# Designing a Computer Game to Teach Einstein's Theory of Relativity

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**Abstract**

*This paper describes an ongoing project to build a computer application that presents Einstein's Theory of Relativity in an interactive game environment. With the current interest in the use and study of how computer games can help teach and educate, so-called 'serious games', the resulting game is expected to have value for educators in communicating the concepts of Relativity to high school students as well as introducing the topic to a wider audience. The focus of this paper is on the initial design and building of an* Asteroids*-styled game and describes features of the physics, graphics and animations, and play mechanics. Directions for future development and studies are discussed.*

*Keywords*—**serious games, games to teach, physics, relativity, relativistic visualisation**

## 1 Introduction

Albert Einstein's Theory of Relativity [1] is one of the most important results of modern physics, and today part of everyday science and technology. Yet despite its significance, knowledge and understanding of the theory remains the domain of the trained physicist. While this lack of comprehension is undoubtedly due in part to the difficult mathematical formalisms and counterintuitive results, it is believed a lack of communication is also at fault.

In recent times computers have enabled researchers to simulate relativistic effects, including visual representations of how things would look in relativistic scenarios. In [11], Weiskopf et al contend that such simulations can assist in communicating the aspects of relativity to the layperson. Current leading-edge relativistic visualisations techniques include non-interactive image [12] and movie [9] generation, and more recently interactive techniques [11] [8]. To date however these have been purely visual simulations, and provide limited scope for demonstrating the other aspects of relativity such as time dilation and energy content of bodies.

In recent years there has been a lot of interest and attention on how computer games teach their players and convey knowledge [3]. Following work on relativistic visualisations, we postulate that presenting relativity in a computer game application could enhance learning and enable communication of a wider range of relativistic effects than possible with just visualisations. One of us (D.C.) has built an initial prototype relativistic game based on a classic game template. The design of the game and visualisations of relativity will be the focus of discussion in this paper; studies of the effectiveness of the game for its target application will be the subject of future publications.

## 2 Serious games

'Serious Games' is an emergent field in the computer games industry and education research area. Its focus is the study and development of methods for using games and game technologies to teach (in classrooms and for recreational learning) and building games whose purposes are not solely entertainment. Well-designed computer games are actually exceptionally good at teaching players how to play them, due to the way the game structure is used to present situated challenges and motivating goals [3]. The central question of Serious Games is whether and in what ways this can be harnessed to train learners in knowledge that is applicable to domain problems outside of the game.

### 2.1 Using games to teach physics

Many games incorporate physics in their gameplay. A physics simulation is often used to define the behaviour of objects in the game world, and can be the entire focus of the game, as in the case of simulation games. A detailed and believable level of physics simulation can be a way of drawing in players and creating more depth to the gameplay, by enabling players to apply their own play style to how they interact and solve problems in the game environment. Players can also learn the behaviour of a well-designed consistent physics simulation and learn to predict the outcomes of given actions.

In the case of the game presented in this paper, we are interested in the ways that a game can *teach* the player *about* physics principles. In this case, the goal is that the physical simulation of the game serve to illustrate how objects interact, and give players practise at anticipating and predicting outcomes, to build mental models of physics behaviours.

An interesting example of an educational physics game is *Supercharged!* [10], which teaches electromagnetism and how charged particles interact. The gameplay is built around the Maxwellian principles of electrostatics, which are quite different to the Newtonian physics traditional games. This we feel is similar to our game approach, which varies the 'normal' classical mechanics with relativistic principles, to produce a markedly different behaviour and gameplay style.

## 3 The Special Theory of Relativity

Einstein's Theory of Relativity [1] has two parts. This discussion will focus only on the part of the Theory known as Special Relativity, which is concerned with the invariance of the speed of light when measured by observers in relative motion, and named for the 'special' case of bodies moving without acceleration. According to special relativity, as a moving observer increases in speed, the speed at which that observer sees light travelling remains constant; however, its time slows down, its mass increases, and space contracts.

### 3.1 Results of special relativity

The description of an 'event' in space and time is given by the three space coordinates $x$, $y$ and $z$ and time value $t$. We consider a first coordinate system denoted $K$, and a second coordinate system $K^1$ which is axis-aligned with $K$ and travelling with a velocity $v$ along the $x$-direction of $K$, and ask: what are the values ($x^1$, $y^1$, $z^1$, $t^1$) of an event with respect to $K1$, when the magnitudes ($x$, $y$, $z$, $t$) of the same event with respect to $K$ are given? In order to preserve the second postulate, the relations that solve this problem are:

$$x^1 = (x - vt)\gamma$$

$$y^1 = y$$

$$z^1 = z$$

$$t^1 = (t - (\beta x)/c)\,\gamma$$

where

$$\beta = \frac{x}{c}$$

$$\gamma = \frac{1}{\sqrt{1-\beta^2}}$$

This system of equations is known as the "Lorentz transformation". From the Lorentz transformation equations we can describe the behaviour of measurements of lengths of space and time as follows:

Say we have a object with a known length at rest, $x_0$, and want to know its length as measured when travelling at speed $v$. Defining the length to be found as $x(v)$, then the relation between them is given by

$$x(v) = x_0\sqrt{1-\beta^2}$$

As $v$ approaches the speed of light $c$, so $x(v)$ will tend to be smaller than $x_0$—a contraction of space with increasing speed. Likewise if we have a measure of time $t_0$ in the rest frame, and want to know what corresponding amount of time $t(v)$ passes in the moving frame,

$$t(v) = \frac{t_0}{\sqrt{1-\beta^2}}$$

With increasing speed $v$, $t(v)$ will be a somewhat longer time than $t_0$, therefore time is dilated. Finally, for an object of mass $m_0$, the kinetic energy is no longer given by $mv^2/2$ but by

$$\frac{mc^2}{\sqrt{1-\beta^2}}$$

Which results in a somewhat larger value for the kinetic energy as velocity increases. If the energy content (given by $E = mc^2$) is taken to include kinetic energy, it is sometimes said that mass increases with increasing speed, which is described by the following equation:

$$m(v) = \frac{E}{c^2} = \frac{m_0}{\sqrt{1-\beta^2}}$$

### 3.2 'Relativistic mass' and relativistic F = ma

With this definition for 'relativistic mass' we can write a relativistic version of Newton's second law, $\mathbf{F} = m\mathbf{a}$, which relates the vectors force $\mathbf{F}$ and acceleration $\mathbf{a}$ by an object's mass $m$. Unlike in the Newtonian situation, where $m$ is a scalar and $\mathbf{F}$ and $\mathbf{a}$ are parallel, this is not always the case in the relativistic situation! To express this fact, we need to use matrix notation, where $\mathbf{v}$ is the velocity vector and $\beta = \frac{\mathbf{v}}{c}$. The acceleration is given by

$$\mathbf{a} = \frac{\mathbf{F} - (\mathbf{F}\cdot\beta)\beta}{m\gamma}$$

We see that in the general case the acceleration produced is not parallel to the direction of the force. We consider a "transverse mass" $m_t$, and a "longitudinal mass" $m_l$, which have the following magnitudes:

$$m_t = m\gamma$$

$$m_l = m\gamma^3$$

It is not hard to see that it's easier to accelerate a mass sideways to its motion, than it is to accelerate along the direction of its motion—that is, the relativistic mass has a directional dependence! This is one reason that the concept of a velocity-dependent mass is actually discouraged (see [4], [5]). With this in mind, the treatment in this paper will nevertheless be using 'relativistic mass' since it enables correspondence with the Newtonian equations to retained.

## 4 Relativistic visualisation

The story *Mr Tompkins in Wonderland* written by George Gamow [2] aims to introduce relativity in an accessible, illustrative way, using the exploration of a world where the speed of light is reduced to 30mph. This causes the effects of special relativity to become apparent in everyday activities, such as where Mr Tompkins observes Lorentz contraction of a passing bicyclist. While Gamow's writing is a novel presentation of relativity and treats the topic in an engaging and entertaining way, the illustrations and details of the story—assuming that what was *described* by relativity (such as Lorentz contraction) would also be *seen*—are unfortunately incorrect. In fact, when travelling at velocities that are a significant proportion of the speed of light, other effects dominate to cause changes to an object's apparent size, shape and colour. These are the subject of the scientific field of *relativistic visualisation* [7][12]. Space does not permit a full treatment of what would really be 'seen' by a relativistic observer in this paper—but it is important to make the distinction that the game being presented does *not* present a relativistic visualisation in the sense of what would be 'seen'. See [11] and [8] for examples and details of the implementation and application of current cutting-edge special and general relativistic visualisation techniques for research and teaching.

An important aspect of introducing interactivity to visualisations is the treatment of the accelerated observer. Since special relativity deals only with inertial frames of reference, it may seem that general relativity is required. However, from a result first presented in Rau et al in [6], accelerations can be treated by finding a co-moving inertial frame for the *instantaneous* velocity at each required moment in time.

### 4.1 'Slow light' concept

One difficulty with describing relativity is the immensely fast nature of the speed of light. In *Mr Tompkins* [2], introduces the concept of 'slow light', which has become a recurring theme in relativistic visualisations and is also used in our game. By assigning a value for the speed of light that is much slower, we are able to illustrate the effects of relativistic travel using familiar real-life scenarios, such as the street scene. Changing the speed of light acts like a scaling; it does not change the physics [7].

## 5 Design of the game

Our game design is a re-imagining of the classic *Asteroids* video arcade game incepted by Atari in 1979 (see http://en.wikipedia.org/wiki/Asteroids_(arcade_game) for general description). Here the main departure from the classic *Asteroids* game design is the inclusion of a relativistic physics engine. The game is implemented in C++ for Microsoft Windows operating systems and uses the Microsoft DirectX 9.0c API for graphics calls.

The original *Asteroids* is a two-dimensional game. The player controls a spaceship, maneuvering around the game screen which is populated with drifting 'asteroids'. The primary spaceship controls consist of thrust, left (counterclockwise) and right (clockwise) rotation, and a fire button. The objective of the game is to shoot and destroy the asteroids, which earns the player points, while avoiding collision with the fragments. When shot, each initial large asteroid splits into two medium-sized rocks, and each medium asteroid splits into two small ones.

The original *Asteroids* was a very popular video game in its time, and has been recreated in several official and unofficial versions. Many of these different versions add or change features of the original game, as does ours. After Squire et al [10] we take the approach of having the concepts we wish to communicate to learners ingrained in the game mechanic, so that learners will learn the concept to beat the game. *Asteroids* was chosen as a game template to develop with relativistic physics due to the gameplay being based around the interactions of inertial objects. The spaceship is treated as a free-moving inertial body; the application of thrust by the player applies a force upon the ship along the direction of its current facing (the effect of drag/friction or other retarding effects is negated here). By the equation relating force, mass and acceleration (detailed in section 3.2), the player ship in *Asteroids* was thought to be an ideal way of communicating the concept of 'relativistic mass', as its inertia and handling will change with speed as compared to the classical case.

### 5.1 Game mechanics

The game that has been developed is essentially *Asteroids* with dual physics simulation models (so-called physics 'engines'): one for describing the motions of objects under the laws of Classical mechanics, and the other with the laws of Relativistic mechanics. This results in different interpretations of the laws of inertia, and elastic collisions (implemented in the game but beyond the scope of discussion in this paper). Our game offers players a choice of game modes, so it can be played with the effects of one

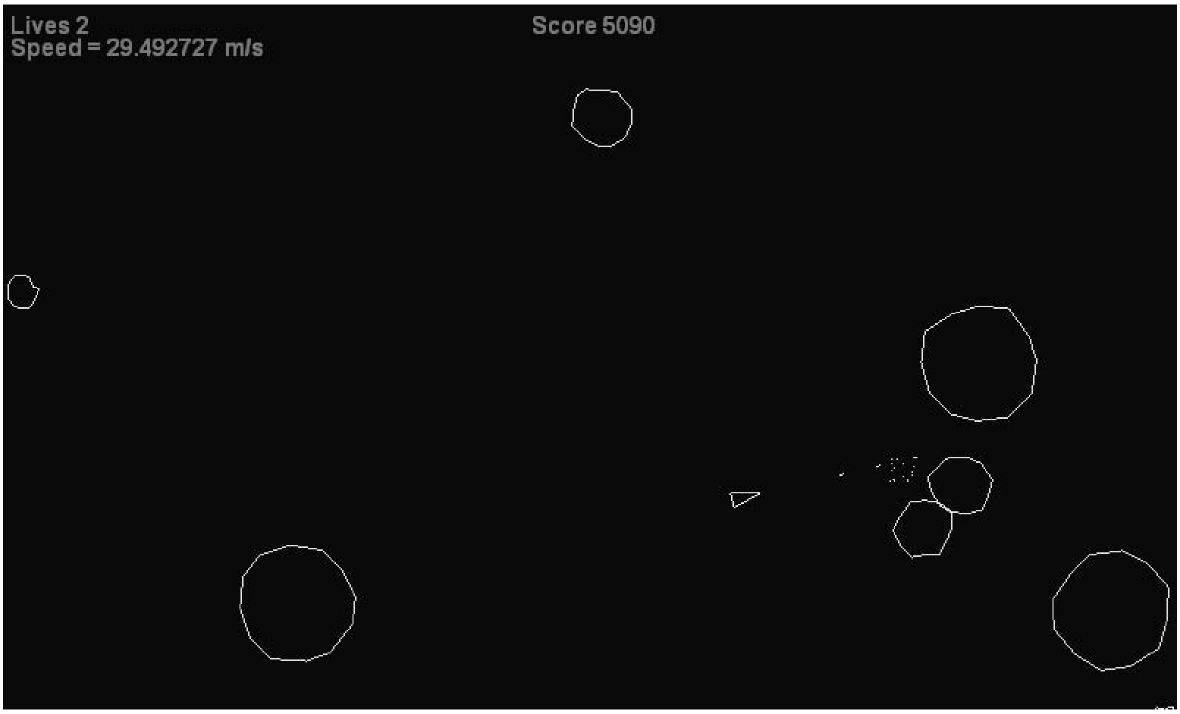


Figure 1: The game being played under the Classical mechanics model.

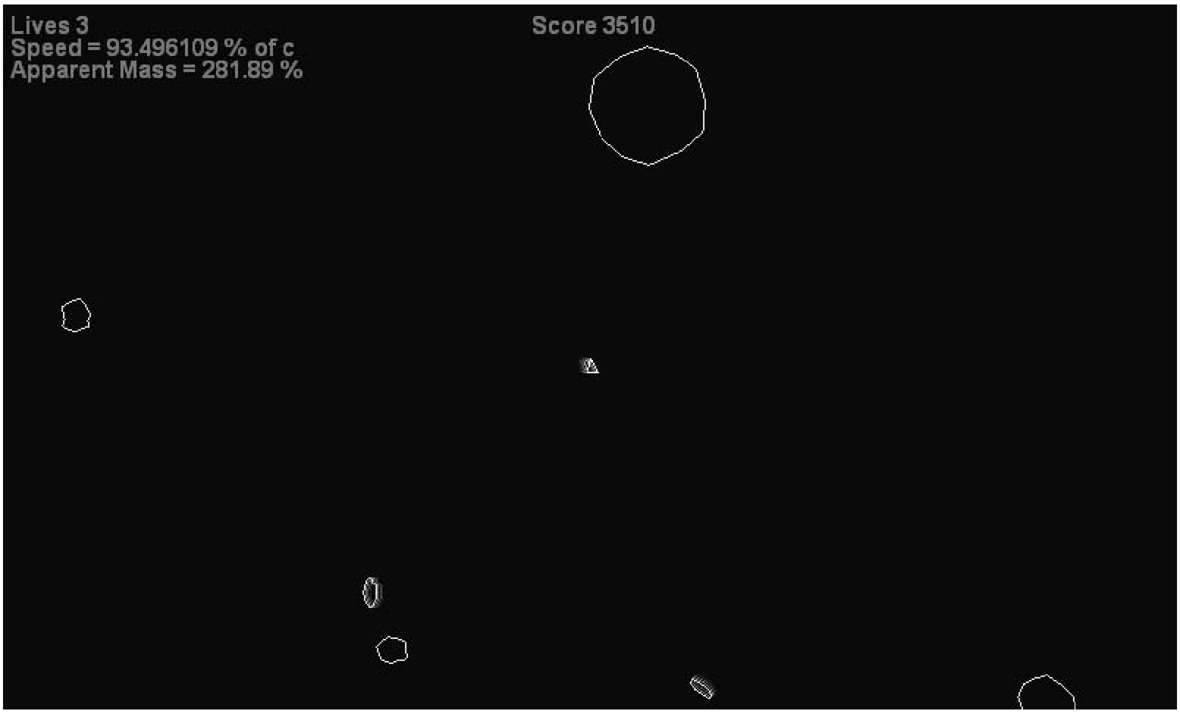


Figure 2: The game being played under the Relativistic mechanics model.

physics system and then the other, demonstrating and contrasting the differences in the behaviour of objects.

In the case of the Relativistic system, the concept of 'slow light' (described in the previous section) is utilised, so that game objects can be animated travelling at comprehendible rates on the screen and relativistic effects emphasised and exaggerated. We enable the speed of light to be set to differing values—most pertinently being a value that is easily attainable by the spaceship under Classical mechanics, so that relativistic effects enter into the game experience readily.

The primary effect and difference of playing under the Relativistic physics engine, is that objects increase in inertial mass with velocity. This affects the handling of the player spaceship avatar: as it becomes more massive with speed, it takes a greater effort by the player in order to effect direction changes. Also, consistent with special relativity, no object can attain or exceed the speed of light—it effectively becomes a 'speed limit' for all objects in the game. The Lorentz contraction of space for fast-moving objects is also present in the game. This results in objects shapes being distorted both visually (they appear shortened along their direction of travel), as well the interpretation of their boundaries for determining collisions.

### 5.2 Game graphics

For the purposes of visual representation, the game screen is treated as a static observer frame of reference. Therefore, game objects such as the player ship, asteroids and projectiles are in relative motion to the observer frame. Figures 1 and 2 show screenshots of a game in progress, being played under classical and relativistic mechanics respectively. Note the text readouts in the upper-left corner of the screen, which expresses the absolute velocity of the player spaceship when played under classical mechanics, and proportional velocities and mass in the relativistic case.

In the relativistic example, the Lorentz contraction of fast-moving objects is readily visible for objects travelling at speeds approaching the 'slow light' limit. (As previously discussed, this should not be viewed as a literal representation of a relativistic scene.) In addition, a 'trail' graphical effect has been implemented to help emphasise and give a visual cue to the object's proportional relativistic mass. Objects in motion have been programmed to leave a 'ghost trail' of afterimages in their wake; the length of the trail varies proportionately with the object's relativistic mass ratio. Thus, objects moving at a significant proportion of the speed of light are not only shown compressed along their direction of travel, but also with a trail effect intended as a visual device to give the player a sense of the increased inertia of the object. These effects are shown more clearly in the expanded Figure 3.

## 6 Discussion

In its current state, the game described offers a play experience based on the template of the classic *Asteroids*, with a twist of variant game modes that play to different models of physics. We feel that the presentation of the classical and relativistic models together in the game provide a clear illustration of some of the aspects of relativity and the ways that they differ from the classical physics. This project is ongoing to continue to develop and improve the game, and ultimately to test to what extent playing a game such as this can help learners to intuit relativistic principles by an evaluative study.

Proposed additions to the game mechanics to increase the pedagogical value of the game include:

- At present, the dilation of time described by relativity is not included in any demonstrative form. One way to incorporate this into the game would be by introducing a time-dependent object(s) to the game, such as a 'ticking time bomb' object.
- The game could be extended to incorporate switching of the observer frame of reference, to illustrate the role of the Lorentz transformation between inertial frames. The static observer frame could switch to a frame co-moving with the player's ship, and back; each different frame would present a different perspective of the graphical display of the game.
- Further exploration of the use of graphical cues to communicate game and object states is planned. The current relativistic mass 'trail' effect could be augmented or replaced with other graphical effects, such as expanding the object's outline, which might be more effective for communicating these notions.

In addition there are other improvements planned aimed at increasing the game's appeal. These include deploying more colourful graphics, creating more variety in game play and configurability, and the possible introduction of statistics tracking both for learning objectives and the entertainment value of 'best score', etc. Other game designs might also be explored, that focus on aspects of relativistic principles that the *Asteroids* template is less suited to (such as frame switching or prediction of elastic collisions as puzzle solutions).

In the longer-term it is also planned to merge the game mechanics techniques developed here with the 3D methods for 'true' relativistic visualisation. This will be a step to create interactive virtual worlds that not only look but behave according to relativistic principles, as well as provide potentials for future 'serious game' design projects.

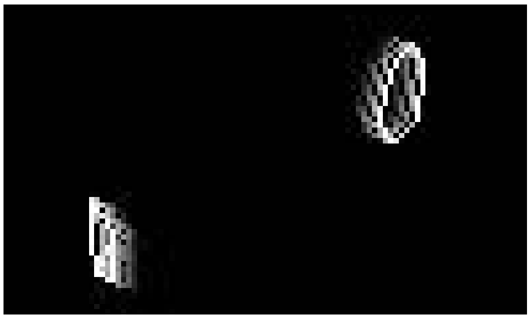

Figure 3: Expanded view of game objects exhibiting Lorentz contraction, and the 'trail' effect visual device.

## 7 Conclusion

In this paper we have briefly described some of the principles and results of Einstein's theory of relativity, and presented a computer game design that enables users to observe and play with these principles from special relativity. We take the approach of incorporating the physics principles into the game mechanics themselves, so that the learner interacts directly with the concepts and should develop an intuitive understanding of them by the experience of playing the game. The modification of a classic arcade game template is discussed, and the ways that a relativistic model of game physics gives strikingly different behaviour from the classical model are shown.

The building of the game presented is still an ongoing project and directions for future development have been given. Scientific evaluation of the game with learning cohorts is planned to measure its potential as a pedagogical tool for teaching relativity. These details and results will be the subject of future publications.


## Acknowledgements

This work is funded by a Charles Sturt University Postgraduate Research Studentship (CSUPRS) scholarship.


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