Oersted Medal Lecture 2007: Interactive simulations for teaching physics: What works, what doesn't, and why

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We give an overview of the Physics Educational Technology (PhET) project to research and develop web-based interactive simulations for teaching and learning physics. The design philosophy, simulation development and testing process, and range of available simulations are described. The highlights of PhET research on simulation design and effectiveness in a variety of educational settings are provided. This work has shown that a well-designed interactive simulation can be an engaging and effective tool for learning physics.
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I. WIEMAN INTRODUCTION

I (CW) am greatly honored to receive the Oersted Medal. I have been involved in working to improve physics education through a variety of activities, but for this lecture, I will focus on work to research and develop interactive simulations through the Physics Education Technology (PhET) project.[1] I will discuss this project and what we have learned about the effectiveness of interactive simulations and what characteristics are critical in their design to make them effective. In the process, I will introduce a few of our simulations and some snippets of our research on simulations.

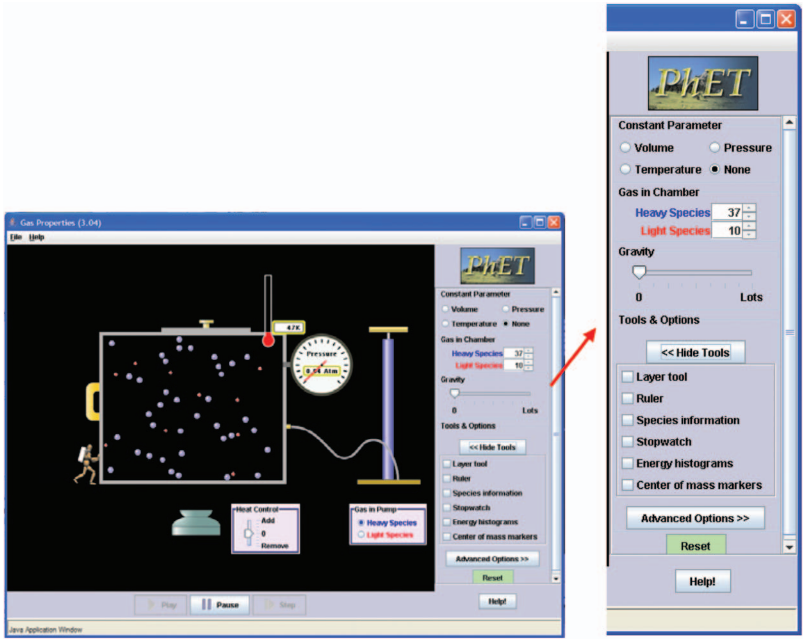
The PhET project has involved the hard work and valuable contributions of many talented individuals including Mike Dubson, Ron LeMaster, Noah Finkelstein, Sarah McKagan, Linda Koch, Patricia Loeblein, Chris Malley, John De Goes, Chris Keller, Mindy Gratny, Alex Adams, Danielle Harlow, and Noah Podolefsky. In particular, I want to single out the contributions of Kathy Perkins, Wendy Adams, and Sam Reid, who have been with the project from its beginning and who have been largely responsible for making it the successful enterprise it has become. (Kathy and Wendy have been so indispensable that I was unable to even write up this lecture without relying on their input.)

I first became aware of the use of interactive simulations, particularly the capabilities of programs in Java, by working with Marty Goldman in the 1990s on his popular Physics2000 website.[2] We developed simulations for this site showing the cooling techniques used in my atomic physics research to produce Bose–Einstein condensation. Over the years I have used these simulations in my many talks on the subject and came to realize that they are a very powerful new educational tool. Often the simulations would be the primary thing people would remember from my talk. Based on their questions and comments, it appeared that they consistently learned the physics represented in the simulations. What was particularly remarkable was that my audiences found the simulations engaging and educationally productive whether the talk was a physics department colloquium or a presentation to a middle school class. I had never seen an educational medium able to effectively address such a wide range of backgrounds. So when I received support through the NSF Distinguished Teaching Scholars program in 2001, I used it to start the PhET project to systematically research and develop interactive simulations for teaching physics. The PhET project has been greatly extended through support from the Kavli and Hewlett Foundations, the University of Colorado, my Nobel Prize money, and additional NSF support.

II. INTRODUCTION TO THE PHYSICS EDUCATIONAL TECHNOLOGY PROJECT

Interactive simulations are a new way to convey scientific ideas and engage students in educational activities.[3] The combination of advances in personal computer hardware, platform independent software such as Flash and Java, and the Internet provide tremendous new capabilities. The opportunities span a large space from simple animations with limited or no interactivity to Physlets,[4] which are small Java applets that can be readily adapted by instructors to video game-like simulations. PhET has focused on the high end of the complexity scale, producing highly interactive simulations with sophisticated graphics which involve many person months of development and testing. In many respects they are mini video games, and it is unrealistic for instructors to expect to modify the underlying code. The fundamental valuable characteristic that all these animations and simulations share is that, if written in a language such as Flash or Java, they can be run through a standard browser anywhere in the world. This capability provides exceptional flexibility in their educational use. They can be integrated into a lecture or laboratory, used by students in doing homework assignments, or used as an informal resource.

The wide range of possible simulations and ways to use them raises questions about their educational effectiveness. What characteristics of a simulation make it more or less effective? How should simulations be best used to maximize



Constant Parameter
○ Volume ○ Pressure
○ Temperature ● None
Gas in Chamber
Heavy Species 37
Light Species 10
Gravity
Tools & Options
☐ Layer tool
☐ Ruler
☐ Species information
☐ Stopwatch
☐ Energy histograms
☐ Center of mass markers

Fig. 1. In *Gas Properties* users can pump the handle to add heavy or light particles to the box and see them move about, colliding with each other and the walls. Users can cool the box with "ice" and see the particles' motion slow as the thermometer and pressure gauge readings fall. Users can also increase gravity and see a pressure gradient form.

learning? These questions are fundamentally linked. If badly used, an excellent simulation will be ineffective, as will an excellent activity that utilizes a poorly designed simulation. The PhET project is grounded in research on these questions. We draw from existing research literature on how students learn, student conceptual difficulties and misconceptions, and educational technology design.[5,6] We also make extensive use of student interviews and classroom testing to explore issues of usability, interpretation, and learning.[7–10] Our research has consistently shown that when simulations are designed and used in a way that directly aligns with well-established principles of learning, they are highly effective. If their design or use strays from those principles, simulations can be of little or negative educational value.

PhET has now developed over 60 simulations. We have three primary goals for these simulations: increased student engagement, improved learning, and improved beliefs about and approach toward learning. Most of these simulations are in physics and cover a range of topics from introductory material in mechanics and E&M to advanced topics such as quantum mechanics, lasers, and magnetic resonance imaging. One notable characteristic of these simulations is that they blur the division between elementary and advanced material, so many high school teachers find simulations on "advanced" topics quite useful, and university faculty and students from first-year to graduate students find that "introductory" simulations can provide new insights. The success of these physics simulations has stimulated us to expand our coverage, and we now have a growing number of programs in chemistry and basic mathematics.

All of our simulations are freely available.[1] They can be easily run online. For convenience, single simulations or the entire website may be downloaded to a local machine or installed from a CD. The website also has a database for teachers who use PhET simulations to share activities and exchange ideas. We have supported substantial in-house development of activities that are consistent with the research-based learning principles in our guidelines.[11] The use of PhET simulations at the university and K-12 level has grown dramatically in the last three years. Between January and July of 2007 there were more than 2.25 million simulations run online from the PhET website,[1] and the offline usage of PhET simulations is probably significantly greater.

PhET programs are specifically designed to engage students in active learning and provide a rich environment in which they can construct a robust conceptual understanding of physics through exploration. Each simulation provides an animated, interactive, and game-like environment that is appealing to students and invites them to interact and explore in an open-style play area. All interface controls are the result of substantial testing to ensure that they are simple and intuitive (for example, click-and-drag manipulation, sliders, and radio buttons). In *Gas Properties* (Fig. 1), for example, the opening panel greets the user with an invitation to "Pump the handle!" We emphasize connections to everyday life both to engage the students and to support their learning. This approach influences the small details (for example, using a bicycle pump to add gases) and the larger design where the science is often presented in the context of real-life phenomena (for example, learning about buoyancy with hot air and helium balloons in the companion simulation *Balloons and Buoyancy*).

All of the PhET simulations directly couple students' actions with animations. The change of any control results in an immediate animated response in the visual representation, making the simulations particularly useful for helping students discover cause-and-effect relations and for enhancing students' abilities to connect multiple representations. *Moving Man* (Fig. 2), for example, helps students develop an understanding of the relations between acceleration, velocity, and position as well as make connections between different representations (graphs, vectors, and mathematics) of mo-

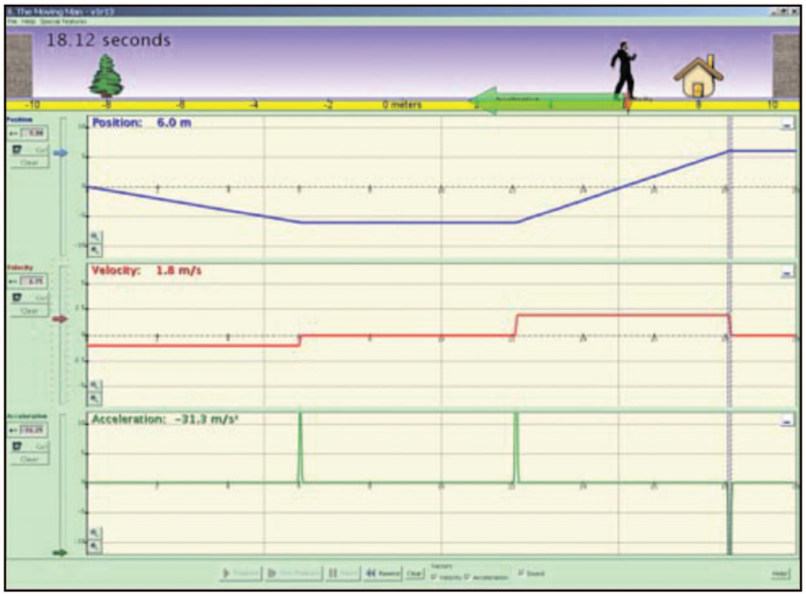


Fig. 2. In *Moving Man* users control the man's motion either by dragging the man or using the position, velocity, or acceleration controls. By graphing the motion simultaneously and including a "playback" feature, this simulation helps students build connections between actual motions and their graphical representation.

tion. For more quantitative explorations, the programs provide various measurement instruments, such as a ruler, stop watch, voltmeter, thermometer and pressure gauge.

III. PhET DESIGN AND RESEARCH PROCESS

PhET simulations require a large investment of time and money ($10–40,000/ program). Hence, over the years we have had to establish a formal process for their design, creation, and testing. The development of each simulation involves a 4–6 member team composed of faculty members, software engineers, and science education specialists (all working on the program part time). For each proposed simulation, the team first examines the learning goals, potential user base, coding complexity, and opportunities for unique educational contributions. Once we decide to create a particular simulation, the team develops an initial design. The simulation is then coded, evaluated by the team and several additional people, typically revised significantly, and then tested with students and revised accordingly one or more times before final release. This process normally ends up taking about twice as long as initial estimates.

The first stage of testing with students is by individual interviews.[7] In a typical interview, a student who is not familiar with the material being covered by the simulation is presented with one to play with in a "think aloud" format, sometimes guided by a very general question. The student is videotaped and observed by a science education researcher. If necessary, the observer may ask the student questions to stimulate explanation or investigation of particular features of the simulation. From the analyses of these interviews, we have identified key features of educationally effective simulations and have developed some general guidelines for interface design. Here we will briefly review some highlights of this research. For a complete discussion of the interview process and our findings, see Ref. 7. In addition to the material discussed here, Ref. 7 includes a discussion of the characteristics we have found that make an interface intuitive and fun to use.

Nearly all of our findings on effective program design and use are consistent with what has been found in research on learning in other contexts. Perhaps the most important, although hardly surprising lesson from these studies, is that students perceive and think differently from experts, and so testing with students is always revealing and is essential for creating an effective simulation. A series of interviews on *Radio Waves and Electromagnetic Fields* during the development process illustrates this point.[7] The initial version of the program opened showing the full oscillating electric field emanating from the transmitting antenna [see Fig. 3(a)], a view that physics teachers found very impressive and appealing. However, in the interviews students had very different and quite negative reactions to this mode. Students commented: "Full field view doesn't make sense to me," or "I don't like this view." Students would tend to watch the screen passively and attempted to correct the predictions they had previously made about electromagnetic fields without interacting with the simulation. Their descriptions of electromagnetic fields were incorrect, very superficial, and/or based on bits of prior knowledge. 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." As a result of these interviews and related observations on the impact of the start-up view on student interactivity, we changed the start-up mode to what it is now [see Fig. 3(b)]. When the program starts, nothing is in motion and there is an invitation to the user to "wiggle the electron." When the electron is wiggled, a simple representation of the generated field is shown. This start-up mode leads students to interact far more with the program—actively exploring and eventually getting to the oscillating full field view. The students all appreciated the full field view and made comments such as "this makes sense, the wave has to go out in all directions or

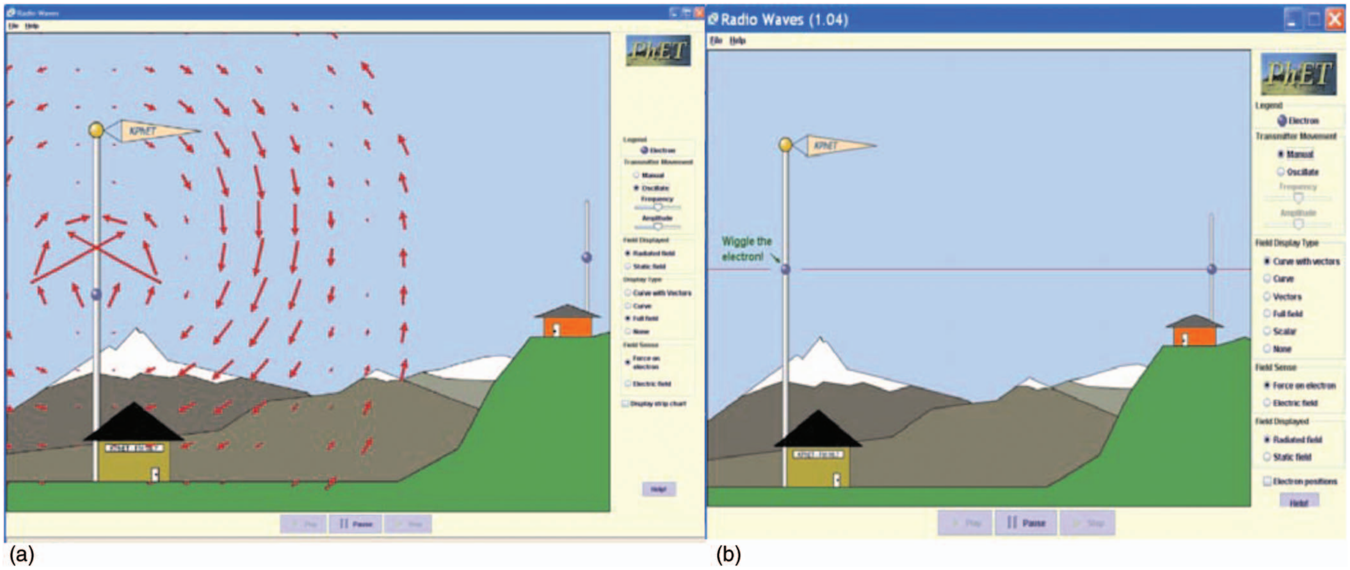


Fig. 3. (a) View on start-up of an early version of *Radio Waves and Electromagnetic Fields*. When the program first opens, the transmitting electron moves up and down along the antenna producing an electromagnetic wave. (b) View on start-up of current version of *Radio Waves and Electromagnetic Fields*. The only motion is the "wiggle the electron" moving in and stopping. When students wiggle the electron, only the curve with vectors along the line is shown.

my radio would only work in one spot" or "this is my favorite view." This example illustrates how important it is to test a program to ensure that it does not show what appeals to an expert, but rather shows what makes sense to students and invites them to interact and explore.

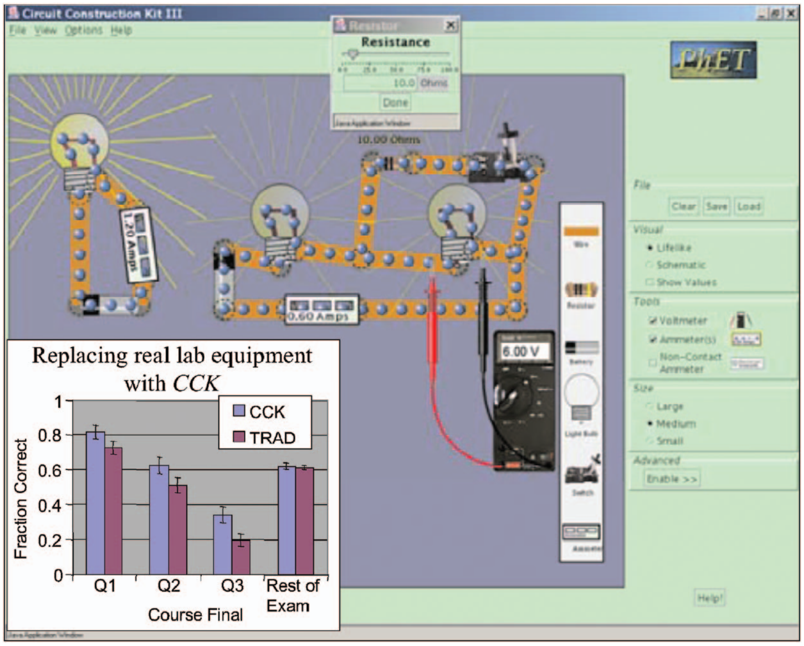
A few other notable results from these interview studies[7] are highlighted in the following.

(1) Student responses to working with the simulations are consistent; interface issues are almost universal, and physics understanding or confusion is more readily apparent than we have seen in other formats we have used in our physics education work (for example, student exams, interviews of students on course material, and observations of student group problem solving). For example, we typically test new programs with six students and find that the significant interface problems are almost always revealed by the first four students with the last two interviews merely confirming issues that had already been identified.

(2) Simulations are very powerful, but not necessarily beneficial. A good simulation can lead to the relatively rapid and very effective learning of difficult subjects. However, if there is something about a simulation that the student interprets differently than is intended, they can effectively learn the wrong idea. For example, in an early version of *Energy Skate Park,* we asked students if it takes more work to lift an identical object on the moon or on earth. Nearly all students ($>90\%$) initially believed that it took more energy to lift an object on earth. After playing with the simulation, less than 20% of the students believed that it took more energy to lift an object on the Earth. After closer inspection, we found that the default mass of the object on the Earth and Moon was 1 kg and 1650 kg, respectively, but the students were not recognizing this difference and as a result, learned an incorrect idea. Even after our extensive experience, we routinely see students perceive what is happening in a simulation differently from the designers who are experts in the subject. And it is common for students to find the initial interface design difficult or confusing or to find the simulation boring even when the experts feel that it's fun and engaging for students. These instances reinforce the point that testing with students is essential.

(3) Interactions, guided by students' personal questioning, are vital in making simulations an effective learning tool. We consistently observed that students engage in exploration and sense making only after they begin to interact with the program. This observation suggests that the educational value of animations without interactivity is quite limited—an idea consistent with research showing little educational benefit from only watching a classroom demonstration.[12,13] An important design feature of a good simulation is to encourage and guide the discovery process by providing a fun and appealing environment where students can ask questions, such as "Why does that happen?" "Will it depend on this parameter?" and "Did it respond as I predicted when I changed this parameter?" with the simulation providing the feedback needed to discover the answer.

Research on learning has established that expert competence not only requires factual knowledge, but more importantly requires the development of an organizational structure which allows for efficient retrieval and application of ideas.[5] Several characteristics of PhET simulations support the development of an expert-like organizational structure. For instance, many of the PhET simulations explicitly show the visual and conceptual models that experts use to organize and apply science ideas. One advantage of simulations is that we can show what is not ordinarily visible to the eye (for example, atoms, electrons, photons, and electric fields) and how experts model their behavior. In *Circuit Construction Kit*, for instance, blue balls represent the expert's mental model of electrons flowing through the circuit and the connection between the rate of this flow and the current. After



File

Visual
● Lifelike
○ Schematic
☐ Show Values

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

Size
○ Large
● Medium
○ Small

Advanced

Fig. 4. In *Circuit Construction Kit* students can construct these circuits, close the switch, and immediately see the response—the electrons flow faster from the battery, the ammeter reads higher, the voltage meter reads lower, and one bulb dims while the other bulb glows brighter. Results from a recent study (inset) show improved performance on the final examination by students using *CCK* in lab, compared to students doing same lab with real equipment (see Ref. 8).

building the circuit in Fig. 4, students can close the switch and change the resistance of the 10 ohm resistor. Simultaneously, the students observe the effect on the motion of electrons, the brightness of the bulbs, and the measured voltage difference. Several common student misconceptions identified in the literature are directly addressed by explicitly showing this model; for example, this visual model contradicts students' common ideas that current is "used up" as it travels around a circuit and that a battery operates as a fixed-current supply.

In addition, PhET simulations are specifically designed to productively constrain students' focus on the aspects experts believe are most important. The design is tweaked—enhancing certain features, hiding others, adjusting time scales and so on—until the desired student perception is achieved. In this way, our simulations have an advantage over real-world demonstrations or labs which typically include enormous amounts of peripheral, but unavoidable, information.

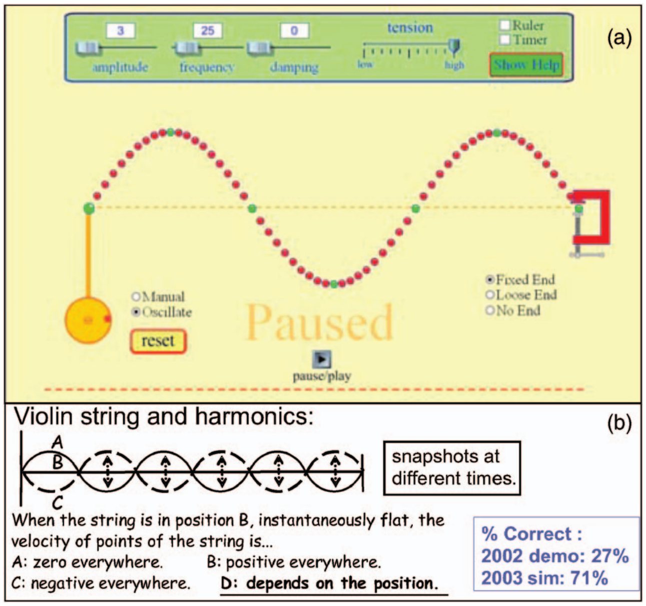
Instructors who are experts in the subject normally filter out this extraneous information automatically. Because the student has not learned what should be filtered out, this other information produces confusion and a much heavier cognitive load. This effect has been observed in studies of lecture demonstrations,[13] and in our observations of the use of simulations as lab replacements, including the published comparison of a lab using the *Circuit Construction Kit* with a lab using real components.[8] The student's attention may often focus on things seen as irrelevant by the instructor, so the instructor may not even notice, for example, the color of the wire in an introductory circuits lab. Finally, simulations also reduce cognitive load by freeing the learner from the typical language barrier of highly technical terminology that can often inhibit student understanding in the classroom. In the interview studies as well as in grading student responses to long-answer examination questions, we see that students are more comfortable and accurate when they are able to discuss their thinking about the physics in terms of the simulation components and behaviors rather than the terminology of the textbook. Avoiding such language barriers not only makes learning more effective, but likely also frees up cognitive resources for creativity and innovation in the learning process.

IV. EDUCATIONAL USE OF PhET SIMULATIONS

Each PhET simulation is created as a stand-alone learning tool, giving teachers the freedom to choose which simulations to use and how to use them. Although the simulations are honed to be highly effective learning tools, how they are used is very important and determines their ultimate effectiveness. The simulations are most effective when their use is well aligned with the principles/best practices of effective learning.[5,6] In the following we discuss a variety of ways that the simulations can be incorporated into instruction, with some data on effectiveness.

Lecture. The PhET simulations are versatile tools for teaching in lecture and serve as powerful visual aids, complement traditional classroom demonstrations, and provide opportunities for interactive engagement through interactive lecture demonstrations or concept tests.[14]

When limited to using pictures, words, and gestures in lecture, it can often be difficult to convey to students the dynamic models commonly used in physics. Simulations can make this communication much easier, and allow the teacher and students to focus their time and cognitive attention on creating an understanding of the physics. In teaching about the physics of violins, for example, we wanted students to have a good visualization of a standing wave on a string. In 2002, we used the conventional demonstration of shaking a long tygon tube stretched across the lecture hall to create a standing wave. In 2003, we gave a similar lecture but dem-



amplitude: 3
frequency: 25
damping: 0
☐ Ruler
☐ Timer
○ Manual
● Oscillate
● Fixed End
○ Loose End
○ No End

Violin string and harmonics:

When the string is in position B, instantaneously flat, the velocity of points of the string is...

A: zero everywhere.
B: positive everywhere.
C: negative everywhere.
D: depends on the position.

% Correct :
2002 demo: 27%
2003 sim: 71%

Fig. 5. In *Wave-on-a-String*, users can wiggle the end of the string with the mouse or a piston to create a wave and explore the effects of tension and damping. Here we use the simulation (a) to help students visualize a standing wave, then follow up with a concept test (b). Only 27% of the students shown the traditional tygon tube demonstration answered correctly, compared with 71% of the students shown the simulation.

onstrated the motion of a standing wave with our *Wave-on-a-String* simulation [see Fig. 5(a)]. We followed each demonstration with the concept test in Fig. 5(b). As shown, the simulation was much more effective at helping the students visualize and understand the string's motion. This success was not an accident. Our testing of this simulation allowed us to shape its appearance, time scale, and controls to optimally focus the students' attention on the desired behavior.

Moving Man (Fig. 2) provides a good example of how simulations can be used for interactive lecture demonstrations. This program can be used directly with Thornton and Sokoloff's force and motion interactive lecture demonstration,[15] in which students predict the graphs of position, velocity, and acceleration for a described motion. By using *Moving Man*, students' predictions are tested as the instructor reproduces the described motion of the man on the sidewalk; the graphs plot simultaneously. This motion can be repeated with the program's "playback" feature. Velocity and acceleration vectors can be displayed, and the position scale on the sidewalk can be flipped with the "invert x-axis" option to guide students' thinking about the meaning of the signs of velocity and acceleration. This simulation illustrates a particularly powerful pedagogical feature of our programs, namely the ability to directly link multiple representations. Here it is linking the physical motion of an object with its graphical representation.

Lab, Recitation, and Homework. PhET simulations work best when coupled with activities that allow students to work directly with the program to construct their own conceptual understanding of science through exploration.[11] These sorts of activities can be used with small learning groups in lab or recitation or as homework assignments. Although we have not yet conducted extensive research on such activities, we have explored their use in all of these formats and have observed positive results when the activities are consistent with other findings of educational research—the activities have well-defined learning goals and guide, but do not excessively constrain students' exploration of the simulation.

Several studies have shown that using the *Circuit Construction Kit* in place of the real circuit elements in the University of Washington tutorials[16] achieves comparable and excellent results. In a recent study Finkelstein *et al.*[8] found that the students who used the *Circuit Construction Kit* in laboratory performed better on conceptual questions about circuits on the final examination than the students who used real equipment (see Fig. 4).

Fully integrated into a course. An example of the effectiveness of using well-designed simulations to improve student understanding at a more advanced level comes from our experience teaching quantum mechanics in a reformed modern physics course.[17] As McKagan has found from extensive student interviews and classroom observations,[17] one of the major hurdles that students have in mastering this material is developing a conceptual model. Because they cannot visualize the phenomena, many students fall back on blindly memorizing and manipulating the formulas without any understanding. They are very frustrated by this approach, but are unable to do anything else. McKagan *et al.*[18] have seen that the PhET quantum simulation, when used suitably—in this case thoroughly integrated into all aspects of the course—helps a great deal with this problem of developing conceptual models. For example, McKagan *et al.*[19] have examined the result of teaching the photoelectric effect using a novel curriculum that fully integrates the *Photoelectric Effect* simulation into both lectures and homework assignments in order to address established student difficulties. They find that student mastery of this phenomenon was dramatically improved over the traditional coverage of the material—80% of the students correctly predicted the effect on the current to changing the applied voltage after completing the simulation-based curriculum. Prior research at the University of Washington had shown that only 20% could predict correctly with traditional coverage of this topic and 40% could after instruction using a research-based computer tutorial.[20]

V. FINAL THOUGHTS AND SPECULATIONS

Interactive simulations can be uniquely powerful educational tools. They must be carefully designed and tested and used in pedagogically effective ways. The results of our research on the testing and use of simulations matches closely with previous research on learning and effective educational practices.

We conclude with some speculations about how these powerful educational tools might also become powerful tools for educational research. These speculations are driven by three observations. (1) Simulations are effective with students with a far wider range of backgrounds than other educational material. We have numerous simulations which are being used effectively by middle school students and by advanced, even graduate level, physics students (for example, *Lasers*, *Microwaves*, *Gas Properties*, and *Circuit Construction Kit*). (2) A good simulation will stimulate students to explore the material in far greater depth than is usually the case from textual or oral presentations—this behavior is routinely observed in our interview studies. (3) The level of clarity and communication in student responses in our interviews is very high relative to other forms of probing student thinking about physics that we have used. Our speculation is that these results arise because the environment of the simulations provides a common context and language for discussing the phenomena. These commonalities eliminate many barriers to communication, particularly language and differing experiences.

Our speculation is these features cause simulations to offer a direct and hence powerful tool for probing student thinking and learning. For example, observing students exploring a simulation during a "think aloud" interview will help researchers to understand how students think about and learn the material and to identify what questions students need to ask themselves and the responses students need to observe in the simulation to achieve those "ah hah" moments of learning. Such observations could provide insights into the general learning process and content-specific learning; some examples of this potential are seen in Sec. 5 of Ref. 17. These insights could then be used to both guide and increase the efficiency of designing more effective educational experiences.

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