.g. will students notice this feature or that feature? will users realize the relations among various components of the simulation?). After complete coding, each simulation is then tested with multiple student interviews and summary reports returned to the design team. After the utility of the simulation to support the particular learning goals is established (as assessed by student interviews), the simulations are user-tested through in-class and out-of-class activities. Based on findings from the interviews, user testing, and class implementation, the simulation is refined and re-evaluated as necessary. Knowledge gained from these evaluations is incorporated into the guidelines for general design and informs the development of new simulations (Adams et al., n.d.). Ultimately, these simulations are posted for free use on the internet. More on the PhET project and the research methods used to develop the simulations is available online (PhET, 2006).

From the research literature and our evaluation of the PhET simulations, we have identified a variety of characteristics that support student learning. We make no claims that these are necessary or sufficient of all learning environments – student learning can occur in a myriad of ways and may depend upon more than these characteristic features. However, these features help us to understand why these simulations do (and do not) support student learning in particular environments. Our simulations incorporate:

An Engaging and Interactive Approach. The simulations encourage student engagement. As is now thoroughly documented in the physics education research community and elsewhere (Bransford, Brown, & Cocking, 2002; Hake, 1998; Mazur, 1997; Redish, 2003), environments that interactively engage students are supportive of student learning. At start-up for instance, the simulations literally invite users to engage with the components of the simulated environment.

Dynamic feedback. These simulations emphasize causal relations by linking ideas temporally and graphically. Direct feedback to student interaction with a simulation control provides a temporal and visual link between related concepts. Such an approach, when focused appropriately, facilitates student understanding of the concepts and relations among them (Clark & Mayer, 2003). For instance, when a student moves an electron up and down on an antenna, an oscillating electric field propagates from the antenna suggesting the causal relation among electron acceleration and radio wave generation.

A constructivist approach. Students learn by building on their prior understanding through a series of constrained and supportive explorations (von Glasersfeld, 1983). Furthermore, often students build (virtual) objects in the simulation, which further serves to motivate, ground, and support student learning (Papert & Harel, 1991).

A workspace for play and tinkering. Many of the simulations create a self-consistent world, allowing students to learn about key features of a system by engaging them in systematic play, "messing about," and open-ended investigation (diSessa, 2000).

Visual models / access to conceptual physical models. Many of the microscopic and temporally rich models of physics are made explicit to encourage students to observe otherwise invisible features of a system (Finkelstein, et al., 2005; Perkins et al., 2006). This approach includes visual representations of electrons, photons, air molecules, electric fields etc., as well as the ability to slow down, reverse and play back time.

Productive constraints for students. By simplifying the systems in which students engage, they are encouraged to focus on physically relevant features rather than ancillary or accidental conditions (Finkelstein, et al., 2005). Carefully segmented features introduce relatively few concepts at a time (Clark & Mayer, 2003) and allow for students to build up understanding by learning key features (e.g., current flow) before advanced features (e.g., internal resistance of a battery) are added.

While not an exhaustive study of the characteristics that promote student learning, these key features serve to frame the studies of student learning using the PhET simulations in environments typical of college and other educational institutions: lecture, lab, recitation, and informal settings.

Research Studies

Lecture

Simulations can be used in a variety of ways in the lecture environment. Most often they are used to take the place of, or augment chalk-talk or demonstration activities. As such, they fit within a number of pedagogical reforms found in physics lectures, such as *Interactive Lecture Demonstrations* (Sokoloff & Thornton, 1998) or *Peer Instruction* (Mazur, 1997).

In a comparative study of the utility of demonstration with real equipment versus simulation, we studied the effects in a large-scale (200 person) introductory physics course for non-science majors during lectures where students were taught about standing waves. One year, students were taught with a classic lecture demonstration, using Tygon tubing. The subsequent year a similar population of students was taught the material using the *Wave on a String* simulation (Figure 2) to demonstrate standing waves. Notably, just as with the lecture demonstration, physical parameters may be varied (driving frequency and amplitude); additionally, damping and string tension may be dramatically and dynamically varied to allow students to easily observe what would happen in radically different conditions. In this case, wave speed may be slowed significantly and individual segments of the string may be observed to oscillate up and down. That is, by manipulating the simulation parameters appropriately, the instructors constrain the students to focus on phenomena that are otherwise hard to detect in a physical system. In each of the two conditions (real demonstration and simulation) students were asked multiple choice concept tests (Mazur, 1997) in lecture immediately following the demonstrations and discussion. On a question regarding velocity of a segment of a string (being vertically displaced in a standing wave), students from the real equipment demonstration lecture answered 28% correctly (N=163); whereas, students observing the course using the simulation answered 71% correctly (N=173 statistically different at $p<0.001$, via two-tailed z-test) (Perkins et al., 2006). On a similar follow-up question, students learning from equipment answered 23% correctly, compared to 84% correctly when learning from the simulation (N_1= 162, N_2=165, $p<0.001$).

In another investigation substituting simulations for real demonstration equipment, we studied a several-hundred student calculus-based second semester introductory course on electricity and magnetism. The class was composed of engineering and physics majors (typically freshmen) who regularly interacted in class through *Peer Instruction* (Mazur, 1997) and personal response systems. The large class necessitated two lecture sections (of roughly 175 students each) taught by the same instructor. To study the impact of computer simulations, the *Circuit Construction Kit* was substituted for chalk-talk or real demonstration equipment in one of the two lectures.

The *Circuit Construction Kit (CCK)* models the behavior of simple electric circuits and includes an open workspace where students can place resistors, light bulbs, wires and batteries. Each element has operating parameters (such as resistance or voltage) that may be varied by the user and measured by a simulated voltmeter and ammeter. The underlying algorithm uses Kirchhoff's laws to calculate current and voltage through the circuit. The batteries and wires are designed to operate either as ideal components or as real components, by including appropriate, finite resistance. The light bulbs, however, are modeled as Ohmic, in order to emphasize the basic models of circuits that are introduced in introductory physics courses. Moving electrons are explicitly shown to visualize current flow and current conservation. A fair amount of attention has been placed on the user interface to ensure that users may easily interact with the simulation and to encourage users to make observations that have been found to be important and difficult for students (McDermott & Shaffer 1992) as they develop a robust conceptual understanding of electric circuits. A screen shot appears in Figure 3.

In this study, students in both lecture sections first participated in a control activity– a real demonstration not related to circuits followed by *Peer Instruction*. Subsequently the two parallel lectures were divided by treatment – students in one lecture observed a demonstration with chalk diagrams accompanying a real circuit demonstration (traditional); students in the other lecture observed the same circuits built using the *CCK* simulation (experimental). Students in both lectures under both conditions (traditional and experimental) participated in the complete form of Peer Instruction. In this method, the demonstration is given and a question is presented. First the students answer the question individually using personal response systems before any class-wide discussion or instruction; then, students are instructed to discuss the question with their neighbors and answer a second time. These are referred to as “silent” (answering individually) and “discussion” (answering individually after discussing with peers) formats.

In the control condition, Figure 4a, there are no statistical differences between the two lecture environments, as measured by their pre- or post-scores, or gain ($p > 0.5$). In the condition where different treatments were used in the two lectures (Figure 4b) – Lecture 1 using CCK and Lecture 2 using real equipment – a difference was observed. While the CCK group (Lecture 1) is somewhat lower in “silent” score, their final scores after discussion are significantly higher than their counterparts (as are their gains from pre- to post- scores, $p<0.005$, by two-tailed z-test). Both sets of data (Figure 4a and 4b) corroborate claims that discussion can dramatically facilitate student learning (Mazur, 1997). However the data also illustrate that what the students have to discuss is significant, with the simulation leading to more fruitful discussions.

While we present data only from a small section of lecture courses and environments, we note that the PhET simulations can be productively used for other classroom interventions. For example, PhET simulations may be used in addition to or even in lieu of making microcomputer-based lab measurements of position, velocity and acceleration of moving objects for the 1-D Interactive Lecture Demonstration (ILD) (Sokoloff & Thornton, 1998). In PhET's *Moving Man*, we simulate the movement of a character, tracking position, velocity and acceleration. Not only does the simulation provide the same plotting of real time data that occurs with the ILDs, but *Moving Man* also allows for replaying data (synchronizing movement and data display), as well as assigning pre-set plots of position, velocity and acceleration and *subsequently* observing the behavior (inverting the order of ILD data collection). The utility of PhET simulations has been applied beyond the introductory sequence in advanced courses, such as junior-level undergraduate physical chemistry, where students have used the *Gas Properties* simulation to examine the dynamics of molecular interaction to develop an understanding of the mechanisms and meaning of the Boltzmann distribution.

In each of these instances, we observe the improved results of students who are encouraged to construct ideas by providing access to otherwise temporally obscured phenomena (e.g., *Wave on a String*), or invisible models (such as electron flow in *CCK* or molecular interaction in *Gas Properties*). These simulations effectively constrain students and the focus their attention on desired concepts, relations, or processes. These findings come from original interview testing and modification of the simulation to achieve these results. We hypothesize that it is the simulations' explicit focus of attention, productive constraints, dynamic feedback, and explicit visualization of the otherwise inaccessible phenomena that promote productive student discussion, and the development of student ideas.

Laboratory

Can simulations be used productively in a laboratory where the environment is decidedly hands-on and designed to give students the opportunity to learn physics through direct interaction with experimental practice and equipment?

In the laboratory segment of a traditional large-scale introductory algebra-based physics course, we examined this question. Most of the details of this study and some of the data have been reported previously (Finkelstein et al., 2005), so here we briefly summarize. In one of the two-hour long laboratories, DC circuits, the class was divided into two groups – those that only used a simulation (*CCK*) and those that only used real equipment (bulbs, wires, resistors, etc.). The lab activities and questions were matched for the two groups.

On the final exam, three DC-circuits questions probed students' mastery of the basic concepts of current, voltage, and series and parallel circuits. For a given series and parallel circuit, students were asked to: (1) rank the currents through each of the bulbs, (2) rank the voltage drops across the bulbs in the same circuit, and (3) predict whether the current through the first bulb increased, decreased, or remained the same when a switch in the parallel section was opened. In Figure 5, the average of number of correct responses for the DC circuits and non-DC-circuit exam questions are shown. The average on the final exam questions not relating to the circuits was the same for the two groups (0.62 for CCK, with N = 99; σ=.18, and 0.61 for TRAD, N = 132; σ=.17). The mean performance on the three circuits questions is 0.59 (σ=.27) for CCK and is 0.48 (σ=.27) for TRAD groups. This is a statistically significantly difference at the level of $p<0.002$ (by Fisher Test or one-tailed binomial distribution) (Finkelstein et al., 2005).

We also assessed the impact of using the simulation on students' abilities to manipulate physical equipment. During the last 30 minutes of each lab class, all students engaged in a common challenge worksheet requiring them to assemble a circuit with *real* equipment, show a TA, and write a description the behavior of the circuit. For all CCK sections, the average time to complete the circuit challenge was 14.0 minutes; for the Traditional sections, it was 17.7 minutes (statistically significant difference at $p<0.01$ by two tailed t-test of pooled variance across sections). Also, the CCK group scored 62% correct on the written portion of the challenge, whereas the traditional group scored 55% – a statistically significant shift ($p<0.03$ by a two-tailed z-test) (Finkelstein et al., 2005).

These data indicate that students learning with the simulation are more capable at understanding, constructing, and writing about real circuits than their counterparts who had been working with real circuit elements all along. In this application the computer simulations take advantage of the features described above – they productively engage students in building ideas by providing a workspace that is simultaneously dynamic and constraining, and allows them to mess about productively.

Recitation Section

Most introductory college courses include 1-hour recitations or weekly problem solving sections. Recently we have implemented *Tutorials in Introductory Physics*

(McDermott & Schaffer, 2002) in the recitations of our calculus-based physics course. These student-centered activities are known to improve student understanding (McDermott & Schaffer, 1992), and we have recently demonstrated that it is possible to replicate the success of the curricular authors (Finkelstein and Pollock, 2005). In addition to implementing these Tutorials, which often involve student manipulation of equipment, we have started to study how simulations might be used to augment Tutorials or replace the equipment used in recitation sections.

In two of the most studied Tutorials, which focus on DC circuits, we investigated how the *Circuit Construction Kit* might be substituted for real light bulbs, batteries and wires. In nine recitation sections (N~160), *CCK* was used in lieu of real equipment, while in the other nine sections, real equipment was used. As described in Finkelstein and Pollock (2005), this course included other reforms such as *Peer Instruction* in lecture. On the mid-term exam following the Tutorial, six questions were directly related to DC circuits. In Figure 6, student performance data on these questions are plotted by treatment (CCK) and control (Real) along with the average score across all these questions. Students in the CCK group outperform their counterparts by an average of approximately 5% (statistically significant $p < 0.02$ by two-tailed z-test).

We note that simply using simulations in these (or other) environments does not guarantee success. How these simulations are used is important. While the *CCK* successfully replaced the bulbs and batteries in recitation, we believe its success is due in part to the coupling of the simulation with the pedagogical structure of the Tutorials. Here, the students are encouraged to engage, by building circuits (real or virtually) and are constrained in their focus of attention (by the Tutorial structure). However, the CCK group works with materials that explicitly model current flow in a manner that real equipment cannot. In other instances when these heuristics are not followed, the results are more complex. In another Tutorial on wave motion, students are asked to observe an instructor demonstrating a transverse wave (using a long slinky). Allowing students the direct manipulation of the related simulation, *Wave on a String*, does not improve student performance on assessments of conceptual mastery. In fact, in some cases these students did worse. We believe that in this case, not having structure around the simulation (with the Tutorial activity not written for direct student engagement) means that students miss the purpose of activity, or are not productively constrained to focus attention on the concepts that were the object of instruction. As a result, students were less likely to stay on task.

Informal settings:

We have briefly explored how effective computer simulations might be for student learning of physics concepts in informal unstructured use. These studies were conducted by testing students on material that they had not seen in any of their college courses. The students were volunteers from two introductory physics courses, and they were tested by being asked one or two questions on a basic conceptual idea covered by the simulation

Students in the treatment group were assigned to one of three subgroups: i) a group that read a relevant text passage and was asked a question (*read*), ii) a group that played with the simulation and then was asked the question (*play first*), and iii) a group that was asked the question first as a prediction, then played with the simulation and was asked the question again (*predict and play*). A sample question for the static electricity simulation is shown in Figure 7 below a snapshot of the simulation. A control group selected from the two physics course was asked the same question for each simulation to establish the initial state of student knowledge. There were typically 30 to 50 students per group and tests were run on five different simulations.

We found that there was no statistically significant difference for any individual simulation between the control group and the group that played with the simulation with no guidance (*play first*) before being asked the question. Similarly, the group that only read a text passage that directly gave the answer to the question (*read*) also showed no difference from the control group. When results were averaged over all the simulations, both *reading* and *play* groups showed equivalent small improvements over the control group.

More significant was the comparison between control group and the *predict and play* group whose play with the simulation was implicitly guided by the prediction question. The fraction that answered questions correctly improved from 41% (control group) to 63% (predict and play group), when averaged over all five simulations (significant at $p< 0.001$, two tailed z-test). Greater insight is provided, however, by looking at performance on concept questions associated with a particular simulation, rather than the aggregate. These are shown in Table 1, with the uncertainties (standard error on the mean) in parentheses.

We believe these large variations in the impact of playing with the simulation to be indications of the manner in which the simulations are used and the particular concepts that are addressed. That is, particular questions and concepts (e.g. on the microscopic nature of charge) are better facilitated by a simulation that makes explicit use of this microscopic model. Furthermore, just as learning from all the simulations was significantly improved by the simple guiding scaffolding of a predictive question, some simulations require more substantial scaffolding than others to be effective. For a simulation like *Balloons*, where students learn about charge transfer by manipulating a balloon as they would in real life, little support is needed, but for more complex simulations involving manipulations more removed from every day experience, more detailed exercises are required. By observing students using these simulations to solve homework problems in a number of courses, we have extensive qualitative data corroborating the variation in levels of scaffolding required for various simulations.

We have noticed that simulation interface design and display greatly impact the learning in these sorts of informal settings, more so than they do in more structured settings. We see this effect routinely in the preliminary testing of simulations as part of their development. Student difficulties with the use of the interface and confusion over what is being displayed can result in negligible or even substantial negative effects on learning. In observations to date, we have found such undesirable outcomes are much less likely to occur when the simulation is being used in a structured environment where there is likely to be implicit or explicit clarification provided by the instructor.

Conclusion

This paper has introduced a new suite of computer simulations from the Physics Education Technology project and demonstrated their utility in a broad range of environments typical of instruction in undergraduate physics. Under the appropriate conditions, we demonstrate that these simulations can be as productive, and often more so, than their traditional educational counterparts, such as textbooks, live demonstrations, and even real equipment. We suspect that an optimal educational experience will involve complementary and synergistic uses of traditional resources, and these new high tech tools.

As we seek to employ these new tools, we must consider how and where they are used as well as for what educational goals they are employed. As such, we have started to delineate some of the key features of the PhET tools and their uses that make them productive. The PhET tools are designed to: support an interactive approach, employ dynamic feedback, follow a constructivist approach, provide a creative a workplace, make explicit otherwise inaccessible models or phenomena, and constrain students productively. While not an exhaustive list, we believe these elements to be critical in the design and effective use of these simulations.

Acknowledgements

We thank our PhET teammates for their energy, creativity, and excellence: Ron LeMaster, Samuel Reid, Chris Malley, Michael Dubson, Danielle Harlow, Noah Podolefsky, Sarah McKagan, Linda Koch, Chris Maytag, Trish Loeblein, and Linda Wellmann. We are grateful for support from the National Science Foundation (DUE #0410744, #0442841), Kavli Operating Institute, Hewlett Foundation, PhysTEC (APS/AIP/AAPT), the CU Physics Department, and the Physics Education Research at Colorado group (PER@C).

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Table 1

Student performance (% correct) on conceptual questions for each of five different simulation content areas for two different groups: students not playing with simulation (Control) and students making a prediction and playing with simulation (Predict and Play). Uncertainties plotted in parentheses.

Simulation Topic	Energy Conservation	Balloons Static Elec	Signal Circuit	Radio Waves	Sound	Weighted average
Control	56(7)	29(8)	35(9)	18(7)	60(8)	41(3.7)
Predict & Play	77(8)	63(9)	69(8)	41(8)	69(8)	63(3.8)

Figure Captions

Figure 1. Screenshot of PhET simulation, *Radios Waves & Electromagnetic Fields*.

Figure 2. Screenshot of *Wave On a String* simulation.

Figure 3. Screenshot of *Circuit Construction Kit* simulation.

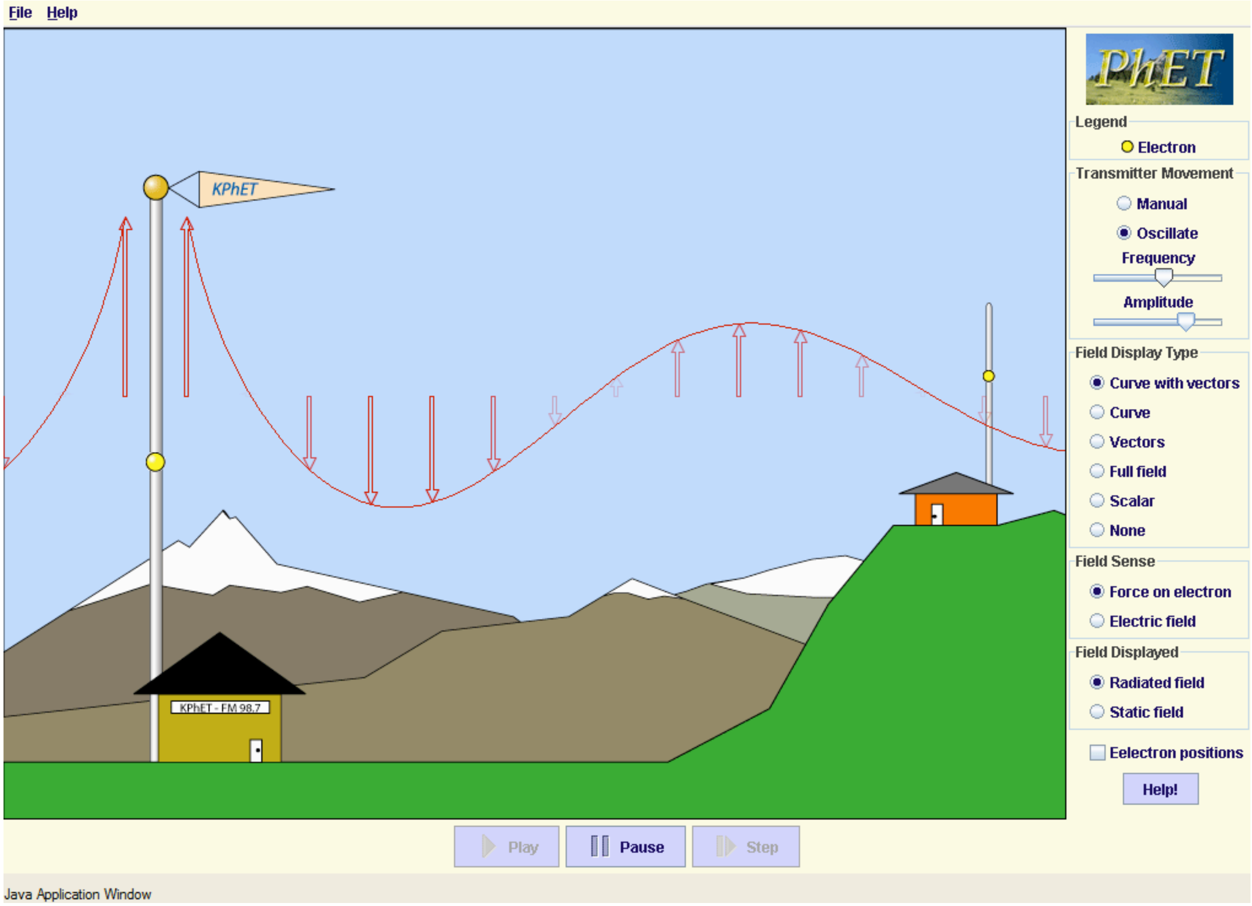
Figure 4. Student performance in control (left 4a) and treatment (right 4b) conditions to study the effectiveness of computer simulation in *Peer Instruction* activities. Standard error of the mean is indicated.

Figure 5. Student performance on final exam questions. CCK indicates student groups using *Circuit Construction Kit* simulation; TRAD indicates students using real lab equipment. Error is the standard error of the mean.

Figure 6. Student performance on midterm exam for students who learned about circuits in recitation section using the *Circuit Construction Kit* simulation or real equipment. Std. error of mean is indicated.

Figure 7. Screenshot from *Balloons and Static Electricity* simulation and sample conceptual question.

Figure 1



Transmitter Movement
○ Manual
● Oscillate

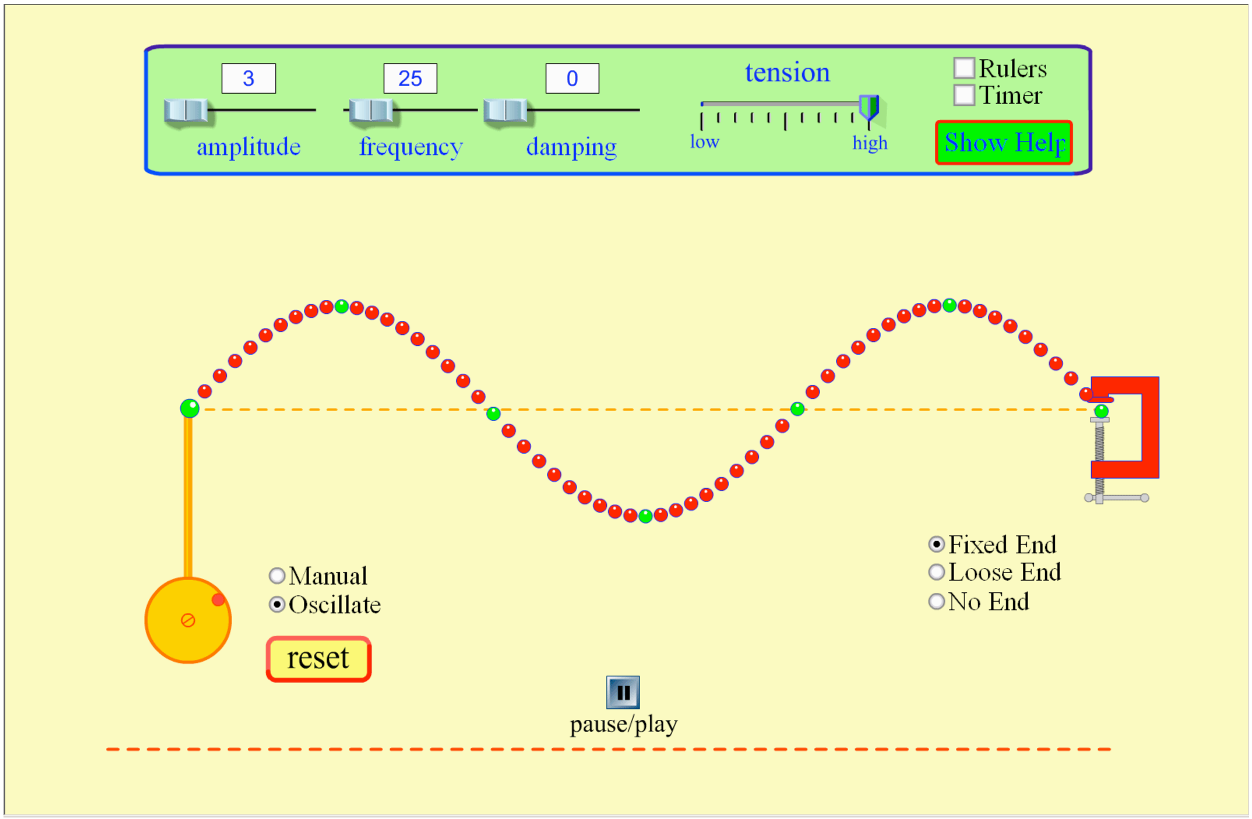
Field Display Type
● Curve with vectors
○ Curve
○ Vectors
○ Full field
○ Scalar
○ None

Field Sense
● Force on electron
○ Electric field

Field Displayed
● Radiated field
○ Static field

☐ Eelectron positions

Figure 2



amplitude 3

frequency 25

damping 0

☐ Rulers

☐ Timer

○ Manual

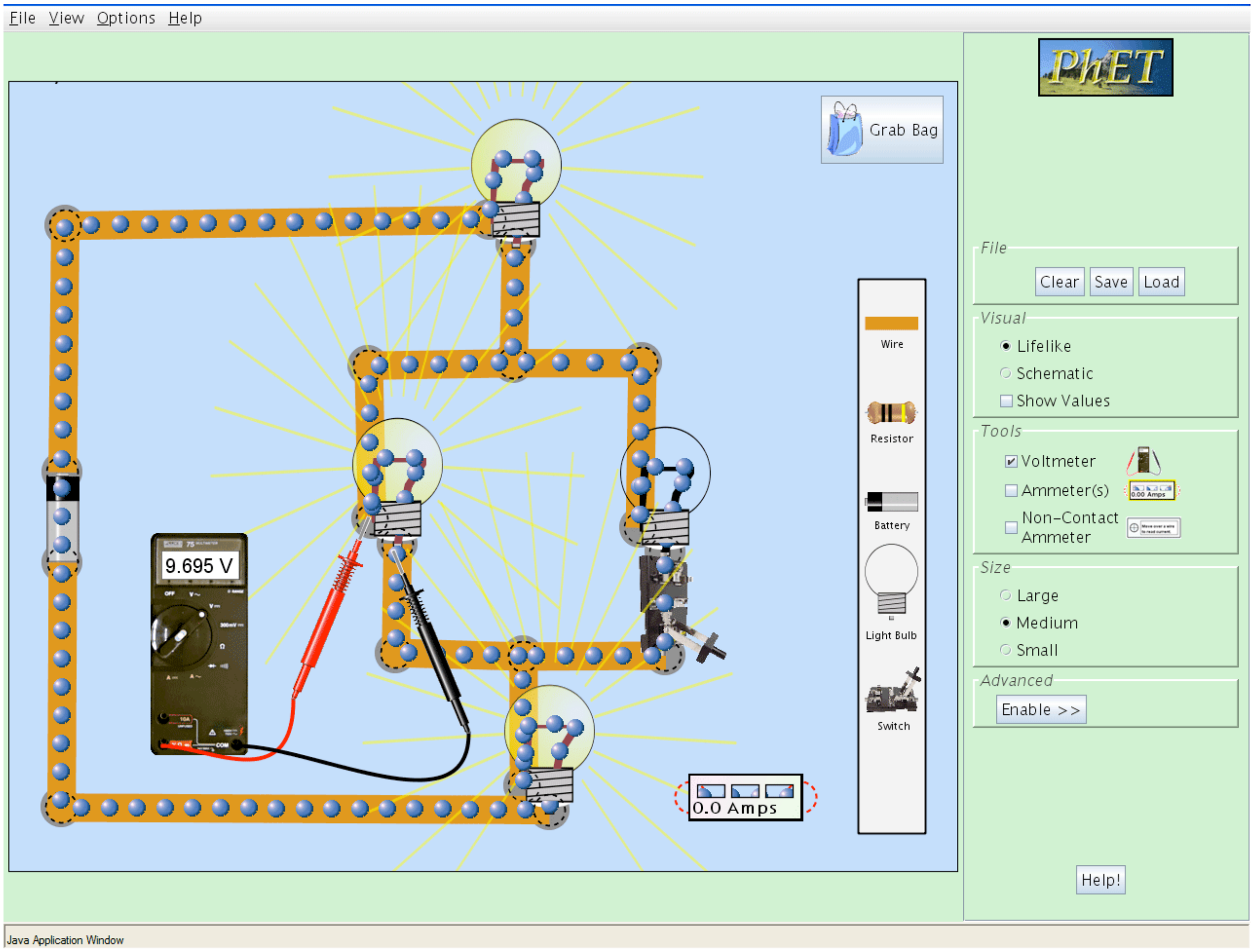
● Oscillate

● Fixed End

○ Loose End

○ No End

Figure 3



Visual
● Lifelike
○ Schematic
☐ Show Values

Tools
☑ Voltmeter
☐ Ammeter(s)
☐ Non-Contact Ammeter

Size
○ Large
● Medium
○ Small

Figure 4

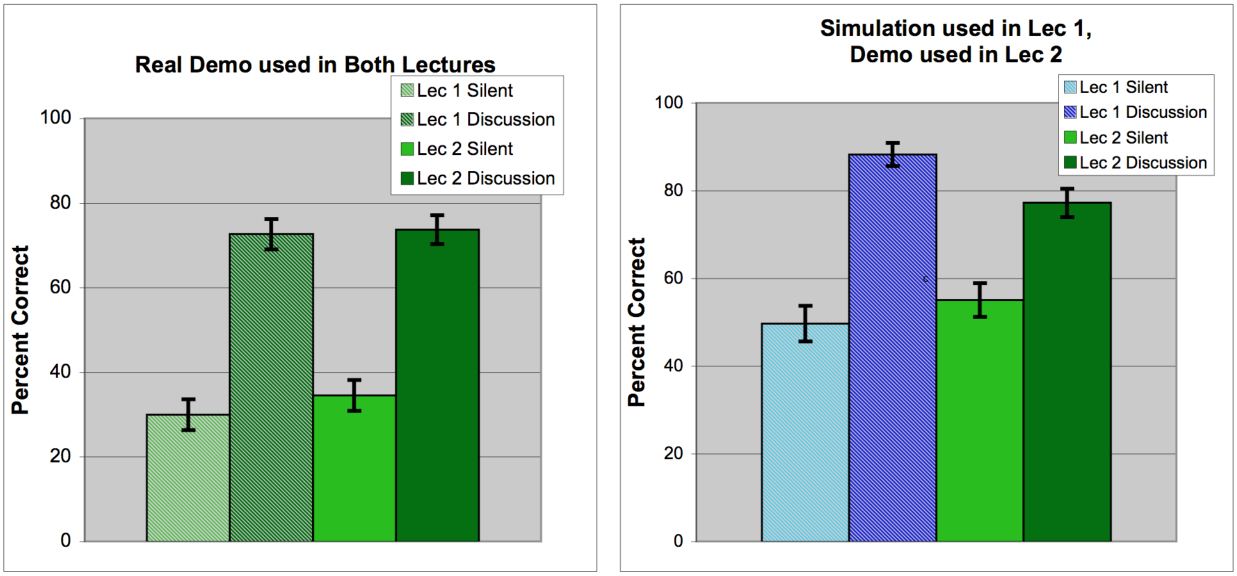
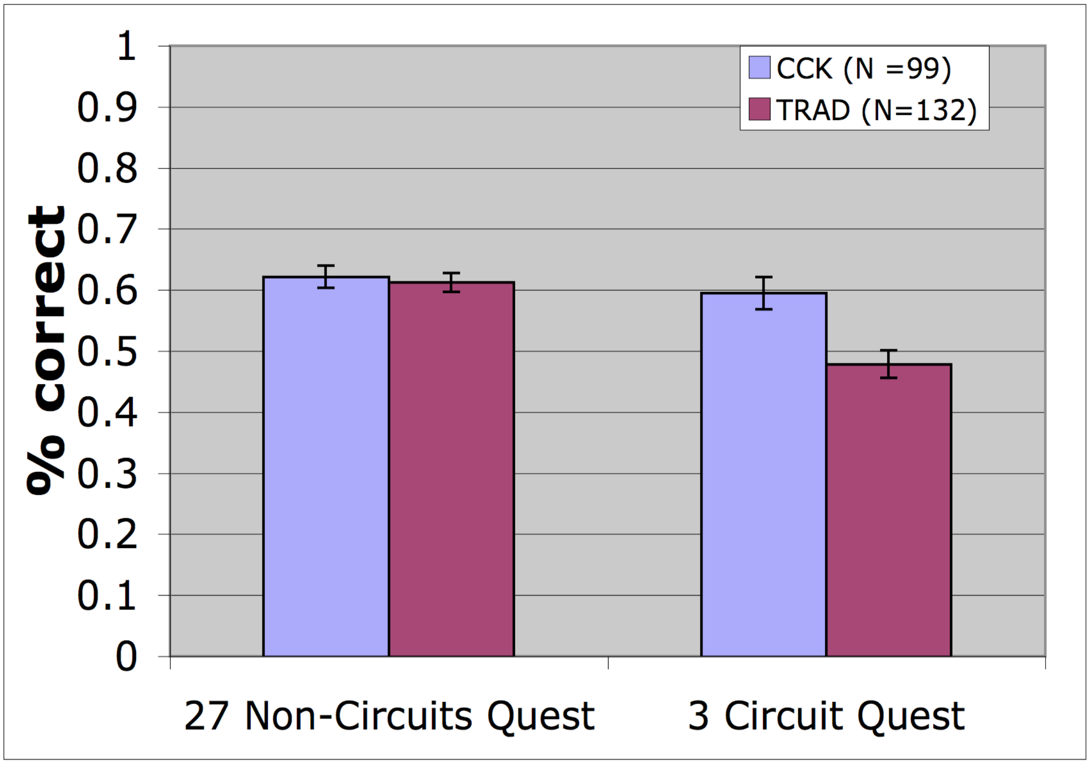

Real Demo used in Both Lectures
Percent Correct
100
80
60
40
20
0
Lec 1 Silent
Lec 1 Discussion
Lec 2 Silent
Lec 2 Discussion
Simulation used in Lec 1,
Demo used in Lec 2
Percent Correct
100
80
60
40
20
0
Lec 1 Silent
Lec 1 Discussion
Lec 2 Silent
Lec 2 Discussion

Figure 5



1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
% correct
CCK (N =99)
TRAD (N=132)
27 Non-Circuits Quest
3 Circuit Quest

Figure 6

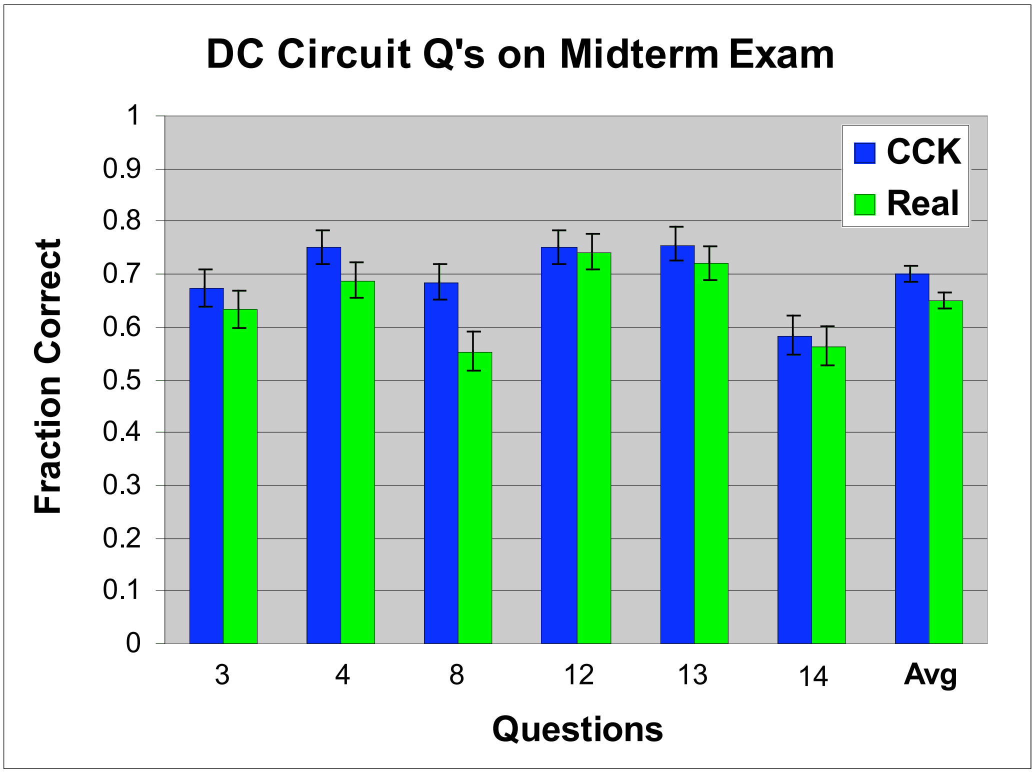
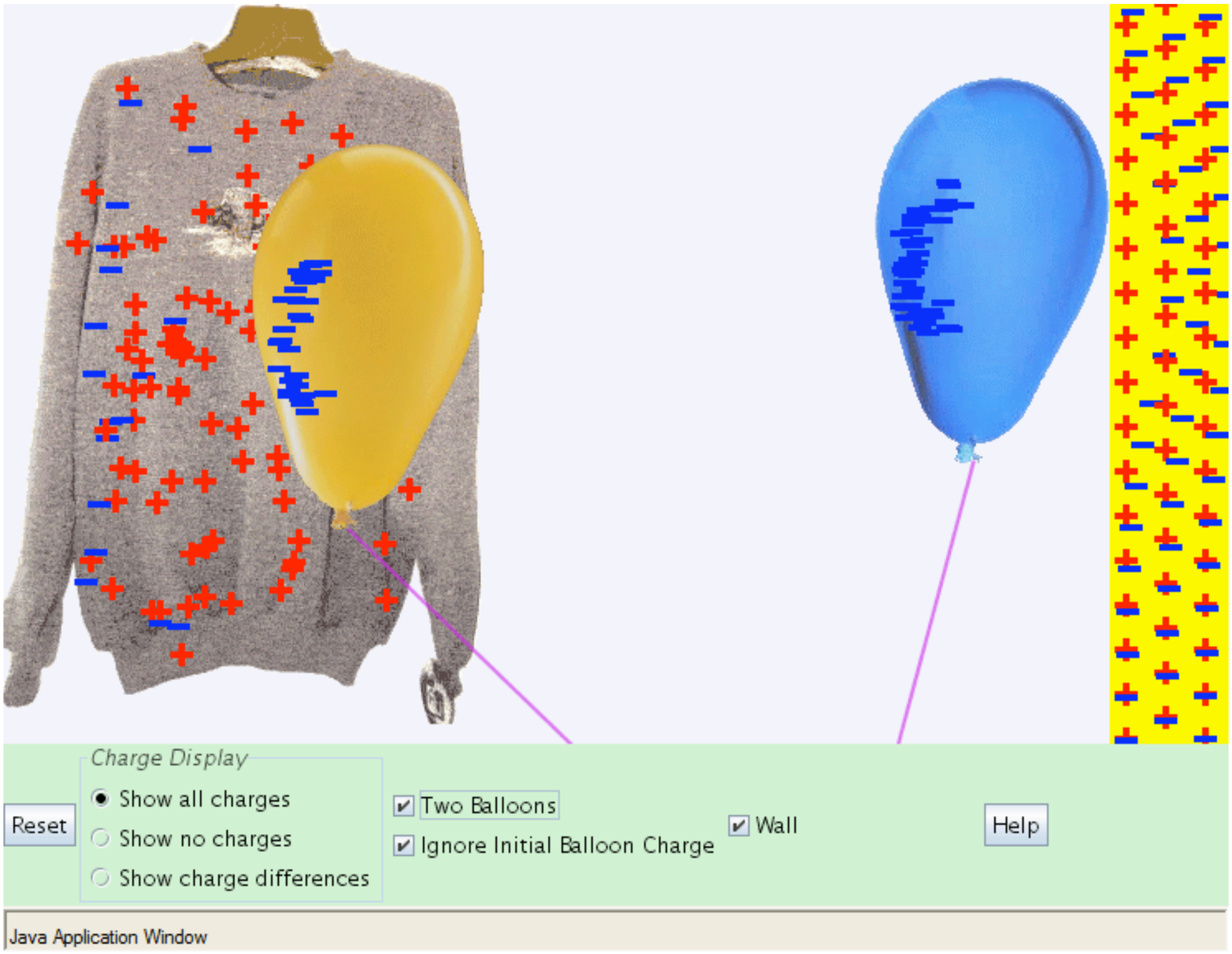

DC Circuit Q's on Midterm Exam
Fraction Correct
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
CCK
Real
3
4
8
12
13
14
Avg
Questions

Figure 7



Charge Display
● Show all charges
○ Show no charges
○ Show charge differences

☑ Two Balloons
☑ Ignore Initial Balloon Charge
☑ Wall

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

a) protons are created by rubbing if it becomes positively charged or electrons are created if it becomes negatively charged.

b) either protons or electrons transfer to/from the object. Whether it is protons or electrons that transfer depends on whether the object becomes positively or negatively charged.

c) only protons transfer to or from the object. The direction depends on whether the object becomes positively or negatively charged.

d) only electrons transfer to or from the object. The direction depends on whether the object becomes positively or negatively charged.

e) both protons and electrons transfer. Protons transfer to the object and electrons from the object if it becomes positively charged, and vice versa if it becomes negatively charged.