Game Development for Teaching Physics

G Kortemeyer
Michigan State University, East Lansing, MI 48825, USA
kortemey@msu.edu

Abstract: We describe two video games recently developed to teach physics concepts: “A Slower Speed of Light” was designed to teach aspects of Special Relativity, while “Kirchhoff’s Revenge” aims to teach circuit laws. Both are based on the Unity 3D platform, which allows rapid cross-platform development.

1. Introduction
Perhaps due to the fact that computers have a long tradition in physics research dating back to the earliest days of computing machines, video games and interactive game-like environments have been explored as a means of teaching physics ever since personal computers became widely available (see for example Bork [1], DiSessa [2], White [3], Zollmann [4], Savage et al. [5], Gordon and Gordon [6], and Rose et al. [7]). In addition to games, highly engaging simulations such as Physlets [8], PhETs [9], and ReleQuant [10] have been extensively and successfully used in physics teaching.

This paper describes two video games that we have developed in recent years to convey concepts of Special Relativity (A Slower Speed of Light) and circuit laws (Kirchhoff’s Revenge). Both games have in common that abstract physics concepts are made accessible in human-scale environments and first-person view. In A Slower Speed of Light [11], players encounter Special Relativity in an environment where the speed of light is lowered to everyday velocities, while in Kirchhoff’s Revenge [12], they encounter macroscopic circuit elements and charges.

2. Unity 3D
Most video games are programmed using so-called game engines, which are software frameworks that provide rendering, object management, and some basic “physics” and collision functionality. While this physics functionality itself has been used for physics teaching [13], in general it supports development. Some of these engines such as GameMaker [14] are mostly for educational purposes to learn about programming in general and game development in particular, while others such as the Unreal Engine [15] are definitely in the professional realm. The Unity 3D Engine [16] occupies a unique position at the intersection between the educational and professional usage. While on the one hand, it provides extensive tutorials, easily accessible programming languages (C# and JavaScript), and flexible licensing that allows free usage for purely educational purposes, on the other hand, it also enables the development of cross-platform high-end commercial games. As such, Unity 3D is the engine of choice for a large number of college programs in game development.

Several educational physics video games have been implemented using Unity 3D, for example Potential Penguin [17] and Quantum Moves [18]. Unity 3D has also been the platform used for the development of the games described here.
3. A Slower Speed of Light

"What would you see if you were riding a beam of light?" This thought experiment, which Einstein reports having “conducted” at the age of 16 [19], has no sensible answer: as he published a decade later, one can never reach the speed of light [20]. However, it does make sense to ask what an observer would see if he or she were traveling close to the speed of light, and one of the first physicists to embark on this effort was George Gamow in his whimsical Mr. Tompkins in Wonderland [21]. His protagonist is speeding on a bicycle through a city where the speed of light is lower than in reality. Gamow ingeniously takes advantage of the fact that Special Relativity scales with \( \sqrt{1 - v^2/c^2} \), and by slowing down light, effects become noticeable at everyday speed in everyday environments. He provides drawings of what Mr. Tompkins and people at the curb would see in this slow-light city, that is, what they would see if one only took into account two of the effects: Length Contraction and Time Dilation.

Gamow, unfortunately, neglected or was unaware of finite light runtime effects first identified by Lampa: what an observer would see is different from what he or she would measure [22]. It took almost two decades after Gamow before the topic would get picked up again, namely by Terrell [23] and Penrose [24], this time accounting for the fact that light which was emitted at a farther distance comes further from the past. As a result, Length Contraction is not always visible as a contraction, and interestingly, spheres always appear spherical. Also, two more effects need to be taken into account to get the full picture: Doppler Shift and Relativistic Aberration (“Searchlight Effect”), leading to phenomena like the familiar “red shift” and the fact that more photons hit observers from the direction into which they are traveling.

Illustrating all of these effects in concert requires more than the pencil and paper even of a Mr. Gamow: it takes a computer to get it right. Foundations for this visualization were laid four decades later by Weiskopf [25], which led to several computer-generated movies [26], including (inspired by Gamow) a bicycle ride through the German city of Tübingen [27]. Due to the high computation requirements, these renderings were not distributed in an interactive format.

Today’s students are quite used to operating in environments with randomly modified physics, for example, through Portal [28] or Quantum Conundrum [29], so it can be hoped that they would find their way through an environment in which the physics is altered correctly; while the visualizations in our games are “unphysical” in the sense that in reality physical constants are immutable, within our virtual environments, only the scales are changed. The first interactive first-person visualization of Relativity was provided by Savage et al. as Real Time Relativity [5]. The philosophy of this project is slightly different in that it does not slow down light, but moves players into space, where they travel fast. However, the movement of the first-person viewer is completely controllable, and different effects can be switched on and off to see their visual impact. The Real Time Relativity engine does not include third-party movement, which would pose significant challenges in tracing the “history” of an object to find out when it would have emitted photons that are momentarily visible to the viewer. Doat et al. [30] implemented such a history buffer in their virtual billiards game, which tracks the motion of a limited number of third-party objects in a virtual reality cave. An advantage of this approach is that the same scenario can be viewed asynchronously from different frames of reference. However, their current version of this billiards game does not take into account Doppler and Searchlight effects.

Our group released A Slower Speed of Light based on a new first-person relativity visualization engine called OpenRelativity [31], which we also developed. 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 limitation is due to the lack of a history buffer, which turned out to be too computationally and storage intense for immersive environments.

Our game presents a simple object collection mechanism, where the speed of light is slowed down every time a player collects such an object. Thus, the more objects the player collected, the more “relativistic” the environment becomes, and the more challenging it becomes to collect the next object; Figure 1 shows a screenshot, where the player is moving sideways. The game follows a “flipped” teaching philosophy, where the player is first confronted with the effects, and only after collecting all
objects receives an explanation of what just happened. The hope was to spark curiosity and better engage the player in subsequent explanations.

![Figure 1. A screenshot from A Slower Speed of Light.](image)

Recently, we analyzed YouTube gameplay videos and associated comments of *A Slower Speed of Light*, which yielded some insight into informal learning through this game [32]. Overall, the game sparked enthusiasm and extensive viewer discussions about the physics phenomena, but there were also shortcomings that should be addressed in future games based on *OpenRelativity*.

- The “flipped” pedagogy of first exposing the players to the scenario and only later offering explanations did not work as expected. Players did not recognize phenomena or know what to look for.
- The interplay of different effects makes it hard to identify particular cause-effect relationships. While it is cumbersome to separate effects, it might be helpful to drop players back into the environment with only selected physics phenomena “switched on” as they work through explanations. While “switching off” effects is unphysical, a good argument can be made that otherwise color effects completely obscure Lorentz Transformation and Finite Runtime Effects [33].
- 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 [34] that the game does not address.
- It is confusing to the player that infrared, ultraviolet, and darkness due to the Searchlight Effect all appear black on the screen. While physically correct, it does not allow the player to distinguish those effects.
- The alien landscape, while human-scale, may keep the player from experiencing the desired “everyday” immersion.
- Players and viewers 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 [35]. This misconception may be amplified by misunderstanding the Finite Runtime Effects.

The concept of Relativistic Velocity Addition is not effectively conveyed by the game, while on the other hand, many viewers comment on it.

We also implemented a planetarium show based on OpenRelativity, which provides a guided tour of Special Relativity while making use of the pixel-level full-dome capabilities of modern digital projection systems [36], see Figure 2. This environment allows the audience to see both in front of and behind a traveling observer and thus, for example, illustrate red- and blue-shift within one image.

![Figure 2. Full-dome planetarium rendering of an environment, based on OpenRelativity.](image)

4. Kirchhoff’s Revenge

Kirchhoff’s Revenge [12] is a computer game designed to teach concepts of electrical current and potential in circuits. In the United States, this topic is a staple in any second-semester physics course at high school and college. A commonly encountered problem is that charges are invisible and that students rarely develop a conceptual understanding of current, potential, resistance, inductance, and capacitance. They may be able to calculate the currents in complex circuits based on the formal Kirchhoff Rules, but fail to make straightforward predictions even for simple circuits [37].

In Kirchhoff’s Revenge, circuit elements are macroscopic and transparent, making moving charges visible. The environment is a slightly anachronistic sprawling factory complex in the late 1800s with some steampunk-style elements. Figure 3 shows some screenshots. The gameplay is similar to games like Portal [28], where players have to solve a series of puzzles to free themselves for the lair of their captor, in this case, a fictional Gustav Kirchhoff.
The puzzles in *Kirchhoff's Revenge* are based on research into learners' understanding and conceptions of electrical current and potential \([38,39]\). At each level, the game has the main challenge, but also side rooms with teaching setups and informational blackboards that are designed to teach concepts. The current proof-of-concept is single-player, and the learner needs to individually assemble circuits according to the challenges posed by the fictional Kirchhoff. A drone accompanies the player through the levels and delivers overhead imagery of the circuit setups.

Currently, only eight levels of the game are developed. The simulated circuit elements include DC batteries (ideal), wires, light bulbs (ohmic), and Volt and Ampere meters. Already modeled are capacitors and inductances with plans for time-dependent DC-RL and DC-RC circuits. Long-term plans include AC voltage sources, diodes, transistors, and an oscilloscope, so phenomena like RLC-resonance can be explored.

The game has been used in introductory physics courses as lab replacement for one session. Students worked individually or in small groups from a single first-person perspective. Students were generally able to solve all six levels in one class session, though surprisingly some students had not played first-person video games before. Working in groups appeared to be an effective way to also encourage peer-teaching.

Thus, independently, we are exploring a multiplayer version of the game, where players (represented as avatars) can collaborate on solutions to the puzzles. Figure 4 shows a mockup of this proposed functionality.

### 5. Conclusions

Game platforms like Unity 3D provide a straightforward way to implement immersive, interactive gameplay similar to what students are used to from recreational gaming. We find that gameplay can be highly engaging, but needs to be structured and include explanations in order to address learning goals.
6. References

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