CHAPTER 3

Using Computer Simulations to Enhance Science Teaching and Learning

Randy L. Bell and Lara K. Smetana

Have you ever been able to have your students vary the force of gravity and determine the effects on an object's motion? Explore nuclear fission at the molecular level and discover whether the daughter atoms are always the same? Move tectonic plates while investigating the differences between divergent and convergent boundaries?

Computer simulations make these types of interactive, authentic, meaningful learning opportunities possible. Learners can observe, explore, recreate, and receive immediate feedback about real objects, phenomena, and processes that would otherwise be too complex, time-consuming, or dangerous.

Broadly defined, computer simulations are computer-generated dynamic models that present theoretical or simplified models of real-world components, phenomena, or processes. They can include animations, visualizations, and interactive laboratory experiences.

In a simulated environment, time changes can be sped up or slowed down; abstract concepts can be made concrete and tacit behaviors visible. Teachers can focus students' attention on learning objectives when real-world environments are simplified, causality of events is clearly explained, and unnecessary cognitive tasks are reduced through a simulation.

Technological advances have increasingly brought instructional digital technologies into the science classroom. Teachers may have greater access to Internet-connected classroom computers, wireless laptop carts, computer projectors, and interactive whiteboards than ever before. As you consider how these resources can be used to enhance science teaching and learning, you may find yourself turning often to computer simulations, especially since they are tools frequently used by scientists in their daily work.

You are likely to find at least one simulation for any science concept represented in the National Science Education Standards. Many of these simulations can be accessed online (some for a fee, like at *www.ExploreLearning.com*[1]; others at no cost, such as on the PBS You Try It site, *www.pbs.org/wgbh/aso/tryit*). Other more complex simulations with large underlying databases (like Starry Night) are available as commercial software. This chapter seeks to describe how computer simulations can support student learning in science as well as strategies for choosing and appropriately incorporating them in the classroom.

What the Research Says

Simulations have been around practically since the advent of computers, and researchers have been looking at classroom uses of simulations for over 20 years. The following two sections describe what is known about the effectiveness of computer simulations for supporting science teaching and learning and highlighting ways that simulations can be best used to do so. The overview of the literature provides a summary of the past two decades of research, including a discussion of several seminal pieces. Finally, a set of guidelines presents best practices drawn from this body of literature.

Researchers studying the use of simulations in the classroom have reported positive findings overall. The literature indicates that simulations can be effective in developing content knowledge and process skills, as well as in promoting more complicated goals such as inquiry and conceptual change. Gains in student understanding and achievement have been reported in general science process skills and across specific subject areas, including physics, chemistry, biology, and Earth and space science (Kulik 2002).

Although conventional instructional materials such as textbooks present two-dimensional representations, simulations can offer three-dimensional manipulatives that bring the subject matter to life. Visualization results in the development of mental constructs that allow one to think about, describe, and explain objects, phenomena, and processes in a more true-to-life form. These are just the habits of mind scientists rely upon in their daily work. For example, after comparing simulated and hands-on dissection labs, Akpan and Andre (2000) concluded, "The flexibility of these kinds of environments makes learning right and wrong answers less important than learning to solve problems and make decisions. Simulations promote learning about what-ifs and possibilities, not about certainties" (p. 18).

Studies assessing the impact of simulations on process skill development, such as identifying variables, measuring, graphing, interpreting data, and designing experiments, have shown computer simulations to be equally as or more valuable

[1] The ExploreLearning site at the time of this writing offers a free 30-day trial period for the entire collection of science and mathematics simulations. In addition, individuals may use any simulation for five minutes a day at no charge.

than traditional methods. For example, a study by Geban, Askar, and Ozkan (1992) investigated the effects of a computer-simulated experiment on chemistry achievement and process skills. The researchers found greater student achievement with simulated labs than with hands-on labs.

A study by Mintz (1993) found that students were successful in designing, implementing, and analyzing the results of three ecological problems, noting improvement even as the inquiry tasks became increasingly complex. Students also began employing more formal analytical strategies, rather than relying on trial and error.

Trundle and Bell (2005) described students' conceptual understandings about lunar concepts before and after instruction with planetarium simulations. Results indicated that students learned more about moon shapes and sequences, as well as causes of moon phases, by using the computer simulations than by making actual nightly observations and studying nature alone. The ability to make many more observations using the program, the ease of making and testing predictions, and the consistency and accuracy of student measurements contributed to the dramatic improvements in student understanding.

The past 20 years of research indicates that students' misconceptions in science are prevalent and tenacious. Thus, the process of conceptual change is an ongoing challenge in science education. Computer simulations have demonstrated the potential to facilitate this process by highlighting students' misconceptions and presenting plausible scientific conceptions. For instance, using computerized interactive laboratory simulations, learners can confront their beliefs by working with real data, experiencing discrepant events preselected by the program, or forming and testing multiple hypotheses of their own (Gorsky and Finegold 1992; Tao and Gunstone 1999; Trundle and Bell 2005).

Overall, the research shows that interaction with computer simulations resulted in measurable achievement gains and indicates that simulations are equally, if not more, effective than traditional methods. Access to multiple representations of phenomena, the ability to manipulate the environment, ease of posing and testing multiple hypotheses, and ability to control variables are consistently cited in the research as contributing to the effectiveness of computer simulations. Other noted benefits to consider when comparing instructional approaches include cost and time efficiency, student enthusiasm, high engagement, and on-task behavior while working with simulations. Effectiveness, however, varies based on design features, support measures, and sequencing of simulation activities within the curriculum (Bayraktar 2002; Kulik 2002).

Guidelines for Best Practice

Effective uses of computer simulations in the science classroom are abundant and as varied as the teachers who use them. You might incorporate a simulation of cellular mitosis into a lecture to illustrate the new concept; a dissection simulation may serve as a precursor to a hands-on dissection lab; student pairs may build atoms of elements in the alkali metals family while deducing periodic trends; ChemBalancer (a program for balancing chemical equations, available at *http://funbasedlearning.com/chemistry/chembalancer/default.htm*) may serve as an interactive homework review. As teachers respond to increased access to digital technologies such as interactive whiteboards, more and more creative uses of simulations appear. However, students can benefit from simulations even with a basic classroom setup of a single teacher computer connected to a projector.

Remember that technologies like computer simulations are tools to support learning. As with any other educational tool, the effectiveness of computer simulations is limited by the ways in which they are used. Certainly, instructional strategies proven to support meaningful learning should be adhered to when using computer simulations or any other digital technologies. Students should be actively engaged in the acquisition of knowledge and encouraged to take responsibility for their own learning; content should be placed in the context of the real world and connected to their own lives. In order to maximize the potential of computer simulations to enhance meaningful science learning, we have proposed the following guidelines, representing a synthesis of the recommendations from science educators, researchers, and developers.

(1) Use computer simulations to supplement, not replace, other instructional modes. Computer simulations should be used in conjunction with hands-on labs and activities that also address the concepts targeted by the simulation. Indeed, one study has indicated that simulations used in isolation were ineffective (Hsu and Thomas 2002). When preceding a hands-on activity, a simulation may familiarize students with a concept under a focused environment.

For example, chemistry students might become familiar with titration virtually (using a titration simulator like the one created by Yue-Ling Wong at *www.wfu.edu/~ylwong/chem/titrationsimulator/index.html*) before doing a hands-on titration lab. When an interactive simulation is used as a follow-up, students can continue investigations of questions and manipulations of variables that would otherwise be impossible under the constraints of the lab equipment or class schedule. For example, after gaining a basic understanding of the Doppler effect through real-life examples, a Doppler simulation allows students to visualize the movement of sound waves and even develop an explanation of a sonic boom (see, for example, the Absorb Physics courseware site: *www.crocodile-clips.com/absorb/AP5/sample/040103.html*)

When planning for instruction using simulations, ask yourself: "How can this simulation be used to extend what I am doing in the classroom?" "What can I do with this simulation that I would not otherwise be able to do?" "Can using this simulation give me more time to spend on something else?" Integrating simulations into the curriculum also ensures that connections to domain knowledge and real-world applications are made explicit. As with any instructional technology, computer simulations should be chosen to meet your objectives and teach the content (Flick and Bell 2000).

(2) Keep instruction student centered.

By exposing complex concepts and abstract phenomena, computer simulations offer the opportunity to engage students in higher-level thinking and challenge them to struggle with new ideas. Lessons involving computer simulations should remain student-centered and inquiry-based to ensure that learning is focused on meaningful understandings, not rote memorization. Depending on your instructional objectives and classroom arrangement, the student groupings and computer setups will vary. You may choose to integrate simulations such as Stellarium (a free open-source virtual planetarium available at *www.stellarium.org*) into your lectures as a teacher-led demonstration, or students may work in a lab setting individually or in small groups with programs such as Net Frog (an interactive virtual dissection available at *http://curry.edschool.virginia.edu/go/frog*).

When simulations are teacher led, students should be actively engaged through questioning, prediction generation and testing, and conclusion drawing (Soderberg 2003). Connections made to their own lives make the learning more authentic and meaningful. Closure to the lesson is as important for simulated activities as for conventional activities; have students restate their understandings and consider real-world applications.

When students work with simulations individually or in small groups, discussion and collaboration among teachers and peers should be fostered. Regardless of the implementation you choose, students should be prompted to form and test their own hypotheses and justify their decisions. By encouraging reflection on their actions and decision-making, you can help expose student misconceptions, allowing for conceptual change and development. Students can then begin to monitor and take responsibility for their own learning.

(3) Point out the limitations of simulations.

By definition, simulations are simplified models of the real world. Although it is necessary for students to accept the simulated environment as an intelligible and plausible representation of reality, it is also critical that students realize the differences between the simulation and reality. Without understanding a model's limitations, students may form misconceptions. This distinction is particularly important when dealing with submicroscopic objects or invisible phenomena. For instance, it is important to stress that protons, neutrons, and electrons are not actually red, blue, and yellow as they may be depicted in a simulated model of the atom. Attention should also be given to scale and timeframe when they are altered for the sake of simplification. For instance, students should understand that, in reality, volcanoes take hundreds of years to form, not a matter of seconds (as it appears in simulations like the following on the PBS You Try It site: *www.pbs.org/wgbh/aso/tryit/tectonics*). A discussion of why scientists use models and the role they have in scientific inquiry would be a valuable component of any lesson involving simulations (Harrison and deJong 2005).

(4) Make content, not technology, the focus.

When it comes to computer simulations, the range of accessibility is as wide as the topics spanned. Although some simulations are extremely user friendly and self-explanatory, others require a good deal of time to become familiar with. If students are to be using them on their own, they must understand how the program operates. Otherwise, they may get bogged down with logistical issues rather than remaining focused on the educational objectives. To avoid this dilemma, you may choose to lead the class through the simulation as a demonstration, ensuring the type of student engagement described previously. Even when the program is designed for independent student use, be sure to familiarize your students with its features, discuss its limitations, model its use, and provide access to any additional domain knowledge and tools that might facilitate their work. This is particularly important when using highly open-ended simulations that do not provide support structures, such as tutorials, guided questions, or help menus. For example, begin by working through an initial problem as a class, allowing students to steer you through manipulations of parameters. Then, students can work through subsequent problems independently, with your scaffolding. Certainly the most effective type of support and means of providing it are dependent upon the ability and needs of your students and the specific learning goals.

Examples of Best Practice

Activities using four highly interactive simulations are described in this section: StarryNight and ExploreLearning simulations are commercial, and the Virtual Optics Bench and Atom Builder are available free online.

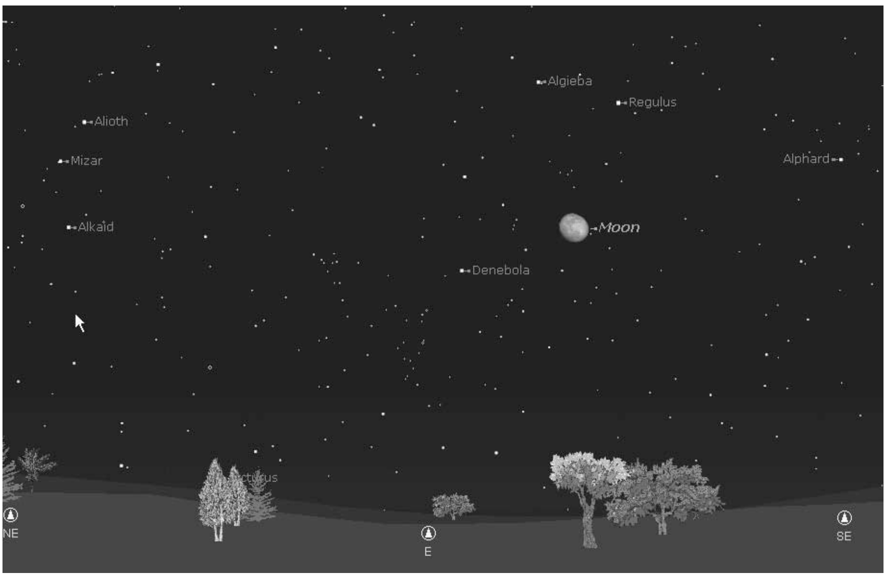
Virtual Planetarium Software

Teaching an astronomy unit over the course of a few weeks during daylight hours in a typical classroom setting is a formidable challenge. No wonder students have so many alternative conceptions! Virtual planetarium simulations offer one solution. They allow students to investigate astronomy from any perspective, from any place on Earth, at any point in time, under the ideal conditions of a controlled environment (i.e., no obstructions, clouds, or fog). For example, a commercial virtual planetarium program called StarryNight can be used in a class demonstration to answer the question "How do stars appear to move in the sky?" (Figure 1) Although it by no means replaces the experience of an evening field trip to view the stars, you can select your own location, current date, and time to keep the investigation authentic and meaningful to students.

Students can make preliminary predictions, then view and review the motion

Figure 1.

Screen capture from Starry Night virtual planetarium software



of the stars through the sky. You can engage students in conversation about their observations, having them generate additional questions and revise their predictions, then develop their own definition of circumpolar stars. By further investigating Polaris, Ursa Major, and the Big Dipper from the equator and the North Pole, for instance, students can notice differences in the apparent motion of the stars, depending on their viewpoint. Discuss with students possible explanations, leading students to understand that the apparent movement of the stars is due to the Earth's rotation. Then encourage students to make their own observations of the stars in the night sky from home and share their findings in class over the course of the next week. (Students should be made aware that distortions on the edges of the Moon and other planetary bodies result from attempting to represent a three-dimensional object on a two-dimensional computer screen.

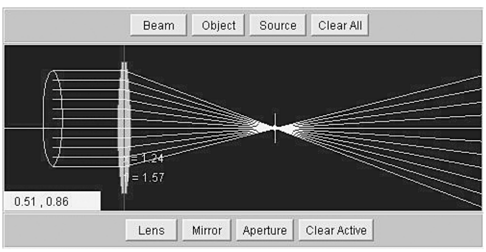
Virtual Optics Bench

Virtual Optics Bench is a java applet that takes instruction using ray diagrams to a new level. (This OpticsApplet is available free online at *http://webphysics.davidson.edu/Applets/optics4/default.html* or in a larger format at *www.hazelwood.k12.mo.us/~grichert/optics/intro.html*) You and your students have access to concave and convex lenses and mirrors, point light sources, culminated light sources, and objects for showing real and virtual images with the click of a mouse. In this dynamic environment, students are able to visualize and investigate the effects of changing parameters, such as the focal length of a lens or the location of a light source.

A lesson may begin with students experimenting with a variety of lenses, noticing differences in the appearance of an image when viewed through lenses of various curvatures (Figure 2). After introducing the term *focal length* as a description of how curved a lens is, pose the question, "What impact does focal length have on the position and size of the image formed?" Initial qualitative observations can be extended to a more in-depth quantitative analysis using the Virtual Optics Bench. Although doing so with the traditional approach of drawing ray diagrams is time-consuming and tedious for students, this inquiry investigation is easily accomplished with the computer simulation. Students can make and test their predictions using the Virtual Optics Bench.

Figure 2.

Screen capture from the Virtual Optics Bench.



Insert an object (shown as an arrow) and a convex lens on the workbench. Draw students' attention to how the lens refracts the light rays to form an image of the object. At this point, it is important to ensure students understand that the ray diagrams shown are only a simplification of reality and that light given off by an object actually extends infinitely in all directions. Drag the lens to change the focal length. The size and location of the object and image are measured by the program, allowing for both quantitative and qualitative analysis. The investigation can be easily extended to include concave lenses and mirrors. At the end of the unit, you may choose to include screen shots of the virtual workspace in your assessments.

ExploreLearning Mouse Breeding

Rarely do students have the opportunity to perform genetics experiments in the classroom, due to lack of time and resources. Using the interactive online Mouse Breeding simulation at *www.ExploreLearning.com*, students can perform virtual genetic experiments.[2] Students can use this simulation to explore questions like, "Can dark-haired

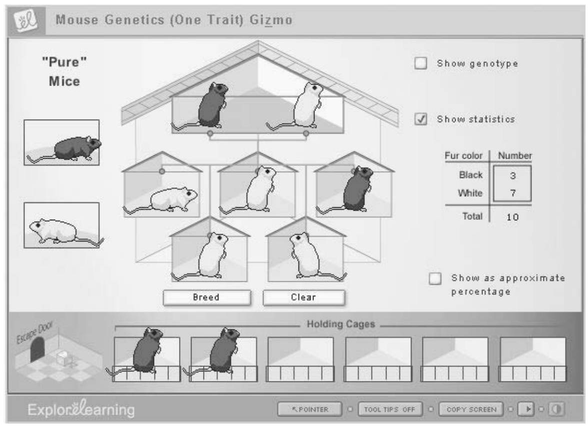
[2] This site requires a subscription for long-term use, but you may take advantage of the free 30-day trial period.

parents produce light-haired offspring?" The Mouse Breeding simulation is appropriate for students to use on their own in the computer lab, individually or in small groups. (You should provide guidance on how to operate the program's features and model a few preliminary crosses as a class demonstration.) Students should keep track of their results, including parent genotypes, Punnett squares, and phenotype ratios, in a lab notebook.

Students can breed various pairs of mice, making predictions first and then running simulated trials (Figure 3). Experiments might include pairing two black-fur mice, two white-fur mice, a purebred black-fur mouse with a purebred white-fur mouse, and two of the resulting hybrid mice. Students will discover that the recessive white fur trait returns, and you can discuss with them why the experimental outcomes do not always match those of the Punnett square and direct students back to the initial question.

Figure 3.

Screen capture from ExploreLearning Mouse Breeding gizmo.



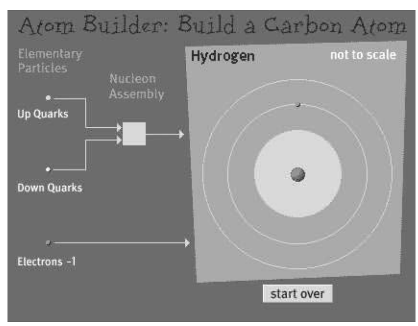
For a more detailed description of this activity, see the TeacherLink website (*www.teacherlink.org/content/science/instructional/activities/genetics/home.html*).

Atom Builder

Did you ever think you would be able to take your class inside an atom? Atom Builder, an interactive Bohr model (available free online at the PBS You Try It site: *www.pbs.org/wgbh/aso/tryit/atom/#*), challenges students to build neutral atoms out of elementary particles (Figure 4).

Figure 4.

Screen capture from Atom Builder simulation.



You might begin an activity by asking students what would need to be added in order to change a hydrogen atom into a helium atom. Raise questions such as, "What do you think will happen if three up quarks are put together in the Nucleon Assembly area?" or "Could an electron be placed in the outer energy level?" Encourage students to pose and test their own questions as the class builds other atoms. Throughout, students should explain their decisions, take notice of and reflect on the consequences. As an assessment, have students explain how an

MORE GOOD SIMULATIONS ON THE WEB

- **Learning Science:** A vast collection of animations, simulations, and web-based resources for all subject areas *(www.learningscience.org/index.htm)*
- **Visual Elements:** A visual representation of the Periodic Table *(www.chemsoc.org/viselements)*
- **Virtual Chemistry Lab:** A fully stocked virtual chemistry lab *(www.chemcollective.org/vlab/vlab.php)*
- **OhmZone:** A virtual circuit board *(www.article19.com/shockwave/oz.htm)*
- **Physics Education Technology:** A collection of interactive simulations of physical phenomena *(www.colorado.edu/physics/phet/web-pages/index.html)*
- **Cell Biology Animations:** A collection of animations for a variety of topics, from DNA replication to photosynthesis *(www.johnkyrk.com/index.html)*
- **Interactive Human Body:** An interactive exploration of the human organs, muscles, skeleton, and nervous systems *(www.bbc.co.uk/science/humanbody/body/interactives/3djigsaw_02/index.shtml?skeleton)*

atom changes from one element to another, what is the balance between protons and electrons, and what constitutes a stable atom. Students should also be able to compare the composition of neutrons and protons.

During the lesson closure, it is important to point out that the Bohr model has been replaced by a more complex quantum model of the atom. Your students may find it interesting to research how contributions of scientists like Werner Heisenberg, Louis de Broglie, Erwin Schrodinger, and Wolfgang Pauli working during the 1920s marked a profound shift in the way scientists thought about the atom.

Conclusion

Computer simulations have the potential to enhance the way you teach and your students learn. They allow you to bring even the most abstract concepts to life for your students and incorporate otherwise impossible or impractical experiences into your daily instruction. When used in conjunction with the guidelines presented here, your students will be engaged in inquiry, further develop their knowledge and conceptual understanding of the content, gain meaningful practice with scientific process skills, and confront their misconceptions. Additionally, they will gain scientific habits-of-mind (such as the ability to visualize, contemplate, and explain complex concepts and phenomena) that are both encouraged in the recent reform documents and necessary for future careers in science.