
PhET: Interactive Simulations for Teaching and Learning Physics

Katherine Perkins, Wendy Adams, Michael Dubson, Noah Finkelstein, Sam Reid, and Carl Wieman, University of Colorado at Boulder
Ron LeMaster, Kavli Operating Institute

The Physics Education Technology (PhET) project creates useful simulations for teaching and learning physics and makes them freely available from the PhET website (<http://phet.colorado.edu>). The simulations (sims) are animated, interactive, and game-like environments in which students learn through exploration. In these sims, we emphasize the connections between real-life phenomena and the underlying science, and seek to make the visual and conceptual models of expert physicists accessible to students. We use a research-based approach in our design—incorporating findings from prior research and our own testing to create sims that support student engagement with and understanding of physics concepts.

We currently have about 50 sims posted on our website. Many of the sims cover introductory high school and college physics, while others introduce more advanced topics, e.g., lasers, semiconductors, greenhouse effect, radioactivity, nuclear weapons, and Fourier analysis. Users, however, have included students from grade school through graduate school. On the website, the sims are organized under nine loose categories: Motion; Work, Energy & Power; Sound & Waves; Heat & Thermo; Electricity & Circuits; Light & Radiation; Quantum Phenomena; Chemistry; Math Tools; and Cutting Edge Research. We update the website regularly with newly developed or improved sims. We have also recently translated the sims into Spanish and have added a new searchable database that allows the community of educators using PhET sims to share teaching materials (homework

activities, demo ideas, etc.) with one another.

Creating PhET Sims for Engagement and Learning

We have two main goals for the PhET sims: increased student engagement and improved learning. Sims are specifically designed to support students in constructing a robust conceptual understanding of the physics through exploration. While we draw from research literature¹ on how students learn, conceptual difficulties in physics, and educational technology design, we also make extensive use of student interviews and classroom testing to explore usability, interpretation, and learning issues, and to develop general sim design principles.

We design the sims to present an appealing environment that literally invites the student to interact and explore in an open-style play area. All controls are simple and intuitive, e.g., click-and-drag manipulation, sliders, and radio buttons. In the *Gas Properties* sim (Fig. 1), for example, the opening panel greets the user with a wiggling invitation to “Pump the handle!” We emphasize connections to everyday life, both to engage the students and to support their learning. This approach influences both the small details (e.g., using a bicycle pump to add gases) and the larger design where the science is often presented in the context of real-life phenomena (e.g., learning about buoyancy with hot air and helium balloons in the companion *Balloons and Buoyancy* sim [not shown]).

The PhET sims use dynamic graphics to explicitly animate the visual and conceptual models used by

expert physicists. In many cases, the sims show what's not ordinarily visible to the eye, such as atoms, electrons, photons, and electric fields. All of the PhET sims directly couple the student's actions with the animation. Adjustment of any controls results in an *immediate* animated response in the visual representations, making these sims particularly useful for establishing cause-and-effect relationships and for enhancing students' abilities to connect multiple representations. For more quantitative explorations, the sims provide various measurement instruments, e.g., ruler, stop watch, voltmeter, thermometer, pressure gauge. The *Gas Properties* sim illustrates many of these design features.

Making PhET Sims Accessible

We write the sims in either Java or Flash so that they can be run directly from the website using a standard web browser. In addition, users can download and install the entire website (currently about 60 MB) onto any local machine for use offline. This is particularly convenient when student computer labs or lecture halls do not have an Internet connection. These sims run best on PCs. Macs will run the Flash sims well, but the Java sims run less reliably on older versions of Mac OSX.

Teaching and Learning with PhET Sims

Each PhET sim is created as a stand-alone learning tool, giving teachers the freedom to pick and choose which sims to use and how to use them. The sims are most effective when students' exploration is somewhat guided, either by the instructor in lecture or by homework, lab, or recitation activities using a guided-inquiry approach to learning. Here, we introduce some of the PhET sims and provide some suggestions for how to effectively use our sims in different learning environments.

Lecture. These sims are versatile tools for teaching in lecture: serving as powerful visual aids, complementing traditional classroom demos, and providing opportunities for interactive engagement through sim-based interactive lecture demos² or concept tests.

Every physics teacher knows that it is often difficult for students to visualize the physics. We use pictures,

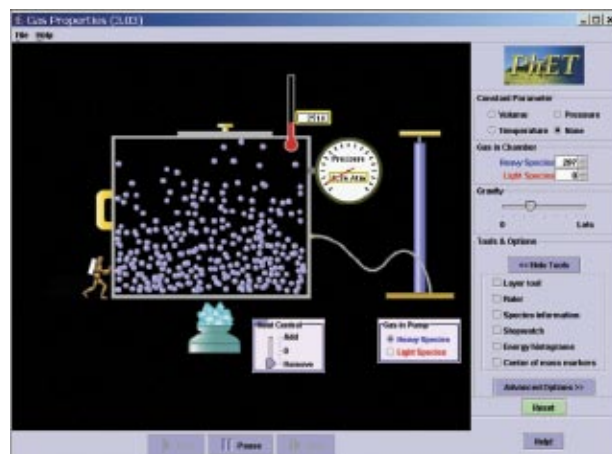


Fig. 1. In the *Gas Properties* sim, pump the handle to add heavy or light particles to the box and see them move about, colliding with each other and the walls. Cool the box with "ice" and see the particles' motion slow as the thermometer and pressure gauge readings fall. Increase gravity and see a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

words, and gestures in an attempt to help them share the same visual models that have worked for us. Unfortunately, this is not always successful—a student's picture may not be the same or necessarily useful. When using the sims, the students and the teacher see the same objects and motions, allowing the teacher and students to focus their time and attention on creating an understanding of the physics rather than on establishing a common picture.

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 our lecture hall to create a standing wave. In 2003, we demonstrated the motion of a standing wave with our *Wave-on-a-String* sim, shown in Fig. 2A. We followed each demo with the concept test in Fig. 2B. As shown, the sim was much more effective at helping the students visualize the string's motion.

We regularly use the sims to show students what is not visible to the eye. When teaching about electrostatics, for instance, we follow the traditional balloon demos with the *Sweater-Balloon* sim (not shown) where the students *see* electric charges move in response to rubbing a balloon on a sweater. Bringing a charged balloon near a wall shows polarization of the wall through the motion of negative charges.

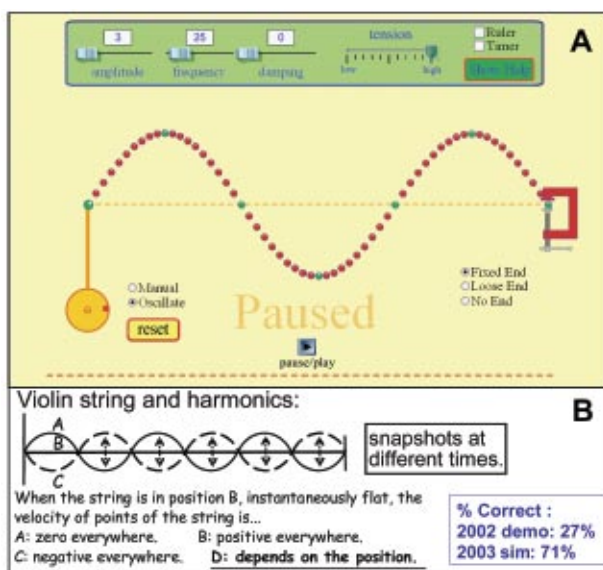


Fig. 2. In the *Wave-on-a-String* sim, you can wiggle the end of the string with the mouse or a piston to create a wave and explore the effects of tension and damping. Here we use the sim (A) to help students visualize a standing wave then follow with a concept test (B). Only 27% of the students shown the traditional tygon tube demo answered correctly, compared with 71% of the students shown the sim.

These sims couple naturally with the use of many interactive engagement techniques. In our classrooms, we use an adaptation of Mazur's *Peer Instruction*³ technique with both concept tests and interactive lecture demos. In teaching about electromagnetic waves, we use the *Radio Waves* sim to help the students develop an understanding of how EM waves are created by accelerating charges, how they exert forces on charges, and how their frequency, wavelength, and wave speed are related. As shown in Fig. 3, we ask the students to discuss and vote on how the speed of the wave is measured. About 1/3 of our students had not yet clearly distinguished the ideas of frequency and speed. By using the sim, we were able to immediately address this confusion; we focused the students' attention on following the peak as it moved to the right and relating that motion to the speed of the wave.

The sims are also useful tools for interactive lecture demos (ILDs). For instance, the *Moving Man* sim (Fig. 4) is ideal for use with Thornton and Sokoloff's force and motion ILD where students predict the graphs of position, velocity, and acceleration for a described motion.² Using the *Moving Man* sim, stu-

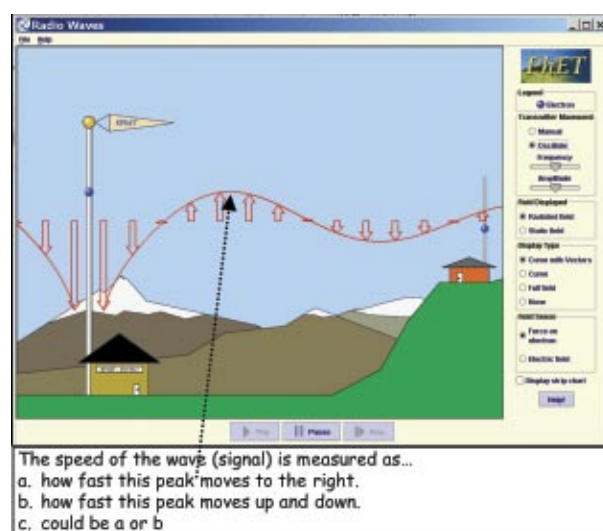


Fig. 3. This concept test uses a screen shot from the sim *Radio Waves* to help students distinguish between wave speed and frequency. In *Radio Waves*, users create EM waves by moving the electron in the broadcasting antenna by hand (mouse) or by setting the frequency and amplitude of oscillation.

dents' predictions are tested as the instructor reproduces the described motion of the man on the sidewalk and the graphs plot simultaneously. This motion can be repeated with the sim's "playback" feature. Velocity and acceleration vectors can be displayed, and the position scale on the sidewalk can be flipped with "invert x-axis" to guide students' thinking about the meaning of the signs of velocity and acceleration.

We have noticed that using sims in lecture often leads to unprompted high-quality questions and comments from students, e.g., connecting to their own experiences, asking probing "what if" questions, or extending the discussion to applications or consequences of the physics. Because of the open design of the sims, we are often able to immediately use them in an ad hoc manner to test students' ideas or answer their questions.

Lab/Recitation. The PhET sims are designed to allow students to construct their own conceptual understanding of physics through exploration. This makes the sims useful learning tools for small group activities in lab or recitation. We have found that

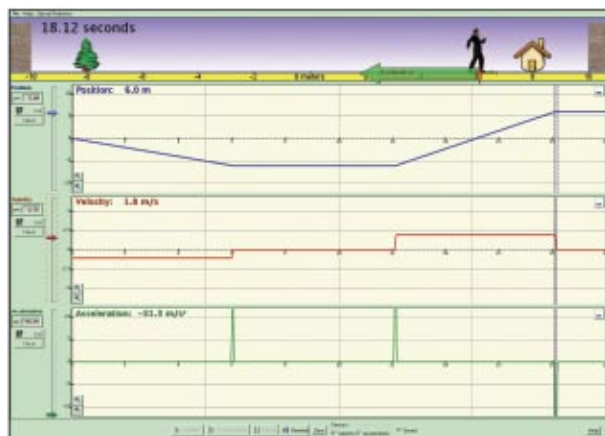


Fig. 4. In *Moving Man*, users control the man's motion either by dragging the man about or using the position, velocity, or acceleration controls. By graphing the motion simultaneously and including a "playback" feature, this sim helps students build connections between actual motions and their graphical representation.

such activities need to have well-defined learning goals and be designed to guide, but not excessively constrain, the students' exploration of the sim, promoting lines of inquiry that help students develop their understanding of the concepts.

A number of the PhET sims are particularly well-suited for such use, including *Moving Man*, *Circuit Construction Kit*, *Masses and Springs*, and *Gas Properties*. In *Masses and Springs* (Fig. 5), students can complete traditional laboratory activities, such as hanging objects on springs and measuring spring displacement or oscillation period. In addition, students can extend their explorations by slowing down time and following the conversion between different forms of energy, by transferring the apparatus to a different planet or by varying the spring constant. The lifelike look of the sims mimics the students' real-world experience in many ways. Through guided activities that investigate the physics of spring scales or bungee jumpers, for example, students can develop a conceptual understanding of a range of topics including Hooke's law, damped and undamped harmonic oscillators, and conservation of energy.

The *Circuit Construction Kit* (CCK) sim (Fig. 6) offers a learning environment similar to a real-life lab. Students connect light bulbs, switches, batteries, resistors, and wires to create arbitrarily complex dc circuits. Realistic-looking voltmeters and ammeters are used to measure voltage differences and currents.

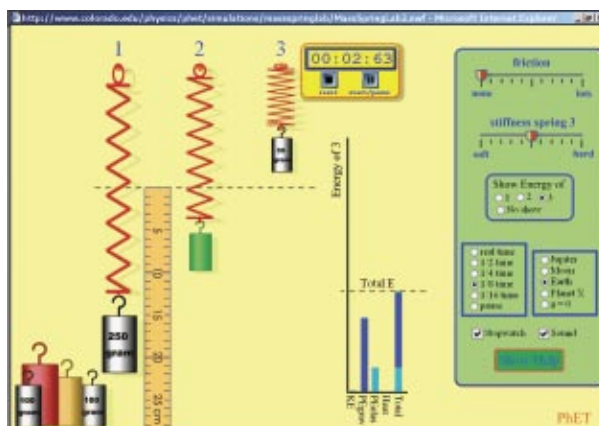


Fig. 5. The *Masses and Springs* sim creates an open lab-like environment in which students are free to investigate. Challenge them to measure the mass of the green weight, to measure gravity on Planet X, or to make sense of the energy conversions.

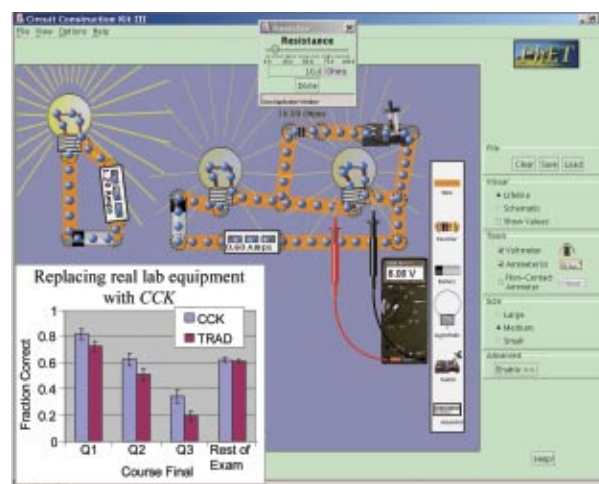


Fig. 6. In the CCK sim, students can construct these circuits, close the switch, and immediately see the response – the electrons flow faster from the battery, the ammeter reads higher, the voltage meter reads lower, and one bulb dims while the other bulb glows brighter. Results from a recent study (inset) show improved performance on the final by students using CCK in lab.

The CCK sim also provides an animation of the electrons flowing through the circuit elements and the ability to continuously adjust the resistance of any component (including the light bulbs) or the voltage of the battery. For example, after building the circuit in Fig. 6, students can close the switch and change the resistance of the 10- Ω resistor. *Simultaneously* the students observe the effect on the motion of electrons,



Fig. 7. In the *Sound* sim (Panel A), a speaker oscillates back and forth producing pressure waves that propagate from the speaker. Students can: adjust frequency and amplitude; see changes in the pressure waves and hear changes in pitch and volume; use a ruler and timer to measure speed, frequency, period, and wavelength; and look at and listen to the interference of waves from two speakers. In Panel B, true/false questions guide students' exploration.

the brightness of the bulbs, and the measured voltage difference. These features provide students with powerful tools for understanding current and investigating cause-and-effect relationships between voltage, current, resistance, and power. In a recent study, we found that the students who used *CCK* in lab performed better on conceptual questions about circuits and in constructing real circuits than the students who used real equipment (Fig. 6 inlay).⁴

While it is useful for students to make sense of non-idealized, real-world situations, these sims use a layered structure to allow students to first explore and construct a conceptual understanding with idealized equipment, and then move from the ideal to the complexities encountered in real life. In *CCK*, for example, the "advanced features" add finite resistivity to the wires and an internal resistance to the batteries.

Homework. When the sims are coupled with homework using a guided-inquiry approach, students interact with the sim to discover, explain, or reason about the important physics concepts. Often we ask

the students to explore cause-and-effect relationships, both qualitatively and quantitatively, or make connections to their everyday life experiences. In homework on sound, for example, we ask students to make sense of what the *Sound* sim (Fig. 7A) is showing with true/false (Fig. 7B) and essay questions: "You hear a Concert A tone from the speaker. Describe the required motion of the speaker and how this motion leads to detection of *Concert A* by your ear. Include in your explanation the chain of cause-and-effect logic." In a discovery exercise, students are asked to use the ruler and timer in the "Measure" panel to develop a procedure for measuring the speed of sound, and then measure its speed at 200 Hz and at 400 Hz. We ask them: "Does the speed depend on the frequency? How are your observations consistent or inconsistent with your experience in everyday life? Explain."

Hearing from the Students

At the end of the term, we asked the students in one of our large lecture courses how useful the sims were for their learning, responding on a 5-point scale from "not useful" to "a great deal." For the usefulness of sims in lecture, 62% of the students rated the sims as very useful for their learning (4-5), with an additional 22% finding them somewhat useful (3). The usefulness of homework questions coupled with sims was rated as very useful by 49%, while 24% found them somewhat useful. In contrast, the textbook was rated of little use (1-2) by 52% and very useful by only 27%.

In a calculus-based physics course running the *Tutorials-in-Physics*,⁵ we used the *CCK* sim for the circuits tutorial. In a follow-up survey, we asked students to comment on which of the tutorials (out of the nine they had completed) had been particularly effective. Of those who listed specific tutorial(s), about 70% identified the circuits tutorials in which they used *CCK*, with many commenting on how helpful it was to be able to easily experiment and adjust the circuits and how the sim helped with visualizing electricity:

Student 1: "I really like the circuits tutorial where i [sic] got to build circuits on the computer and change variables to see an instantaneous reaction. This really helped me conceptualize circuits, resistors, etc..."

Student 2: “I liked the Voltage, Current and Resistance tutorial with the computers. I am a visual learner, and I am struggling with electricity because it is not something you can really see. I mean you can see a light bulb go on, but you cannot see what is going on inside. The tutorial with the computers helped me out, because they showed what was really going on inside the circuit.” (data courtesy of Steve Pollock and Chris Keller)

We invite you to visit the PhET website (<http://phet.colorado.edu>) and explore all the simulations, as well as the database of activities and additional results from our research. We thank NSF and the Kavli Operating Institute for supporting this project. We also thank our PhET coworkers and the PER Group at Colorado for their valuable contributions.

References

1. For example, *How People Learn*, edited by J.D. Bransford, A. L. Brown, and R.R. Cocking (Nat'l. Academic Press, Washington, D.C., 2002); references within L.C. McDermott and E.F. Redish, “Resource letter on physics education research,” *Am. J. Phys.* **67**, 755–772 (1999); R.C. Clark and R.E. Mayer, *e-Learning and the Science of Instruction: Proven Guidelines for Consumers and Designers of Multimedia Learning* (Pfeiffer, San Francisco, 2003).
2. D. Sokoloff and R. Thornton, “Using interactive lecture demonstrations to create an active learning environment,” *Phys. Teach.* **35**, 340–346 (1997).
3. E. Mazur, *Peer Instruction: A User's Manual* (Prentice Hall, Upper Saddle River, NJ, 1997).
4. N.D. Finkelstein et al., “When learning about the real world is better done virtually: A study of substituting computer simulations for laboratory equipment,” *Phys. Rev. ST Phys. Educ. Res.* **1**, 010103 (2005).
5. L.C. McDermott, P.S. Shaffer, and the Physics Education Group at the University of Washington, *Tutorials in Introductory Physics* (Prentice Hall, Upper Saddle River, NJ, 2002).

PACS codes: 01.40.gb, 01.40.Rr, 01.50.ga

The authors: Carl Wieman, Distinguished Professor of Physics and a Fellow of JILA, leads the PhET project housed in the Department of Physics at the University of Colorado at Boulder. The other authors are part of the PhET team: Katherine Perkins (assistant professor attendant rank), Wendy Adams (graduate student), Michael Dubson (senior instructor and flash programmer), Noah Finkelstein (assistant professor), Sam Reid (software engineer), and Ron LeMaster (software engineer supported by the Kavli Operating Institute).

Contact: Katherine Perkins, Department of Physics, UCB 390, University of Colorado at Boulder, Boulder, CO 80309; Katherine.Perkins@colorado.edu
