PHYSICS

PhET: Simulations That Enhance Learning

A library of interactive computer simulations aids physics instruction worldwide.

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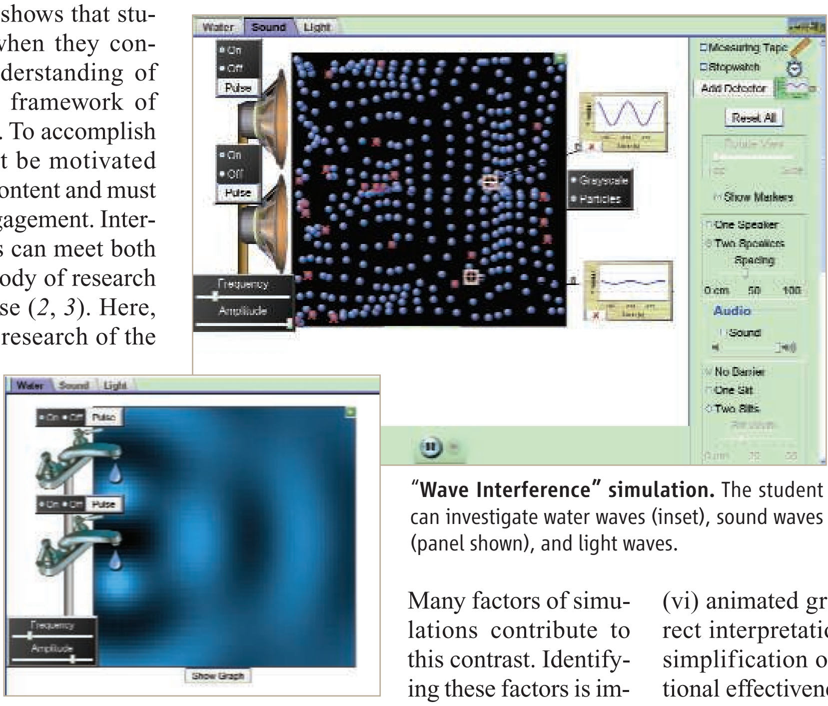
Research on learning shows that students learn better when they construct their own understanding of scientific ideas within the framework of their existing knowledge (*1*). To accomplish this process, students must be motivated to actively engage with the content and must be able to learn from that engagement. Interactive computer simulations can meet both of these needs. A growing body of research analyzes their design and use (*2*, *3*). Here, we summarize some of the research of the Physics Education Technology (PhET) project, particularly that related to simulations and student motivation.

We find that an important element of educationally effective simulations is that students view these simulations much as scientists view their research experiments (*3*). The scientist approaches research as an enjoyable opportunity to explore basic concepts, as well as to challenge, correct, and add to his or her understanding of how the world works. Similarly, the student usually finds exploring the simulations fun and, through this exploration, discovers new ideas about the science. A well-designed simulation focuses the student's attention on the basic scientific concepts. When something unexpected happens, the student questions her understanding and changes parameters in the simulation to explore and improve her understanding—approaches similar to those taken by a scientist working with an experiment. This behavior is in contrast to the way students approach hands-on experiments typically used in classes. Students often think that their goal with such experiments is to reproduce a preordained result as fast as possible, without making a mistake.



"Wave Interference" simulation. The student can investigate water waves (inset), sound waves (panel shown), and light waves.

Many factors of simulations contribute to this contrast. Identifying these factors is important for effective design and use of educational simulations and could help improve typical in-class experiments.

The PhET project (http://phet.colorado.edu) has developed more than 80 interactive simulations. These cover various topics in physics and real-world applications, such as the greenhouse effect and lasers. There are 16 simulations on chemistry topics, as well as several simulations for math, biology, and earth science. PhET simulations run through standard Web browsers and they can be integrated into a lecture, used with laboratories or as homework assignments, or used as informal resources. A PhET simulation requires several months to create, has 10,000 to 20,000 lines of code, and is tested through a series of student interviews. These simulations are used worldwide and at all levels—from grade school through upper-level university courses.

The "Wave Interference" simulation (see figure above) illustrates common PhET simulation features: (i) familiar elements (audio speakers and faucets) to build real-world connections; (ii) visual representations to show the invisible (the motion of air molecules in a sound wave); (iii) multiple representations to support deeper understanding (pressure differences visualized by density of air molecules, by light and dark shading on the gray-scale view, and by the pressure versus time graph); (iv) multiple directly manipulated variables (sliders controlling frequency and amplitude of the wave, as well as choice of number and spacing of the sources); (v) instruments for quantitative measurements and analysis (measuring tape, clock, and pressure meter); (vi) animated graphics tested to ensure correct interpretation; and (vii) distortion and simplification of reality to enhance educational effectiveness.

In PhET simulations, the visual display and direct interaction help answer students' questions and develop their understanding. Animated graphics are used to convey how scientists visualize certain phenomena such as electrons, fields, and graphs (see figure, page 683). Interacting with the simulation helps users develop their own mental models and understanding of the science. This is particularly helpful for students of quantum mechanics (*4*).

Research by the PhET project on design and use of simulations in a variety of educational settings (*5*) generated the following findings. Students doing a 2-hour exercise using the "Circuit Construction Kit" simulation in a one-semester course demonstrated higher mastery of the concepts of current and voltage on the final exam than students who did a parallel laboratory exercise with real electrical equipment (*6*). In a quantum mechanics course using a curriculum based on the "Photoelectric Effect" simulation, ~80% of the students demonstrated mastery of the concepts, whereas only 20% did so in a course using traditional instruction (*4*). When used as a lecture demonstration, the "Wave on a String" simulation resulted in

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greater conceptual learning than did the standard demonstration (*2*).

We have also conducted more than 250 interviews of individual students using PhET simulations in a think-aloud format. These interviews reveal how and why students interact with simulations and how this interaction leads to learning (*7, 8*). First, students find the simulations to be fun and intellectually engaging. Students (and teachers) will spontaneously play for hours with some simulations in educationally productive ways. We have identified a number of characteristics that make a simulation this engaging, many of which are what make video games engaging (*9*). These include (i) dynamic visual environments that are directly controlled by the user, (ii) challenges that are neither too hard nor too easy, and (iii) enough visual complexity to create curiosity without being overwhelming. Items (ii) and (iii) are best developed through iteration and testing with students.

We find that students are not able to make sense of the science in the simulation just from watching. They must interact actively with the simulation. Most of the learning occurs when the student is asking herself questions that guide her exploration of the simulation and her discovery of the answers. When students engage in such self-driven exploration, they learn better. For example, nonscience students with no prior knowledge of physics are able to provide quite good explanations of an electromagnetic wave after less than an hour playing with the "Radio Waves" simulation. (Even physics majors have a hard time explaining electromagnetic waves after a year of physics.)

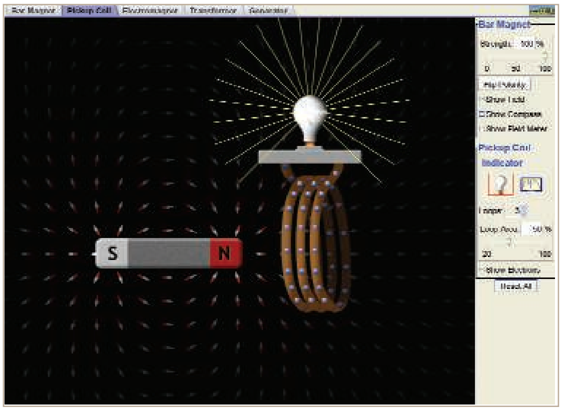
This sort of self-driven exploration is very similar to what a scientist does with an experiment. It is the students' perceptions of the simulations that encourage them to explore in a similar manner. Students have little fear of breaking the simulations or hurting themselves, and they trust the simulations to be correct. Some learning goals are not addressed through the simulations, such as operating complex laboratory equipment (*3*).

In the study comparing the use of "Circuit Construction Kit" with equivalent real equipment (*5*), students were observed to do more spontaneous experiments with the simulation than with the corresponding real electrical equipment. Groups using the real equipment frequently stopped to ask questions of the Teaching Assistant (TA) that indicated concerns over hurting themselves or breaking the equipment. The simulation groups rarely asked questions of the TA and were constantly discussing within their peer groups and trying various circuit configurations to test their ideas. In another study, we used the simulations "Moving Man," "Projectile Motion," and "Energy Skate Park" to supplement the use of laboratory equipment. Students expressed a strong preference for simulations over the real equipment. They repeatedly commented that it was easier to see what was happening with the simulations and that they were more fun than the real equipment. In contrast, unexpected results with the real equipment were commonly blamed on human error or defective equipment, and there was very little exploration. We heard numerous comments about how it was nice that the simulations were always correct and they (the students) could not break them, as they could the real equipment (*10*).

As scientists, we perceive our experiments through an "expert filter" arising from our extensive experience and knowledge, and this perception allows us to see our experiment much the way these students perceive PhET simulations. As scientists, we recognize the important aspects of the apparatus and ignore the trivial, so it is neither overwhelmingly complex nor frightening. We perceive challenges that engage us to carry out exploration and discovery.

A good simulation provides the student with the equivalent of training wheels on a bicycle, effectively substituting the constraints and display of the simulation for expertise. This support allows students to carry out exploration and learning that is cognitively similar to that of a scientist, something they do not have the experience or motivation to do with most real equipment in physics. With real equipment, the numerous complex unknowns are mysterious, uncontrollable, and threatening. Without an "expert filter," every detail is seen as equally important. For example, we have seen students in electric circuit laboratories spend considerable time worrying about the significance of the (irrelevant) color of plastic insulation on the wires. We also see in simulation testing how rapidly expert-like understanding can change a person's perception. With the "Radio Waves" simulation, if students are initially faced with the full-field view, they are overwhelmed. They find the simulation unpleasant, and they are reluctant to interact with it. However, if a student begins with the standard simple start-up panel, they will readily explore and develop an understanding so that, when they later encounter the full-field view, they understand it and actually prefer it. Simulations can therefore be designed to introduce students to increasing levels of complexity and messiness, which may be an effective and engaging way to prepare students for real scientific research.

Carefully developed and tested educational simulations can be engaging and effective. They encourage authentic and productive exploration of scientific phenomena, and provide credible animated models that usefully guide students' thinking.



Faraday Laboratory. In a series of panels, students explore bar magnets and electromagnets, induced currents, transformers, and, finally, hydroelectric power generation.

References and Notes:

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3. See supporting material available on *Science* Online for additional information.
4. S. B. McKagan *et al.*, *Am. J. Phys.* **76**, 406 (2008).
5. All research papers by the PhET team can be found at: http://phet.colorado.edu/new/research/index.php.
6. N. D. Finkelstein *et al.*, *Phys. Rev. Spec. Top. Phys. Educ. Res.* **1**, 010103 (2005).
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10. Student perception of the accuracy of simulations is a complex topic that is discussed in the supporting material.
11. The PhET work has been supported by the NSF, the William and Flora Hewlett Foundation, Microsoft, the University of Colorado, the Kavli Operating Institute, and C. Wieman and S. Gilbert. This work represents the valuable contributions of the entire PhET Team.

Supporting Online Material
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