A powerful tool for teaching science

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Although computers have dramatically improved productivity in many areas, their use for improving education has been slow and difficult. Online interactive simulations may soon change all that.

There is considerable evidence that science classes from elementary school through to university are generally failing to provide most students with an understanding of science. Sadly, these classes are also frequently suppressing whatever interest students may have in the subject. Information technology offers tremendous untapped opportunities for improving this situation. We have been exploring the use of a novel aspect of this technology: online interactive simulations (sims). This way, students can construct their understanding through semi-guided exploration. Research has shown this process to be a highly effective and engaging way to learn, and this new medium seems particularly well suited for today's students. Another obvious virtue of online sims is that they are accessible to everyone in the world with internet access or a CD drive. If created using Java or Flash, they can be run through a web-browser and are (nearly) platform independent. Guided by research on learning (see, for example, ref. 1), particularly in science, we have been developing sims and studying their effectiveness. Our data indicate that well-developed and tested interactive sims can convey ideas in very different and more powerful ways than traditional educational media, and resonate with students who have grown up in a culture of internet and video-games. They can also be easily used in a wide range of educational settings and readily converted to other languages. This combination of capabilities and ease of distribution makes interactive sims a very exciting educational tool.

Our Physics Education Technology (PhET) project's team of scientists, software engineers and science educators has now created more than 50 online sims (http://phet.colorado.edu) for teaching physics and chemistry, and we have tested them with students in a variety of environments[2]. There are two main goals for the PhET sims: increased student interest and improved learning. The animated, interactive and game-like environments help students learn through exploration. We emphasize the connections between real-life phenomena and the underlying science, and we seek to make the visual and conceptual models of expert scientists accessible to students, often by making the invisible — for example, electrons,

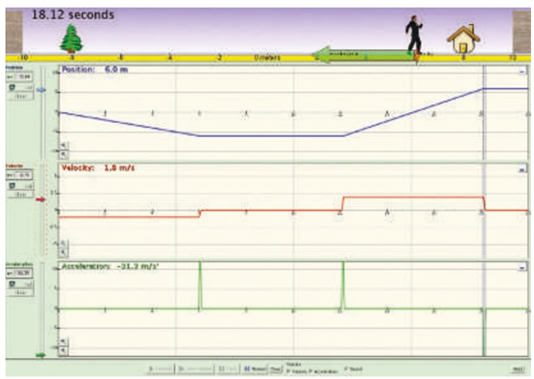

Figure 1 **'The Moving Man'. Users control the man's motion either by dragging the man about or using the position, velocity or acceleration controls. By graphing simultaneously and including a 'playback' feature, this sim helps students build connections between actual motions and their graphical representation.**

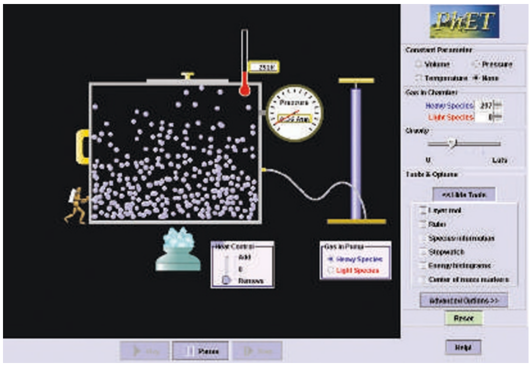

Figure 2 **Particles in a box. In the 'Gas Properties' sim, pump the handle to add heavy or light particles to the box and see them move about, colliding with each other and the walls. Cool the box with 'ice' and see the particles' motion slow as the thermometer and pressure-gauge readings fall. Increase gravity and see a pressure gradient form. The companion 'Balloons and Buoyancy' sim explains the microscopic origin of buoyancy through hot air and helium balloons.**

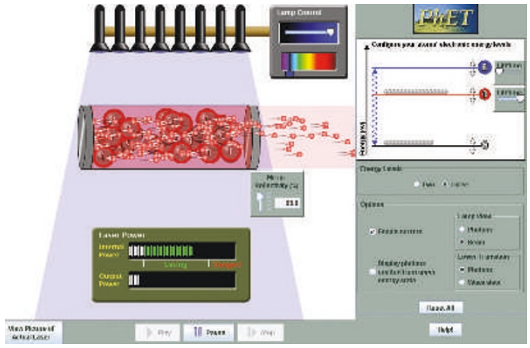

Figure 3 **Amazing lasing. In the 'Lasers' sim, students can explore the interaction of light and atoms under a wide range of conditions, and if they meet the challenge of producing all the required conditions, they will get a laser beam out.**

atoms and photons — visible. Our best sims will occupy students (and, on occasion, faculty) for hours, and result in an ability to understand and use sophisticated models of the science represented therein.

We were intrigued to see such results even when the science would normally be considered too advanced. For instance, our non-science university students use PhET sims to learn the basic physics of lasers and semiconductors. Complex scientific phenomena are presented in the form of dynamic interactive visual models, unencumbered by the usual trappings of technical jargon and mathematics. The result is that topics that were previously inaccessible can now become understandable and interesting to a vastly larger population. Sims are also very effective at conveying important physical cause-and-effect relationships, and can make the connections between multiple representations of phenomena obvious in a way that no other media can.

The ability to readily move between multiple representations is a characteristic of a good scientist, but it is very difficult for most students to learn. Examples of sims that link multiple representations include one called 'Sound' that provides simultaneous audio and visual representations of sound waves, and 'The Moving Man', shown in Fig. 1. When the student drags the little man around using the mouse, graphs of his position, velocity and acceleration are created in real time. Conversely, the student can directly manipulate the man's position, velocity or acceleration and see how the man responds. The student can also 'play back' the man's motion, watch the man move according to the graph, and display velocity and acceleration vectors. These features dramatically improve the ease with which students can grasp and use these different representations.

However, a simulation *per se* does not automatically, or even readily, come with great pedagogical power. In our hundreds of hours of testing them with students, we have found sims can easily be boring, frustrating or misleading. They can also be fun and engaging, but educationally worthless. Thus we find that a development process that involves multiple cycles of careful testing with students and refinement (or massive overhaul) is essential. Through extensive student interviews, we have learned a number of general design features that are very important for ease of use, engagement and learning. Our results are generally consistent with previous research on educational software and software usability, and will be extensively discussed in a future publication. Here we just list the most critical features: (1) highly interactive animation that provides direct and immediate response to user actions; (2) an appealing environment and reasonably sophisticated graphics that literally invite the student to interact and explore; (3) simple and intuitive controls, such as click-and-drag manipulation, sliders and radio buttons, with minimal reading required; and (4) connections to real-life objects.

Creating good simulations requires both expert understanding of the science and careful testing with students. Typically, the creation process pushes experienced scientists such as ourselves to examine and refine our own scientific models. But that is not sufficient. Novice students frequently perceive what is happening on the computer screen differently from experts. Only by going through multiple test cycles with students, and modifying the sim in response, is it possible to be confident that students will have the same interpretation of what is happening in the sim as experts. A correct interpretation is essential for

OUR BEST SIMS WILL OCCUPY STUDENTS (AND, ON OCCASION, FACULTY) FOR HOURS.

students to gain a proper understanding of the science through their interactive explorations. Our extensive testing with students has also given us a greater appreciation of how often classroom demonstrations, textbook visuals and even laboratory equipment can be confusing and misleading for novice students,

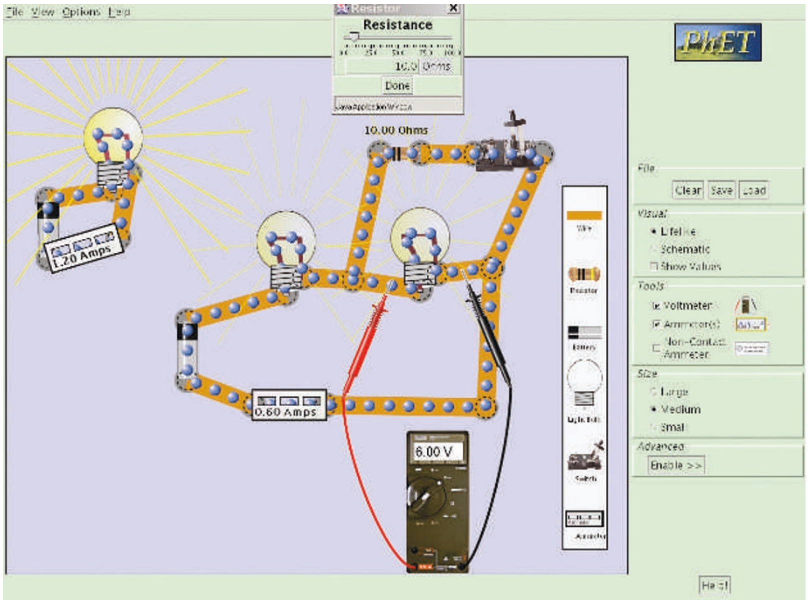

Figure 4 **Build your own circuit. In the 'CCK' sim, students can construct these circuits, close the switch, and immediately see the response — the electrons flow faster from the battery, the ammeter reads higher, the voltage meter reads lower, and one bulb dims while the other grows brighter.**

because of this same gap between expert and novice perception. A pedagogical advantage of the computer over real life is that it enables us to readily hide or enhance particular features and adjust time and distance scales to ensure that expert and novice users perceive the same thing. Studies by our group have shown that good sims can actually be pedagogically more effective than apparently similar (from the expert's point of view) classroom demonstrations and laboratory exercises with real equipment[3].

PhET sims range from simple topics such as 'Balloons and Static Electricity' where the user rubs a balloon on a sweater to see the electrons transferred and observe the resulting attraction, to intermediate topics such as 'Gas Properties' shown in Fig. 2, to advanced topics such as 'Lasers' (see Fig. 3). Many of the design features listed above are illustrated in the sims shown in the figures. For more quantitative explorations, various measurement instruments — from rulers, stop watches, voltmeters, thermometers to pressure gauges — are available, as well as graphical representations of data. Our 'best seller' is the 'Circuit Construction Kit' (CCK), shown in Fig. 4, with which students can build d.c. electric circuits of nearly arbitrary complexity with realistic-looking (or schematic) light bulbs, resistors, batteries and wires. The highly visible electrons move around the circuit, lighting the light bulbs and losing energy, in accordance with Kirchoff's laws.

There are both expected and surprising aspects of how students interact with sims, as well as much yet to be learned. Among the expected is that students will explore and usually discover the many controls/variables more readily than their teachers. Students also consistently explore what happens under extreme conditions. We have learned to take advantage of this by building in little pedagogically effective 'surprises', such as having the CCK battery burst into flames if the current is too large.

Another expected result is that even with very careful design, all but the simplest sims need some questions or activities to guide the students in educationally effective exploration. Each PhET sim is created as a stand-alone learning tool, often with several layers of complexity. This approach gives teachers the freedom to select and use those that best match their students and learning goals. We have started an online database to collect and share user-developed activities related to the sims.

A number of the results concerning student sim use have surprised us. First, these sims can generate a high level of engagement, exploration and understanding among students with very diverse ages and backgrounds. We have come to realize that 'suitable for grade school to grad school' describes most good ones. Second, students are frequently much more inclined to explore a simulation than laboratory equipment. Third, students readily relate physics topics to various real-world situations when encountering the topics through sims — connections that students don't generally make in most classes. A final surprise is that we have yet to see a student be misled by the wildly unrealistic scales commonly used, such as large blue electrons or light that crawls across the computer screen. As long as we give those elements a slightly cartoonish appearance, they are perceived to be unrealistic, but useful, representations. We do most of our testing with university students; it is possible that younger students may react differently, or perhaps this reaction is common among students exposed to the mixture of reality and artifice present in all video games.

It is clear that online interactive simulations have tremendous educational potential, and would be useful in teaching far more subjects than just physics and chemistry. However, there is a rather mundane obstacle preventing the full realization of this potential: it is hard to come up with a good business model for creating educational sims. Because of the necessity for sophisticated graphics and software codes, as well as extensive testing and refinement, a good sim with some complexity might cost $50,000 to produce and test. There are further ongoing costs associated with maintaining them as hardware and software evolves. When spread out over the millions of people who might use such a sim, this investment is a tiny amount of money, but for the typical scientist or teacher who wants to create a sophisticated and effective sim, it is an impossible hurdle. Our group has relied on a 'Mother Teresa' business model, receiving modest charitable support from the National Science Foundation of the US, and private foundations (Hewlett and Kavli) that enable us to create sims and make them available for free over the web. Such a business model, however, severely limits the rate and range of sims produced. Despite this obstacle, we believe that sophisticated interactive simulations will soon take their place as a formidable new educational tool that will make learning all areas of science easier and more fun for students of all ages.

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