Computers in teaching science: To simulate or not to simulate?

Richard N. Steinberg

City College of New York

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Do computer simulations help students learn science? How can we tell? Are there negative implications of using simulations to teach students about real world phenomena? In this paper I describe my experience using a computer simulation on air resistance. In order to parse out the effects of using the computer simulation and of having an interactive learning environment, I compare two interactive learning environments. One includes the simulation and the other uses only a set of paper and pencil activities.

I. Introduction

Computers are used many ways in teaching science. Students use computers to acquire and display experimental data, to digitally analyze videotaped phenomena, and to mathematically model systems. Many studies have shown that students who go through active-engagement computer-based activities do better than students who go through traditional instruction.[1] However, using the computer in the classroom, even if the students are actively engaged, does not guarantee success.[2]

In this paper I consider computer simulations. Simulations make it possible to explore physical situations where conducting the real experiment is impractical or impossible. For example, students do mechanics "experiments" where friction or gravity can be adjusted.[3] Students "measure" what happens to a charged particle in an electric field.[4] Students "observe" particle motion in an ideal gas[5] so they can have a direct visualization of what happens to the atoms when temperature or density is varied.

However, when using computer simulations, instructors are asking their students to learn in a fundamentally different way than scientists originally learned the material. For example, when using a computer simulation of an ideal gas, the students are obviously *not* conducting a physical experiment. In fact, what they are watching is not directly observable in any lab. The series of experiments that have led to our detailed understanding of the particulate nature of gases is complex and highly inferential. Similar arguments can be made about simulations of frictionless motion or planetary motion.

The impact of using a computer simulation in a classroom obviously depends on the details of the program and the way in which it is implemented. In order to explore one particular example, I consider a computer simulation on air resistance that is implemented in an interactive classroom. I compare this environment with one that used interactive learning but did not use a simulation.

II. Research context and methods

The example described below is from first semester introductory-calculus based physics at the University of Maryland. Each week, the students meet in lecture three times ($N \approx 100$) and *tutorials* once ($N \approx 25$). The tutorials use the strategy[6] and much of the curricula[7] developed by Lillian C. McDermott and the Physics Education Group at the University of Washington. Students work interactively in groups of three or four on materials based on studies of how students learn physics. Teaching assistants serve as facilitators of discussion rather than as sources of information.

It is encouraging that we have found that interactive, physics education research-based curriculum and instructional strategies lead to better classroom results *when compared to traditional instruction*.[8] Here I consider three classes, all of which used tutorials – not standard recitations. However, two of the classes used many computer-based tutorials,[9] and the other used exclusively non-computer based activities.[7] The three classes are described in Table 1.

I used several different techniques to compare the two types of instruction. Before and after instruction, students took the Force Concept Inventory[10] and items from the Maryland Expectations Survey.[11] Students were given common examination questions. I made informal observations in both types of tutorial settings and talked to teaching assistants about what they saw in their sections.

Overall, differences between traditional and modified instruction described in references 1 and 8 were clearly much greater than differences between the

Table 1. The three classes in this study. Note that all students used the same book, had standard lectures three times each week, and had a tutorial once each week. For classes A and B, many of the tutorials were computer-based. In class C, none of the tutorials used the computer. These three classes ran the same semester.

	Number of students	Tutorial version
Class A	79	computer-based with air resistance simulation tutorial
Class B	67	computer-based with air resistance simulation tutorial
Class C	83	non computer-based with paper and pencil air resistance tutorial

two versions of tutorials. Below I contrast the two versions of instruction on air resistance.

III. A simulation on air resistance: Does it help?

Force and motion is obviously an important part of many introductory physics classes. One topic that is commonly included when studying force and motion is the behavior of objects moving under the influence of air resistance. In classes A, B, and C of Table 1, each instructor spent part of one lecture on the subject and assigned the same single textbook problem for homework.

A. *Pretest performance*

As part of the tutorial instructional strategy, all students take a *pretest*.[6] This is a qualitative un-graded quiz given prior to the tutorial but typically after the students have seen the material in lecture and homework. It is administered during the lecture period and takes about 10 minutes. The pretest is designed to have students articulate their own ideas prior to working with others in tutorial. Pretests also help instructors gauge what students are thinking coming into tutorial.

Students did the air resistance pretest after they finished covering kinematics and Newton’s laws. They had seen the air resistance lecture and finished the air resistance textbook homework several weeks earlier. A total of 199 students in the three classes took the pretest. Among other things, they were asked to qualitatively sketch position vs. time and velocity vs. time graphs for a projectile thrown straight upward without and then with air resistance. Student success rates in the three classes were very similar to each other.

More than 80% of the students gave a qualitatively correct position graph for motion without air resistance. For velocity, 56% sketched a reasonable graph for either velocity vs. time or speed vs. time. Many of the students incorrectly had non-linear features on their graphs, including ones similar to the position graph.

Students had a much more difficult time sketching graphs for the motion with air resistance. Fewer than 10% of the 159 students who answered this part of the pretest gave a qualitatively correct position graph. For velocity, only 3% of the students gave graphs that resembled a qualitatively correct sketch. In total, only 9% of the students drew graphs that had any kind of terminal velocity, even though they had already covered air resistance in lecture and the text. Some of the incorrect graphs did not account for air resistance at all, such as the one shown in Fig. 1a. Other graphs were like

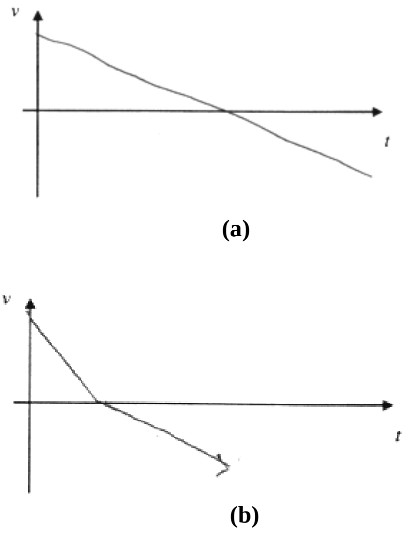


Figure 1. Sample incorrect student graphs from pretest. Students were plotting velocity vs. time for a ball tossed vertically in the presence of air resistance. After traditional instruction, fewer than 5% of the students drew a qualitatively correct graph. (a) Graph corresponding to no air resistance. (b) Graph corresponding to resistive force independent of velocity.

the one shown in Fig. 1b, which corresponds to a resistive force that is independent of velocity.

B. *Computer program*

The computer screen layout for a computer simulation on air resistance is shown in Fig. 2.[12] Students can vary the experimental parameters by typing in numbers. When the simulation is run, the computer calculates the motion, shows how the ball would move and simultaneously graphs position vs. time and velocity vs. time for the student.

C. *Two classroom lessons on air-resistance*

In week seven, all three classes described in Table 1 did a tutorial on air resistance. The entire tutorial was dedicated to the subject. The classes used either a tutorial with the computer simulation or a tutorial with just paper and pencil activities.

1. *An interactive lesson with a computer simulation*

At the University of Maryland, the Physics Education Research Group has developed a series of computer-based tutorials for introductory physics.[9] One of these tutorials is on the subject of air resistance.

The tutorial begins by having students consider the motion of a ball thrown vertically *without* air resistance. They draw free body diagrams of the ball at different points of the motion and make predictions about the shape of the position-time and the velocity-time graphs. They then run the computer simulation shown in Fig. 2 with air resistance set to zero. Students explore the computer generated graphs and compare them with their predictions.

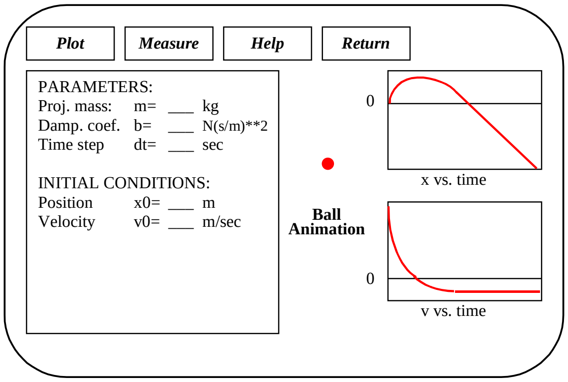


Figure 2. Computer screen layout for air resistance simulation. Students can vary the parameters and initial conditions and then watch the ball move as the graphs are created. This program was used as part of an interactive lesson on air resistance.

The students then consider the motion of a ball thrown vertically *with* air resistance. They discuss real world experiences with air resistance. Three different models of resistive force are presented to the students: proportional to v^2, proportional to v, and independent of v. Students then use the computer simulation with a resistive force proportional to v^2 enabled. Again they see the simulated motion and corresponding kinematic graphs. Comparisons are made with resistance-less motion and features such as terminal velocity are discussed by the students.

2. *An interactive lesson without a computer simulation*

The paper and pencil based air resistance tutorial goes through essentially the same material. Again students begin by considering motion without air resistance and drawing free body diagrams and kinematic graphs. However instead of running a computer simulation at this point, students are asked to compare accelerations of the ball at various parts of the motion. Since there is no simulation or experiment, students have to resolve their comparison by thinking of the graphs and free body diagrams that they have drawn.

As was the case in the computer-based tutorial, the students next consider the motion of a ball thrown vertically with air resistance. They again discuss real world experiences with air resistance and different models of resistive forces. Now instead of using the simulation, students make predictions for the kinematic graphs and draw free body diagrams at different parts of the motion. Students resolve their kinematic and dynamic explanations by using Newton’s second law. Terminal velocity is explicitly discussed.

D. *Classroom observations*

Classroom dynamics in both versions of tutorials are very different than traditional recitation classrooms. In most recitations, teaching assistants (TA’s) are in the front of the class and at the center of attention. In tutorials they are walking around from group to group giving guidance and feedback. Traditionally, students will listen to what the TA says with perhaps a few asking some questions. In tutorials, all groups of students are discussing, arguing, and doing physics whether or not the TA is present at the table.[9] This noisy, interactive environment was present in both versions of tutorials.

Most students running the computer simulation were engaged and diligent. They made predictions, ran the program and then tried to make sense of what the graph on the screen was telling them. Students in the sections where there was no computer were also engaged and diligent. However, since they had no means of “knowing” the answer, they relied more on figuring out whether their predictions about the graph were consistent with their free body diagrams.

In previous studies, David Hammer has contrasted two different approaches to learning physics.[13] He described how some students believe learning physics is a process of remembering and repeating without evaluation. Other students, and most scientists, believe that it is necessary to make sense of or recreate the ideas for oneself. While I was observing the two versions of the air resistance tutorial, there were times that the presence of the computer seemed to encourage the more authoritarian view of learning. Students would rely on receiving the answer from the computer without taking the opportunity to build the answers for themselves. For example, when trying to account for the difference in maximum height that a thrown ball reaches with and without air resistance (as seen on the computer screen), one student said the ball "goes to a shallower height because the graph doesn't go as high." In other words, it is true because the computer says it is true. However, this is circular reasoning. After all, the graph doesn't go as high because the ball goes to a shallower height.

There is a danger that with a computer simulation, students will see no need to take responsibility for their own understanding, to verify, or to challenge. Of course some students successfully turned to an instructor or fellow student for the answer creating the same dilemma in the paper and pencil version of the tutorial. Furthermore, many students used the air resistance simulation actively and productively resulting in the capacity to consider more complex problems than were possible without the computer. However, a computer simulation that quickly and transparently delivers exact answers can encourage students to learn science very passively.

E. Exam performance

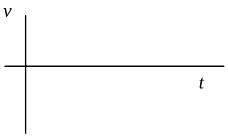
The second midterm for all three classes in Table 1 took place within 24 hours of each other and included the question shown in Fig. 3. The midterm was about two weeks after the air resistance tutorial. Results of how well students did in the three classes are shown in Fig. 4.

In part a, students graphed velocity vs. time for a sled moving under the influence of air resistance. This is similar to the pretest and tutorial, except that the sled starts from rest and moves horizontally instead of vertically. While fewer than 5% of the students answered the corresponding question on the pretest correctly, about two-thirds sketched a qualitatively correct graph for part a in each of the three sections.

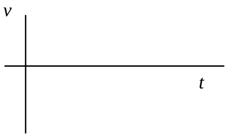
In part b, instead of air resistance, the sled experienced kinetic friction. Even though this is simply motion under a constant force, about half of the students sketched a graph that was not qualitatively correct. Apparently the presence of friction in this context confused many of the students. Some students explicitly tried to incorporate the effect of static friction at the beginning of the motion. Others (roughly 15%) had the sled approaching a terminal velocity at high speeds, as is the case when there is air resistance.

Two identical sleds are pulled with ropes with a constant force **F** to the right.

a. Sled A has a large sail opened but is traveling on slick ice so that **the effect of friction is negligible but air resistance is large.** Sled A starts from rest at t = 0. On the graph at right, sketch the velocity vs. time curve for the sled.



b. Sled B has its sail closed and travels on snow so that **the effect of friction with the ground is large but air resistance is negligible.** Sled B starts from rest at t = 0. On the graph at right, sketch the velocity vs. time curve for the sled.



c. For very small times, is the acceleration of sled A greater than, less than, or equal to the acceleration of sled B? **Explain your reasoning.**

d. For very large times, is the acceleration of sled A greater than, less than, or equal to the acceleration of sled B? **Explain your reasoning.**

e. Suppose F = 200 N and the mass of both sleds is 100 kg. In part B, $F_{air} = cv^2$ where c = 0.5 Ns^2/m^2. In part C, μ = 0.1. Find the acceleration of the sled A and sled B when v = 10 m/s.

Figure 3. Examination question on air resistance. This question was given to all three classes in Table 1.

Parts c and d are conceptual questions on air resistance. Student success rates for these two parts ranged from 43% to 70% in the three classes. In part e, students have to apply what they have learned to answer two quantitative problems on air resistance. About 75% of the students came up with correct answers.

Fig. 4 shows how the three lecture classes did on the exam compared to each other. While student performance was mixed, overall the students did reasonably well on the exam, especially when compared to the general performance on the pretest – which students completed *after* traditional instruction on air resistance. It is noteworthy that for each part of the exam, student performance in the three sections was not significantly different.

During a subsequent semester, there were two introductory calculus-based physics courses, one using each version of tutorials. These are identified as classes D and E in Fig. 5. The same question shown in Fig. 3. was included on the final exam for classes D and E. Overall, student success with the problem was nearly the same as shown in Fig. 4 even though the final was about 2 months after the tutorial. Examination of Figs. 4 and 5

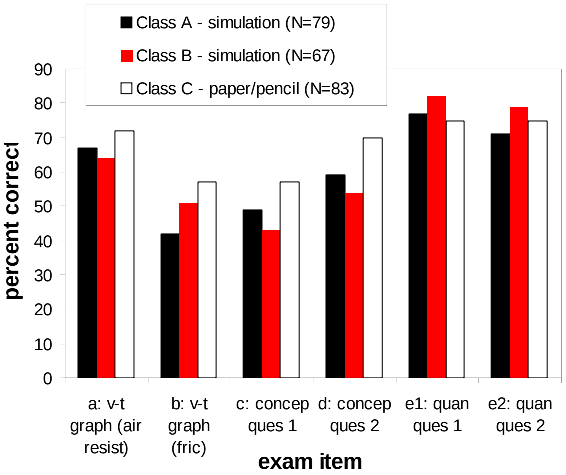


Figure 4. Percentage of students answering each part of the exam question in Fig. 3 correctly. Results are for classes A, B, and C. Exam question was administered on a midterm 2 weeks after the air resistance tutorial.

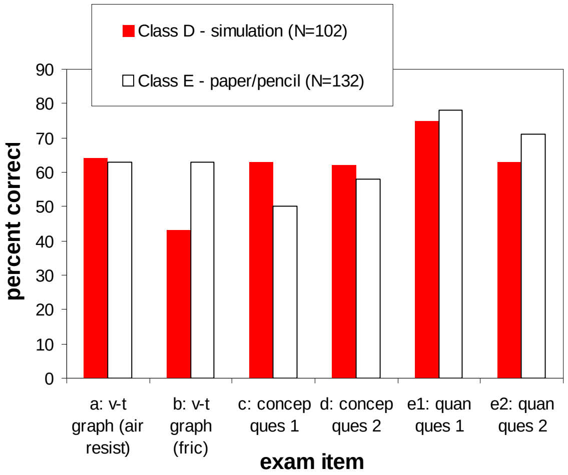


Figure 5. Percentage of students answering each part of the exam question in Fig. 3 correctly. Results are for two classes different than those listed in Table 1. Exam question was administered on a final 8 weeks after the air resistance tutorial.

suggests that the difference in performance of students from the two versions of the tutorials is very small.

IV. Simulations and understanding science

As was the case with many other implementations of active-engagement computer-based instructional materials,[1] an air resistance tutorial using a computer simulation seemed to result in reasonably good student understanding of the subject matter. However, material administered in the same spirit without a simulation yielded nearly identical results on a common exam question. This result suggests that the student success is not simply tied to the simulation.

Figs. 4 and 5 show student success rates on conceptual and quantitative problems. There are also other dimensions of student learning that are not so easily quantified with a histogram. For example, helping students understand what science is and what it means to do an experiment is also important. Obviously running a computer simulation is very different than doing a physical experiment.[14] I described how students interacted differently with the air resistance simulation than they did with the paper and pencil activities. Are we encouraging students to think that the process of doing science consists only of extracting the right answer from some all-knowing source? This would support a very narrow perspective of what it means to do science.

However, if we ignore the critical role of computers to current scientists and engineers we would be doing a great disservice to our students. For example, students should know that simulations make it possible to explore new domains, make predictions, design experiments and interpret results. Unfortunately, many simulations used in teaching introductory physics are just about demonstrating the end product of physics to the student. There is no opportunity for the student to use the computer as a tool while participating in the scientific process.[15]

Instructional computer simulations and other applications of the computer in the classroom will appropriately continue to be an integral part of teaching physics. As part of the process of improving classroom instruction, the physics education community will hopefully continue to try to make sense of what and how students learn.

V. Acknowledgments

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[1] For example, R. Beichner, L. Bernold, E. Burniston, P. Dail, R. Felder, J. Gastineau, M. Gjersten, and J. Risley, "Case study of the physics componenet of an integrated curriculum," *Phys. Ed. Res. Suppl. 1 to Am. J. Phys.* **67**, S16-S24 (1999); D.R. Sokoloff and R.K. Thornton, "Using interactive lecture demonstrations to create an active learning environment," *Phys. Teach.* **35**, 340-347 (1997); E.F. Redish, J.M. Saul, and R.N. Steinberg, "On the effectiveness of active-engagement microcomputer-based laboratories," *Am. J. Phys.* **65** 45-54 (1997); R.N. Steinberg, G.E. Oberem, and L.C. McDermott, "Development of a computer-based tutorial on the photoelectric effect," Am. J. Phys. **64**, 1370-1379 (1996).

[2] For a documented case, see K. Cummings, J. Marx, R. Thornton, and D. Kuhl, *Phys. Ed. Res. Suppl. 1 to Am. J. Phys.* **67**, S38-S44 (1999).

[3] *Interactive Physics* (Knowledge Revolution, San Mateo, CA).

[4] David Trowbridge and Bruce Sherwood, *EM Field* (Physics Academic Software, American Institute of Physics, College Park, MD).

[5] Edward F. Redish, Jack M. Wilson, and Ian D. Johnston, The M.U.P.P.E.T. Utilities, *AIRRES1* (Physics Academic Software, American Institute of Physics, College Park, MD).

[6] L. C. McDermott, P. S. Shaffer, and M. D. Somers, "Research as a guide for teaching introductory mechanics: An illustration in the context of the Atwood's machine," *Am. J. Phys.* **62**, 46-55 (1994).

[7] L.C. McDermott, P.S. Shaffer, and the Physics Education Group at the University of Washington, *Tutorials in introductory physics* (Prentice Hall, New York NY, 1998).

[8] In addition to ref. 1, see E.F. Redish and R.N. Steinberg, "Teaching physics: Figuring out what works," *Phys. Today* **52**(1), 24-30 (1999).

[9] Tutorials, videotapes of the classroom, and an overview of instructional strategies are available at http://www.physics.umd.edu/rgroups/ripe/perg/abp/abptutorials/.

[10] D. Hestenes, M. Wells, and G. Swackhammer, "Force concept inventory," *Phys. Teach.* **30**, 141-158 (1992).

[11] E.F. Redish, J.M. Saul, and R.N. Steinberg, "Student Expectations in introductory physics," *Am. J. Phys.* **66** 212-224 (1998).

[12] Edward F. Redish, Jack M. Wilson, and Ian D. Johnston, The M.U.P.P.E.T. Utilities, *THERMO* (Physics Academic Software, American Institute of Physics, College Park, MD).

[13] D. Hammer, "Epistemological beliefs in introductory physics," *Cognition and Instruction* **12**(2), 151-183 (1994); D. Hammer, "Two approaches to learning physics," *Phys. Teach.* **27**, 664-671 (1989).

[14] In a separate project, I have found that introductory students from a predominantly computer-based laboratory class have difficulties conducting and interpreting simple hands-on experiments on subject matter that they just studied.

[15] In a recent Reference Frame in *Physics Today* (July, 1999) James Langer, referring to current research in physics, notes the need to "think of numerical simulation not as an end in itself, but as a way to probe more deeply than ever before into what is happening inside complex systems."