Game Development for Teaching Physics

G. Kortemeyer

Lyman Briggs College and Department of Physics and Astronomy, Michigan State University, East Lansing, MI 48825-1107, USA

kortemey@msu.edu

Abstract. The paper describes two computer games which we developed to teach abstract physics concepts: *A Slower Speed of Light*, designed to teach Special Relativity, and *Kirchhoff's Revenge*, designed to teach circuit laws. We report on experiences and research results using these games in physics lessons at college and high school level, user feedback, as well as information informally gathered from "Let's Play" videos on YouTube. Finally, we describe plans for future developments.

1. Introduction

Computer games and interactive virtual environments have been explored as a means of teaching physics ever since personal computers became widely available [1-4]; the traditionally close association of physics and computation likely fostered this early work. As a result, efforts within the physics community predated concepts of gamification of learning [5-7] and Serious Games [8]. While Serious Games are frequently associated with social change or behavioral goals, physics games are mostly associated with practicing or solidifying skills [9]. In addition to games, simulations such as Physlets [10] and PhETs [11] have been extensively and successfully used in physics teaching; again, the use of simulations is traditionally deeply engrained in physics practice.

We report on two games, *A Slower Speed of Light* and *Kirchhoff's Revenge*, which we designed to make abstract physics concepts accessible through computer visualization. In particular, *A Slower Speed of Light* brings Special Relativity to human scale by reducing the speed of light to everyday velocities, and *Kirchhoff's Revenge* enlarges microscopic charge carriers to human scale.

Many models for learning through games are based on the concept of motivation [12,13], where the assumption (or hope) is that players are self-motivated to play and learn as a "side-effect;" players voluntarily engage with the games outside of formal educational settings and play for enjoyment and entertainment [14,15]. These intrinsic motivators are contrasted to traditional lecture settings [16], where external motivators like grades oftentimes dominate. In contrast to these self-motivation models, our games *A Slower Speed of Light* and *Kirchhoff's Revenge* had initially been designed to support traditional learning scenarios including laboratory experiments and tutorial sessions, i.e., still operate as assignments within the framework of external motivators. It is unclear if models for learning through games transfer to settings where gameplay is an assigned activity, for example as an in-class activity or homework [17,18], but it has always been our hope that students derive some entertainment from playing these games.

Both games were developed using the versatile Unity 3D engine and have now been published: *Kirchhoff's Revenge* as an early release on the Steam gaming platform, and *A Slower Speed of Light* was self-published for free download. We report on experiences from both games, as well as plans for future developments.

2. Kirchhoff's Revenge

2.1. Concept

Kirchhoff's Revenge is a computer game designed to teach concepts of electrical current and potential in circuits. Around the United States, virtually all 400,000 undergraduate students taking introductory physics each year [19] will need to master these basics of electrical circuits. A common challenge in teaching these concepts is that charges are invisible; as a result, the concepts seem abstract, and students rarely develop a conceptual understanding of (or intuition about) current, potential, resistance, inductance, and capacitance. Students may be able to calculate the currents in complex circuits based on the formal Kirchhoff Rules [20,21], but all too frequently fail to make straightforward predictions even for simple circuits [22].

Virtual experimentation has shown promise in helping learners overcome challenges with these fundamental concepts [23]. In our game, circuit elements are macroscopic and transparent, so moving charges are visible; similar simulations with visibly moving charges have been shown to have higher learning gains than the manipulation of actual physical circuit elements [24,25] (and simulations are less cumbersome than for example physical glitter circuits [26]). Within our game, circuit elements can be picked up, carried around, rotated, and snapped into place within three-dimensional circuit constructions. Currents are determined at every time step, so players receive instant feedback.

Currently available circuit elements include wires, (ideal) batteries, light bulbs, voltmeters, ampere meters, and capacitors. Extremely high currents (for example in case of a short circuit) result in a smoking battery and eventually in an explosion that destroys the flawed circuit.

2.2. Gameplay

The gameplay is similar to games like *Portal*, where the player has to solve a number of puzzles to free themselves for the lair of their captor. In *Portal*, players have to solve puzzles using the fictional physics of directed "portals'" between locations in the game environment [27]. In *Kirchhoff's Revenge*, players have to solve circuit puzzles set up by a fictional Gustav Kirchhoff (the at least initially antagonistic Kirchhoff character is named after the German physicist who contributed to the fundamental understanding of electrical circuits).

The environment is a slightly anachronistic sprawling factory complex in the late 1800s with some Steampunk [28] style elements, Fig. 1 shows screenshots from the current implementation stage. Steampunk is a design fiction movement that coincides with the main character's time period, but imagines an alternative history where technology is driven by steam rather than electricity [29,30] – the visibly moving charges in macroscopic pipes invoke this concept.

At each level, the game has a central puzzle challenge, i.e., a particular task to accomplish with the available circuit elements, but also side rooms with teaching setups and informational blackboards that are designed to teach concepts. This particular style of first-person puzzle-solving mechanics has shown promise in cognitive activation [31]. A drone accompanies the player through the levels and delivers overhead imagery of the circuit setups to aid navigation and literally provide an overview of the setups.

The puzzles in *Kirchhoff's Revenge* are based on research into learners' understanding and conceptions of electrical current and potential [32.33] and research-based in-class tutorials [34]. The concept is different from simulations such as PhET [11] in that there is a storyline with explicit, research-based challenges, offering an immersive, first-person experience. PhETs are free experimentation tools, and the instructors would provide the challenges or worksheets; thus, PhETs are traditionally even more closely embedded into the lecture or laboratory settings.

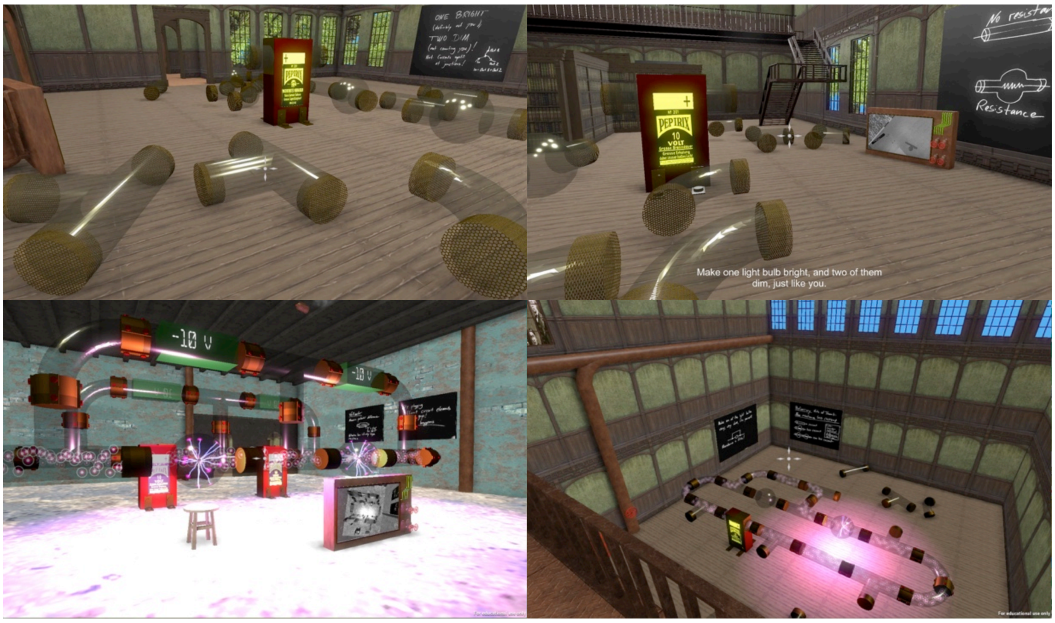

Figure 1. Screenshots from the game *Kirchhoff's Revenge*

Figure 2. High school students playing *Kirchhoff's Revenge* in a school computer lab.

2.3. User Experiences

A play-test was conducted with 200 students in lab sections of an undergraduate physics course. In addition, the game was tested with a 20-student high school course, also in a lab setting (Fig. 2). It takes players an average of about 10 minutes to complete a level, leading to 70 minutes total playtime at this stage for students. Written student comments from the high school class included:

- The puzzles were easy overall but had some harder parts that were explained with blackboards and other hints given in the game. I finished the game, and the final puzzle, while somewhat hard, was still solvable using some basics electronics ideas and some out-of-the-box thinking.
- The game was okay, it was kind of fun to go around and mess with the circuits.
- While I was bad moving around in the game (user error), I found it to be enjoyable. It was not only fun but very helpful allowing users to visualize what is happening in circuits. The commentary was funny, making learning about circuits even more enjoyable.
- I enjoyed the visual representation of what occurs inside of circuits, and being able to freely build a model to fit certain specifications was unique.
- I enjoyed the game and thought it was helpful in conceptualizing things we had learned about circuits in a fun way. I also enjoyed the feature that blew up the circuit if you overloaded it.
- I liked the freedom that the player has to explore and test without much repercussions.

There were also some unexpected challenges, for example students who had never or rarely played first-person video games:

- For a person who does not usually engage in video games I found the game very entertaining. When I first started playing, I found it very challenging to change the camera view and walk. After some searching I discovered I could change the walk speed and mouse sensibility, which made the game much simpler.
- I was dizzy because I don't play many video games.
- The game was fun […] It also gave me a headache and I had to take some motion sickness medicine because of the way the screen was moving.

In addition, the game was released in the Steam game store, which opens it up to a wider, informal player community. Comments in the community discussion section include:

- I like that this actually tries to teach you something about Kirchhoff's law albeit overly simplified.
- Looks like a great concept to be expanded on. I like that it's actually teaching as you go. […] Would like to see more added puzzles that not only open doors but actually make things react prior to exiting room. All in all it will make a fun game when expanded upon with more intricate puzzles added.

"Let's Play" gameplay videos started to appear on YouTube, which will offer additional windows and research avenues into player interactions with the game [35].

2.4. Outlook

Future levels of the game will include more levels with time-dependent circuits, where we will add inductors and AC voltage sources to for example be able to build RLC-oscillator circuits. The existing levels will need additional work, in particular with respect to voice acting and some of the visuals – it is hard to compete with the high-production value titles that students are used to. The drone will likely develop into a helper and conspirator to counteract the negativity of the Kirchhoff character. Finally, the current version is single-player, where the learner needs to individually (or in groups in front of one screen) assemble circuits. A future version of the game may be multi-player, so students can collaboratively solve puzzles.

3. A Slower Speed of Light

3.1. Concept

"What would you see if you were riding a beam of light?" – Einstein is reported to have asked this question at the age of 16 [36] only to find out a decade later that you can fundamentally never travel at that speed [37,38]. You can, however, travel near the speed of light, at least as a thought experiment, but what you would actually see was not correctly answered until yet another two decades later.

Efforts to intuitively visualize a relativistic world started in 1940 with George Gamow's whimsical "Mr. Tompkins in Wonderland" [39]. Mr. Tompkins is riding his bicycle through a city where the speed of light is lower (in fact only a little higher than the speed of a bicycle). Since all of Special Relativity scales with v/c, effects of Relativity thus become visible at everyday speeds. Unfortunately, Gamow apparently was not aware of the work of Lampa [40], who found in 1924 that due to the finite runtime of light, length contraction does not necessarily make objects look shorter: what you measure is not what you see (in educational context, Scherr later described these as ultimate reality versus visual reality [41]). Lampa's work remained virtually forgotten for another two decades, until Terrell [42] and Penrose [43] also took into account that light emitted at a farther distance actually comes further from the past. As a result, length contraction is not always visible as a contraction, and spheres always appear spherical (in fact, even cubes start to look spherical at high relative speeds). To get the full picture, two more effects need to be taken into account: Doppler Shift and Relativistic Aberration ("Searchlight Effect"), leading to "Red Shift" and the fact that more photons are directed at you from the direction into which you are traveling.

Four decades later, Weiskopf [44] laid the foundations for computer-generated visualizations of Special Relativity that took into account all of these effects. This work led to a number of computer-generated movies [45] including – in reference to Gamow – a bicycle ride through the German city of Tübingen. Savage et al. provided the first interactive first-person visualization of relativity as *Real Time Relativity* [46], which has been used for teaching purposes at the Australian National University and elsewhere [47]. The project does not slow down light but instead moves the viewer into space, where he or she travels fast. As opposed to the earlier movies, the movement of the first-person viewer is completely controllable. The *Real Time Relativity* engine, however, does not include third-party movement, i.e., nobody and nothing but the viewer moves. While this may appear like an arbitrary omission and unfounded restriction, it is in fact due to the significant challenges encountered when trying to trace the ``history'' of an object to find out when it would have emitted photons that are momentarily visible to the viewer. Doat et al. overcame this restriction: their virtual billiards game tracks the motion of a limited number of third-party objects. An advantage of this approach is that the same scenario can asynchronously be viewed from different frames-of-reference [48]. The current version of this billiards game, however, does not take into account Doppler and Searchlight effects.

Special Relativity is a physics topic for which it is challenging to develop intuition, and instructors need to be prepared to confront misconceptions and be strategic in refining intuition [41]. The hope with our game *A Slower Speed of Light* and other experiences that are based on its *OpenRelativity* engine is that through interactive visualization, students gain a "feel" for relativity, and that they over time develop an intuition about the effects. Our first-person relativity visualization engine includes simple third-party movement: third-party objects can be generated and destroyed at fixed points in the environment, as long as they are moving uniformly along a straight line in between (this restriction is due to the need to back-track photon emission locations along the lightcone).

3.2. Gameplay

The game takes place in a fictional village, where the player is supposedly a little spirit who has to get used to "being one with the light." The subsequent gameplay is based on a simple item-collection paradigm. Every time the player collects an "orb" (see Fig. 3), light slows down, and the game becomes more difficult as relativity effects become more pronounced. "Spirits" are moving about the village and need to be avoided. Once all orbs are collected, after a short time of free play, explanations are presented about what the player would have experienced; the game follows a "flipped" pedagogy.

Figure 3. Screenshot from *A Slower Speed of Light*

3.3. User Experiences

We were able to gather user experiences from "Let's Play" YouTube videos [35]. The 'flipped' pedagogy of first exposing the players to the scenario and only later offering explanations did not work as expected. Frequently players focused on only a few aspects of the game and came to wrong conclusions about others. Some players completely neglected or only rapidly clicked through the explanations instead of trying to reflect back on the experience.

The interplay of different effects makes it hard to identify particular cause-effect relationships, and it might have been helpful to drop players back into the environment with only select physics phenomena 'switched on' as they work through the explanations; while 'switching off' effects is unphysical at some level, a good argument can be made that otherwise color effects completely obscure Lorentz transformation and finite runtime effects [49]. While we had inserted a segment with color effects switched off at the end of the game, it was not effective, since the videos revealed that several of the players believed instead that they were now traveling at or above the speed of light.

Players frequently attributed 'bending' or 'warping' effects to the presence of large masses, thus invoking concepts of General Relativity. The game does not clarify the difference. Players expect to experience relativistic mass, an unhelpful concept that the game does not address. Players are fascinated by the idea of traveling faster than the speed of light, but the game offers no explanations or conceptual guidance. The title of the game, *A Slower Speed of Light*, may partly be triggering these musings. Closely connected to the idea of traveling faster than the speed of light is the idea of traveling back in time, which is not even mathematically the case [50]. This misconception is not addressed in the game; instead, it may be amplified by misunderstanding the finite runtime effects.

Many players were interested in why light is so unique, in particular connected to the concept of velocity addition. Commentators seemed very much interested in typical thought experiments involving moving light sources. The concept of relativistic velocity addition is not adequately conveyed by the game, while on the other hand, many viewers comment on it in the form of thought experiments of their own design. It was found that while players and viewers enthusiastically engage with the concepts of Special Relativity, the implicit goal of the game, namely making Special Relativity less 'paradoxical' and more intuitive, was not necessarily reached; instead, commentators frequently used the game as a jump-off point for musing about paradoxes and "infinities."

3.4. Outlook

Overall, the game appears to lacks explanations; future games may need to talk the player through the different effects that become apparent as part of the gameplay itself rather than as a separate explanation. An upcoming planetarium show that is based on the same engine, using 1905 Bern as environment, will combine immersive visualization with explanations and question/ answer opportunities [51].

4. Conclusions

We developed and tested two first-person educational games to improve the conceptual understanding of Special Relativity and direct current circuits. Analysis of these games showed both promise and shortcomings, and further iterations of the games will be developed to address the latter.

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