




GAMES FOR SCIENCE AND ENGINEERING EDUCATION

Video games can teach science and engineering better than lectures. Are they a cure for a numbing 200-person class?

By MERRILEA J. MAYO

 **S**econd only to a weapon of mass destruction detonating in an American city, we can think of nothing more dangerous than a failure to manage properly science, technology, and education for the common good over the next quarter century.” This was the prescient conclusion of the 2001 *Hart-Rudman Report* (www.senate.gov/~govt-aff/032901_Excerpts.pdf), which gained much more visibility after September 11 of that year, owing to its accurate prediction that a terrorist attack would soon occur on the U.S. homeland. However, reports concerning U.S. difficulty cultivating science and engineering talent are plentiful, extending back at least 20 years and continuing to this day. Hart-Rudman perceived inadequate science and technology education as a critical weakness in U.S. national security. The 2006 *Gathering Storm* report [3] chronicled the same ills with an eye toward global economic competitiveness.

National Science Foundation data shows that in 2002 [9], the U.S. ranked 73 out of 91 countries surveyed in the fraction of its college students obtaining bachelor's

In the game Dimenxian, students locate creatures on a coordinate grid, then capture them to measure their height and weight to learn the secrets of the island and the story. (Tabula Digita Inc.'s DimensionM, www.dimensionM.com.)

degrees in the natural sciences and engineering; 17% of U.S. students chose to major in these fields, compared to 67% in Singapore, 52% in China, 41% in Korea, 38% in Taiwan, 35% in Iran, and 33% in Russia. In 2002–2003, China graduated 5.8 times as many engineering students as the U.S. [9]. China has also increased science and engineering Ph.D. graduates by a factor of seven in the past 10 years [9]. Nobel Laureate (chemistry) Rick Smalley estimated that by 2010, 90% of the world's Ph.D. scientists and engineers will be Asians living in Asia. The current U.S. stock of engineering Ph.D.s would not survive in any recognizable form without the 60% of each Ph.D. graduating class that comes from other countries to study in the U.S. [9]. Should this supply of talent decide better opportunities lie elsewhere in the global economy, the U.S. would have few natively educated citizens to fall back on.

Problems producing college-educated scientists and engineers begin in the nationwide K–12 school system. The 2003 Trends in International Mathematics and Science Study and Program for International Student Assessment tests found that U.S. fourth graders were 12th in the world in math, dropping to 14th by eighth grade and 24th by 12th grade. Science scores worsen every step of the way, with the U.S. ranking 22nd in the world by 12th grade (see nces.ed.gov/timss/Results03.asp and nces.ed.gov/surveys/pisa/PISA2003Highlights.asp). Thus only a portion of U.S. K–12 students are well-prepared for a college career in math, science, or engineering.

Even those with sound K–12 credentials and a willingness to pursue the craft face more hurdles. The study described in [10] found that about 50% of all self-declared engineering majors in a national sample of four-year institutions drop out. The data showed that this weeding out is not based on ability; the GPAs of those who leave are identical to those who stay. Instead, the study chronicled near-universal antipathy toward the first-year instructional experience, tending to discourage individuals from pursuing science and engineering. The narrow distinction between those who stay and those who leave comes down to an individual's willingness to tolerate it [10].

Almost all (98%) of those who leave engineering and 86% of those who stay cite “poor teaching by faculty” as a major concern [10]. The poor pedagogy to which they refer is essentially the lecture format characteristic of undergraduate science and engineering classes. Quantitative evidence that the lecture format is ill-suited to learning can be found in controlled peda-

gogical experiments in college classes using traditional lecture, active learning, and cooperative problem-solving formats. For example, the Force Concept Inventory (FCI) is a seasoned assessment tool used to evaluate learning in introductory physics classes in U.S. high schools, community colleges, and universities. The degree of learning obtained via a particular mode of instruction is quantified by the $\langle g \rangle$ score on the FCI, calculated as:

$$\langle g \rangle = (\text{posttest}\% - \text{pretest}\%)/(100\% - \text{pretest}\%).$$

When analyzed, the results of a 6,542-student meta-study involving 62 introductory physics classes across the U.S. at about 20 high schools, colleges, and universities showed conclusively that $\langle g \rangle$ is 0.23 ± 0.04 for courses taught in the conventional lecture mode; $\langle g \rangle = 0.48 \pm 0.14$ for courses in which students have at least some kind of “interactive engagement” [4]. What is surprising about this result is not that mass lectures are an intrinsically poor learning vehicle but that the quality of the lecturer matters not at all. Even a superb, highly entertaining lecturer appears to make little difference to the depth of understanding achieved by students.

It would appear that the primary advantage of the lecture format is not pedagogical but economical. Having one salaried teacher/professor instructing many students in parallel makes it possible to provide sophisticated technical education at an affordable price point. Needed is a medium that provides similar cost-effectiveness but with the ability to retain rather than alienate learners.

POTENTIAL ROLE

There is no silver bullet for curing the many ills of the U.S. science and engineering education system. But video games have the potential to address many systemic deficiencies for five reasons discussed here.

Massive reach. A typical immersive game on the Internet (such as *Dark Age of Camelot*, *Final Fantasy XI*, *Everquest*, and *Ultima Online*) typically involves more than 250,000 active subscribers. A free one (*America's Army*) or one that is especially popular (*World of Warcraft*) can attract more than five million paying, playing subscribers. The games need not be violent or feature swords and dragons to be compelling; witness the U.N.-created game *Food Force*, which aims to educate children on the challenges of food-aid distribution. It was downloaded 800,000 times on the day it was released in April 2005. In comparison, U.S. universities graduate about 400,000 bachelor's of science and engineering students a year, including about 60,000 in engineering [9]. The field of college-level

educational video games is too new to conclude that academically intense games would also have greater reach than a nation's-worth of lecture halls, but the medium itself is clearly scalable.

While video games are often stereotyped as appealing only to a 15-year-old male-dominated customer base, the female demographic is at least more broadly represented in video games than in many science and engineering fields. The Entertainment Software Association (www.theesa.com) estimates that in 2004, about 38% of computer and console game players were women. In comparison, the National Science Foundation found only 21% of graduating bachelor's-degree-holder engineers to be women [9]. Certain games (such as *The Sims*) and styles of games (free, downloadable, casual) have attracted a female demographic in the 60%–80% range.

Video games have achieved their massive reach without going through the education system. While they may be an ideal companion to classroom instruction, they do not have to go through the classroom to access students. Other educational reforms depend on the teacher/professor as the medium and do not necessarily take into account the many demands and constraints already faced by educators. Video games give teachers and parents the ability to reach students where they live, bypassing many of the challenges associated with restructuring the education system from the inside out.

Effective learning paradigms. Learning science has begun to isolate the kinds of instruction that lead to improved learning outcomes; some of these findings, with an indication of their application to video games, include:

Experiential learning (“If you do it, you learn it”). This mode of instruction is pervasive in the video game domain. Players must navigate game scenarios and make decisions with consequences;

Inquiry-based learning (“What happens when I do this?”). This well-regarded philosophy among science and math educators is also a natural mode for many video games in which free-form exploration, discovery, and experimentation are encouraged in pursuit of an overall goal;

Self-efficacy (“If you believe you can do it, you’ll try longer/harder, and you’ll succeed more often than you would otherwise”). In games, points, levels, or magic swords are awarded at positive decision points, encouraging players to keep going;

Goal setting (“You learn more if you are working toward a well-defined goal”). All games have goals, a key distinction between games and simulations;

Cooperation (team learning). Studies of classroom techniques show cooperative learning results in about a

50% improvement over either solo or competitive learning; see the meta-analysis of 122 studies in [5]. Some types of games (such as massive multiplayer online games) are intrinsically structured as a team effort toward a common goal;

Continuous feedback, tailored instruction, cognitive modeling. Tutor-type software (such as the Carnegie Mellon Algebra Tutor) can increase TIMSS scores by 30% (see www.carnegielearning.com/web_docs/CMU_research_results.pdf). Such an improvement, applied across all U.S. students, would put the U.S. at the top of international student science and math achievement. Three elements contribute to the success of Algebra Tutor: continuous feedback on performance; the ability to automatically adjust the learning experience based on learner response; and sophisticated cognitive modeling with respect to how to present, order, and emphasize the material to be learned. While Algebra Tutor is not a game, the first two elements of its success are found in almost all video games. It remains for video game developers to become expert in applying the third.

A more extensive description of these learning precepts can be found in [2].

Enhanced brain chemistry. A 1998 study [6] of brain chemistry during video game play found that playing video games stimulates substantial dopamine release. This finding is significant, inasmuch as dopamine is a chemical precursor to the memory storage event. Thus, it may be that video games are able to chemically “prime” the brain for learning. In this study, the brains of video game players showed a steady increase in dopamine levels during play, reaching about twice the amount of nonplayers. The gamer’s performance in the game increased linearly with the amount of dopamine present, achieving a factor of two improvement as well. This effect has not been tested for in educational games in which the key anticipated effect would not be the learning of a physical task but increased retention of game-presented educational material.

Time on task. The Entertainment Software Association’s 2005 survey of video game habits and demographics found the average gamer in the U.S. spends about 6.8 hours a week on video games (www.theesa.com/files/2005EssentialFacts.pdf). The 2004 *American Freshman: National Norms Survey* conducted by UCLA’s Higher Education Research Institute found that college-bound high school students spend five to eight hours per week on homework. Compelling video games that could also deliver educational content would double the time spent learning at

home. It is not just entertainment games that have this engaging effect. For example, a numerical methods course taught using a race-car game as the “homework” resulted in students spending roughly twice the time working on the course outside of class compared to other mechanical engineering courses. The professor of this undergraduate course, Brianno Collier of Northern Illinois University, notes that the time was spent willingly; about 80% of the students went on to take the advanced numerical methods course.

Learning outcomes data. There are perhaps only a handful of solid studies that rigorously measure the learning outcomes of immersive games compared to other teaching methods. Of them, few tackle science and engineering as subject matter. Moreover, to be fair, the games they describe are not multimillion-dollar commercial productions but modest titles pulled together by dedicated professors and their students. Nevertheless, the results are intriguing. In one study [11], a middle school class was divided into two groups. The first (the control group, 32 students) learned electrostatics through interactive lectures, experiments, observations, and teacher demonstrations. The second group (58 students), with the same teacher, mostly played an electrostatics game called *Supercharged* during class time while also receiving lectures and handouts. The 32 in the control group improved their understanding by 15% over their pre-test scores; those who played the game improved their understanding by 28%. Much more impressive was how the simulation contributed to girls’ achievement; among girls, the control group improved on their pre-test scores by only 5% and the game group by 23%. A disturbing conclusion is that, at least in this study, lectures alone did nothing for girls.

The gradation in learning outcomes between traditional lectures, Web-based experiences, and immersive games was captured in a 2001 study [8] that measured learning outcomes from a virtual-world-based geology game called *Geography Explorer* and a virtual-world-based biology game called *Virtual Cell*. The researchers then compared these outcomes against both Web-based presentation of the material and traditional classroom lectures. Lectures produced the lowest learning outcomes, as measured by a graded test. The Web-presented information increased these outcomes by a margin that ranged from not statistically significant (geology) to 13%–30% (cell biology). The games increased learning outcomes by 15%–40% (*Geography Explorer*) and 30%–63% (*Virtual Cell*), compared to the lecture format. These outcomes suggest it is not merely visual representation but active engagement that stimulates improved learning.

As a sign of things to come, the creators of a com-

mercially developed algebra game called *Dimenxian* in 2005 commissioned the Princeton Review, a test education and preparation company (www.princetonreview.com/home.asp), to evaluate the game’s learning effectiveness, in collaboration with the Harlem Children’s Zone and the Grid Lab at Ohio University in Athens, Ohio. In the study of 75 students (tabuladigita.com/ugroups.php?s2=2&s3=0), playing *Dimenxian* reportedly increased students’ algebra knowledge by one grade level (such as from B to A). Underachieving students increased their test scores by as many as three grade levels by playing the game.

The principles of science and engineering can be taught not only by playing games but by designing games. In Brianno Collier’s race car game/numerical methods course described earlier, students taking the game version of the course had to apply their numerical methods knowledge to programming virtual cars to navigate a virtual race track. In a parallel, non-game-playing version of the course, students instead performed textbook exercises throughout the semester. At the end of the year, Collier asked both sets of students to draw concept maps of what they had learned. Game design/playing and non-game-design/playing students were equally able to recall the major topics learned in class and the names of techniques within each topic. In other words, both groups could reproduce the equivalent of a table of contents in a numerical methods textbook. But for game designers, significant improvement was observed in the number of defining features they could ascribe to a main topic (0.494 vs. 0.145 features/topic, $p < 0.001$) and the number of connections they could make between techniques learned (0.82 vs. 0.02 connections/concept map, $p < 0.001$). The game design exercises did not change the breadth of the content learned but did significantly increase the depth and complexity of what was learned.

Beyond science and engineering games, further evidence suggests that games teach not only facts but detailed reasoning applicable to life’s many challenges. Several health-based games have had particularly impressive results. A six-month randomized controlled clinical trial of a diabetes-management game called *Packy and Marlon* found 77% fewer emergency and urgent-care follow-up visits for participating diabetic children (ages 8–16) than for the matched control group [7]. The game was designed by Click Health to teach children how to manage their diabetes through proper nutrition, self-monitoring, and insulin dosing.

Similarly impressive results were observed in a game

called Squire's Quest!, which was intended to help teach healthy eating strategies to fourth-grade children in Houston [1]. The game helped increase fruit and vegetable consumption among 1,578 elementary school students by about 30%, or one serving per day, over a five-week period. Both games taught complex reasoning skills and were structured so children could alternately practice the health-management skills in the game and in real life.

Massively parallel science and engineering education through video games is still in its infancy. The "serious games" community studying and developing nonentertainment video games is barely five years old. There are few available commercial products. Funding models developed for mega-blockbuster entertainment games (as much as \$100 million per title) must adjust dramatically for the much lower price tag that would be supported by professors and students (typically less than \$1 million); for example, Immune Attack, a game-based primer in immunology, was produced for well under \$1 million by the Federation of American Scientists (www.fas.org) (see Henry Kelly et al.'s article in this section). Distribution and marketing are immature: most product titles languish on the personal Web sites of their cottage-industry developers. Standards for the quality of gameplay and pedagogy are nonexistent. Cognitive modeling and assessment modules have yet to be incorporated into most games, rendering both the delivery of outcomes and their evaluation a haphazard proposition. For all the promise of the genre, the current deficiency of world-class academic games, outcomes data for the games, and community experience building them leaves much research for the future.

CONCLUSION

While the U.S. is arguably weak in producing trained scientists and engineers, video games have the potential to directly provide massive (and massively effective) parallel education in science and engineering for at least five reasons:

Scale. Sophisticated video games appeal to very large numbers of people; a single entertainment game can reach 10 times as many people than are graduated annually by the entire U.S. higher-education system in science and engineering;

Anytime. Students already play these games five to eight hours a day; they do it in their spare time, meaning that a video-game-based educational intervention need not go through the education system to be effective;

Compelling. In order to be as compelling as possible, video games are unintentionally being designed according to effective learning paradigms;

Brain chemistry. Video games stimulate chemical changes in the brain that promote learning; and *Better than a lecture.* Initial studies comparing video game teaching effectiveness to the classic lecture show positive improvements, typically 30% or more.

While they will never be a silver bullet for science and engineering education, video games have the potential to be, perhaps, a bronze bullet. But only by using game-based learning in our own educational initiatives, assessing and improving along the way, will we know whether U.S. national competitiveness can be restored through something as fun and engaging as playing a game. **C**

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