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Developing a virtual physics world

Margaret Wegener, Timothy J. McIntyre, Dominic McGrath
The University of Queensland

Craig M. Savage and Michael Williamson
The Australian National University

In this article, the successful implementation of a development cycle for a physics teaching package based on game-like virtual reality software is reported. The cycle involved several iterations of evaluating students' use of the package followed by instructional and software development. The evaluation used a variety of techniques, including ethnographic observation, surveys, student focus groups and conventional assessment. The teaching package included a laboratory manual, instructional support materials and the *Real Time Relativity* software that simulates a world obeying special relativistic physics. Although the iterative development cycle was time consuming and costly, it gave rise to substantial improvements in the software user interface and in the students' learning experience.

Introduction

The use of virtual worlds in the teaching of undergraduate physics offers appealing advantages over more conventional approaches (Dede, Salzman, Loftin & Sprague, 1999). Much of physics is visual, but phenomena are often presented as a collection of equations forming a simplified model of reality, and students - especially those with a weaker mathematical background - can struggle with this teaching style. A virtual world modelled according to the laws of physics provides immediate visual access to a variety of domains, including those beyond everyday experience, such as the very small (quantum physics), the very large (astrophysics and cosmology) and the very fast (special relativity). However, for such innovations to reach their full potential, the student must be able to become immersed in the virtual reality (VR) (Kontogeorgiou, Bellou & Mikropoulos, 2008), and not be excessively distracted by the technological interface (Yeo, Loss, Zadnik, Harrison & Treagust, 2004). Appropriate scaffolding of the students' exploration of the novel virtual environment must also be provided (Wieman & Perkins, 2006). Although all this is well established in the commercial gaming software community, it is less common in educational software development, largely due to substantially greater constraints on time and money. In this article, we present a case study of our development of software for teaching special relativity using VR. By doing so, we hope to provide guidance for others who are planning a similar approach, and to bolster the case for substantially greater investments in developing educational software, particularly that which makes use of VR technologies.

The learning of special relativity is a highly anticipated experience for many first-year physics students, but its teaching and learning are difficult tasks. Special relativity has apparently bizarre implications, and deals predominantly with situations outside everyday experience. Understanding relativity requires one to accept that there is less that is absolute than was once believed, and to accept a model of time and space that is strange and unfamiliar (Mermin, 2005). As such, modifying one's everyday understanding of mechanics to develop accurate constructs of the theory of relativity is extraordinarily difficult (Scherr, 2001; Scherr, Shaffer & Vokos, 2001, 2002). While special relativity is often featured in introductory physics courses, Scherr (2001) indicates that many students fail to develop fundamental concepts in the topic, even after advanced instruction. To address these issues, there have been various efforts to determine students' conceptual misunderstandings and develop activities to address them (see, for example, Mermin, 2005; Scherr, 2001). Since the logical and mathematical structure of relativity is straightforward, the dominant approach to its teaching and learning uses formal logic and mathematics to justify its counter-intuitive conclusions. This is appealing to some students, but leaves many others confused and unsatisfied. Clearly, an alternative approach could be advantageous.

Gamow (1965) pioneered visual representations of relativistic effects in the form of hand-drawn diagrams. With the advent of computers, Taylor (1989) was able to use wireframe graphics to show effects such as the distortion of three-dimensional (3D) objects, colour change due to the Doppler effect, and time dilation. A number of authors have developed more sophisticated computer representations, for example, *Physlets* (Belloni, Christian & Dancy, 2004), photorealistic images and animations (Weiskopf et al., 2005; Savage, 2005), and computer games (Carr, Bossomaier & Lodge, 2007; Carr & Bossomaier, 2011).

Our project, the representation of a complex relativistic world in real time, grew out of the rapidly evolving capabilities of personal computers. The processing power required to faithfully render a virtual world had become available, thanks to the rapid growth in graphics processing unit capabilities driven by the needs of the gaming community. *Real Time Relativity* (*RTR*) renders objects in a virtual world adjusted to factor in relativistic effects. This extends the passive approaches as portrayed in television programs and movies to an interactive, game-like environment very familiar to current students in Australasia. The user has real-time control of how he/she explores and tests the optical, spatial and temporal aspects of near-light-speed motion in a realistic virtual environment. This includes the ability to steer motion in any direction, to change speed and to look around in all directions.

The immersive experience of virtual worlds such as *Second Life* tends to be related to how they visually replicate the space and time of our world, and learning occurs via social interactions within that environment. With relativity, what students have to learn about is the physical surrounds themselves. The point of our virtual world is that it has aspects of space, time and light propagation noticeably different to our familiar physical environment and other virtual worlds. In designing our virtual world, we deliberately decided to avoid the high-tech VR accoutrements of helmets, gloves, CAVEs, etc, so that we could have an accessible product usable on almost any desktop or laptop computer. Computational requirements for personal computers mandated that the virtual environment be rendered by custom-developed software, and *RTR* versions for *Windows* and *Mac OS X* are now available for free online (http://www.realtimerelativity.org/). During 2011, the required processing power became available on mobile platforms such as smart phones and tablets, but *RTR* has not yet been ported to those platforms.

The present study made use of *RTR* to teach special relativity to first-year undergraduate students at two Australian universities, The Australian National University (ANU) and The University of Queensland (UQ). At each university, students worked in small groups in the laboratory (lab) with tutor support for up to three hours. We developed a teaching package, which, along with *RTR*, was evaluated after each implementation, leading to further refinement of both the teaching package and the software. The teaching package includes a lab manual with assessable tasks. The final product is presented in McGrath, Wegener, McIntyre, Savage and Williamson (2010), and items are available online from the project's website (http://www.anu.edu.au/Physics/vrproject/). The process involved in developing the virtual world and associated teaching materials is presented below. Detailed evaluation methods, and data, from specific points throughout the project have been published elsewhere (McGrath, Savage, Williamson, Wegener & McIntyre, 2008; McGrath et al., 2010; Savage, McGrath, McIntyre & Wegener, 2010; Savage, Searle & McCalman, 2007).

The *Real Time Relativity* environment

The user of *RTR* flies through a virtual world governed by relativistic physics. He/she controls a spaceship that can travel almost as fast as the speed of light. When its speed becomes significant compared with the speed of light, relativistic phenomena become apparent. The user selects from various scenarios designed to facilitate particular learning experiences. For example, a cityscape (see Figure 1) contains familiar types of objects to help the user to understand visual distortion due to relativity (aberration). A scenario with clocks on display (Figure 2) allows exploration of the temporal physics of the relativistic world (including time dilation and the relativity of simultaneity). An in-depth description of the virtual environment, and of the relevant physics, is given by Savage et al. (2007).

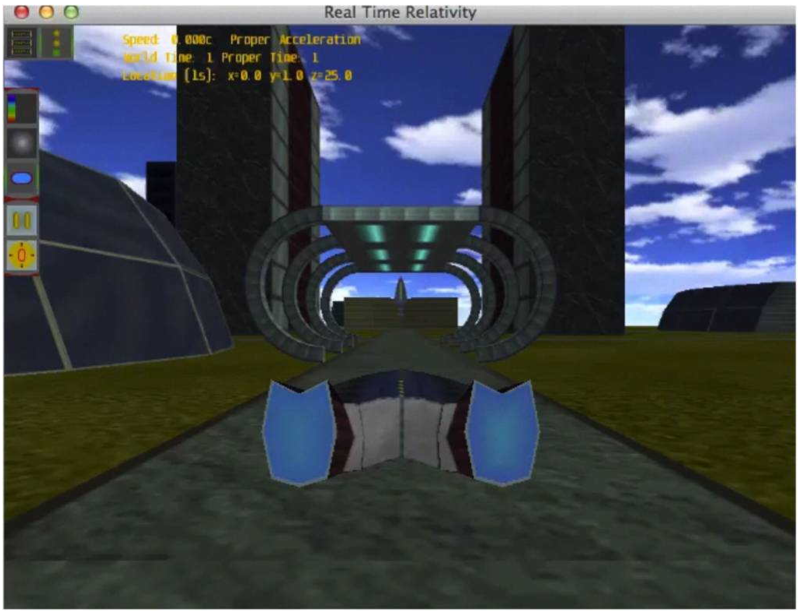
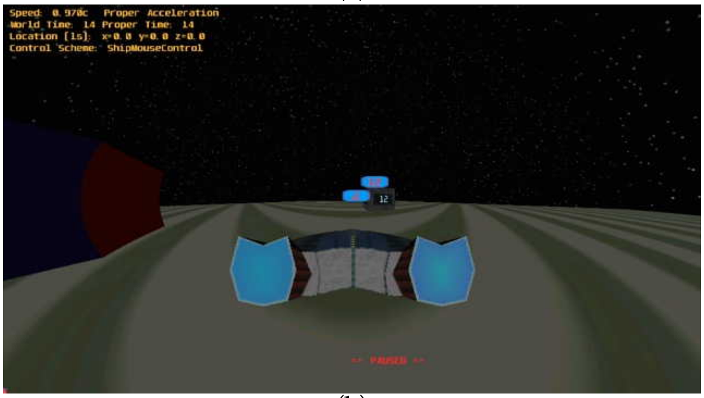


Figure 1: *RTR* screenshot showing a cityscape scenario

(a)



(b)

Figure 2: *RTR* screenshots showing scenes for which there is:
(a) no relative motion; and (b) relativistic motion

As an introduction to special relativity, *RTR* provides an immediate visual experience of how different the world appears when travelling at near-light speed. Students begin by familiarising themselves with the environment they can move around in, then increase speed and observe changes compared with what they viewed before. Figure 2 exemplifies this. When stationary, the spaceship can be observed above a striped landscape facing along the direction of two clocks - this is the 'conventional' nonrelativistic appearance of the objects. However, when in the same position but travelling at near the speed of light, optical distortion produces a scene that is drastically altered. Lines that appear straight in the conventional view now curve and are thinned, a cube that is behind the ship appears to the left, the stars become concentrated and the clocks shrink and move to the middle of the field of view.

A typical early activity in an *RTR* lab session is to start from rest and try to move at high speed towards some buildings. As the user increases speed, the buildings appear to move further away! This visual paradox occurs because relativistic aberration now has a greater effect than motion on visual perspective (relative sizes of objects, which the brain interprets as distance information). This situation captures students' attention. Their moment of confusion stimulates them to question what they are seeing, and motivates them to try to understand; a transformation in thinking then occurs. Students develop understanding by negotiating theoretical justifications for their observations, testing concepts, discussing in groups, with appropriate guidance from tutors. They explicitly connect their experience to theory. What makes this work for learning is the students' belief that what they see on the screen is a true representation of what they would actually see if the virtual world were real. By the end of the session, students design and carry out their own simple experiment to investigate specific relativistic phenomena.

Development and evaluation of the environment and teaching

Our aims with respect to this project were to explore the possibilities for student learning within a relativistic virtual environment, as well as to optimise the virtual environment, accompanying resources and activities to support appropriate learning outcomes for introductory physics. Our research was framed around three aspects of learning:

1. Conceptual understanding of relativity;
2. Attitudes to the topic and the simulation experience;
3. The learning process - how students learnt using the virtual world.

Throughout the project, we engaged in a cyclic process of development, implementation and evaluation, borrowing heavily from game development processes and action research. In our formal evaluation, we used a range of techniques, with the type used at a particular stage dependent on the relevant focus of inquiry at that stage. We collected a broad range of evidence, including personal and group reflection, student usage and performance data. Evaluation of the development process included peer review and regular meetings with a reference group.

An overview of the distinct stages of development of the virtual environment and its use in teaching is given in Table 1. Detailed discussions of each stage follow.

Student project

The *RTR* software was initially created as a student project at ANU. It demonstrated proof of concept for a special relativity virtual world on a standard home computer, and its educational utility (Savage et al., 2007). The possibility of learning special relativity in an innovative way, similar to how players of a computer game learn about the rules of the game's world while they are engaged in playing it, was recognised. The software was exhibited widely to physicists around Australia and internationally, thus undergoing expert peer review.

Initial trials

Teaching with *RTR* was trialled at the home institution of the originators (ANU), and then at UQ. Both ANU and UQ are research-intensive Australian universities; there are, however, differences in the student cohorts studying relativity, and in the amount of time devoted to the topic, at these institutions. Access to computers with the required programmable graphics card in teaching labs was, surprisingly, an issue for uptake.

Table 1: Development summary

Cycle	Development focus			Evaluation focus
	Software (mechanics)	Software (learner requirements)	Teaching package	
Student project pre-2007	Possibility of representing relativistic effects in real-time			Proof of concept
Initial trials 2007		Learning aims - target concepts/phenomena	Exploratory approach	Student response to simulation experience
Funding injection 2008	Redesign on basis of flexible graphics engine, extensibility	• Game/simulator-like implementation - user interface • Clarity of display meaning • Cognitive load	• Exploratory and quantitative approach • Complete rewrite of lab manual • Introductory familiarisation activity • Inclusion of student-designed experiment	Student perceptions, confidence; indicators of learning
Mid-term 2009	Capability to modify and build scenarios	• Multiple scenarios to target specific topics • Minimisation of non-productive confusion and effort	• Conceptual development vs quantitative verification • Minor rewrite of lab manual	Process of students interacting with simulation to learn; changes in conceptual understanding
Final product 2010	*Windows* and *Mac OS X* versions		Progression from guided to self-directed learning	Changes in conceptual understanding

Implementation in practical classes was a clear choice, as the exploratory approach, using and developing generic investigative skills, is aligned with the aims of laboratory learning. The learning aims for the theory of special relativity were also considered closely, so that what was included in the simulations dealt with the concepts considered to make up the canon for first-year university physics. The concepts of reference frames, time dilation, length contraction and the relativity of simultaneity have been repeatedly highlighted as core concepts for understanding special relativity (Mermin, 2005; Scherr et al., 2001, 2002; Taylor, 1989). Besides these standard concepts, *RTR* also displays other less commonly discussed phenomena, because it is a complete description of a world obeying the laws of relativistic physics. Student responses to the simulation learning experience were positive.

Funding injection

There are considerable challenges in further developing such a teaching approach. Detailed knowledge of technology and software capabilities is required, as is knowledge of approaches to teaching and assessment of outcomes; development of a complete package is likely to be beyond the capabilities of an individual. Through funding from the Australian Learning and Teaching Council (ALTC), a team was assembled that consisted of physics academics, a games programmer and an instructional designer. The group used a cyclic development process based on software development and action-learning models. This was undertaken over four semesters, with design, implementation, testing and analysis occurring each semester.

Throughout the development process, updates of virtual world software, teaching materials and evaluation tools were made available online (http://www.anu.edu.au/Physics/vrproject/), and since then have been adopted and used by other institutions, both nationally and internationally (Savage et al., 2010).

The starting point for this investigation was the prototype software together with teaching materials already used at ANU and UQ. The software underwent a rebuild, addressing a wishlist for greater ease of graphical implementation (stability, efficiency), better usability (GUI, more user-friendly interface) and sustainable future development (extensibility, cross-platform support), utilising the open-source *Object-Oriented Graphics Rendering Engine* (*OGRE* at http://www.ogre3d.org/). The teaching package was updated with guidelines for using the software provided, and students were required to complete a set of short-answer questions and calculations during the lab session.

Throughout the project, the design of the virtual world was adapted to optimise engagement and student inquiry (Adams et al., 2008a, 2008b) while minimising confusion and cognitive load (Paas, Tuovinen, Tabbers & Van Gerven, 2003) (specific examples are detailed below.) Students were observed in an extended form of iterative usability testing (Nielsen, 1993) examining the virtual world and learning activities as a combined system. The project used a multi-methods research approach (Schutz, Chambless & DeCuir, 2004), which included surveys, confidence logs, concept tests, observation, interviews and focus groups. The surveys gauged student satisfaction on various aspects, while the confidence logs and concept tests (before and after labs) measured learning gains. Classroom observation of students performing their labs was conducted by one of the authors (McGrath) who was otherwise not involved in the physics course, and focussed on noting evidence of substantive conversations, time taken for activities, and recurring issues and questions.

Students were informally interviewed to allow elaboration on responses and elicit explanations of observed behaviours. Informal interviews of lab tutors were also conducted. Student focus groups examined how learning with *RTR* worked within the course context, and supplied further feedback about the design. Data from previous semesters fed into analysis and design for the next phase in the simultaneous development of the *RTR* simulator and of the associated teaching package. This methodology of iterative cycles of development and evaluation was used to develop a successful final product of software, learning activities and guidelines for users. Table 2 summarises the teaching package activities for each stage (semester) during the project, while Table 3 outlines the specific evaluation aims, tools and outcomes in the various semesters.

The package was first trialled with a relatively small student cohort at UQ. The first *RTR* activity undertaken by students was exploration of the virtual environment. Students took, on average, 23 minutes to complete a familiarisation activity in which they developed competency with the user interface and an awareness of the virtual environment and basic effects of *RTR.* This was considered suitable within a standard three-hour lab session. Students were guided through a variety of activities to observe and validate various relativistic effects.

Table 2: Teaching implementation

Semester/ year	Content of activity	Assessment tasks	Comments
S1/2007	• Java applet and *RTR* simulations • Length contraction, time dilation, Doppler effect • Observe and explain	In-class short answers and calculations	Based on earlier UQ and ANU experiences
S2/2007	• Java applet and *RTR* • Time dilation, Doppler effect • Observe and explain	Pre-lab and in-class short answers and calculations	Introduced pre-lab questions, dropped length contraction (difficult to measure)
S1/2008	As above	As above	First year of ALTC funding
S2/2008	• *RTR* only • Observations of clocks, time delay, time dilation, aberration, distortion, length contraction, Doppler effect • Verify time dilation	As above	Laboratory notes rewritten
S1/2009	As above	As above	Activity completed by all students in class
S2/2009	• Time delay, time dilation, aberr-ation, length contraction, Doppler effect, alternate reference frames • Verify time dilation	As above	Minor rewrite of notes - more exploratory, less prescriptive

Table 3: Evaluation

Semester/ year	Aim(s)	Items	Observations
S2/2007	• Explore affective outcomes, both nominated and with respect to other experiments	• Likert perception questions (pre and post) • Open-response questions (post)	• Evidence that special relativity is seen as an abstract subject, and that the *RTR* lab activities are seen as more abstract than other lab activities • Students perceived having a poor understanding of special relativity before undertaking activities, and a better understanding after • Open-response statements identified some issues in the usability of *RTR*
S1/2008	• Explore affective outcomes, both nominated and with respect to physics in general, other experiments and other topics • Provide evidence as to where students encoun-ter difficulties, weight of each activity, what students do	• Likert perception questions (pre and post) • Open-response questions (post) • Observation and timing of students undertaking activities • Student focus groups • Student workbooks and exams	• Issues in the usability of *RTR* identified, including how students dealt with these issues • Timing provided indication of student focus and issues • Observational data indicated how students used the *RTR* interface, and what conversations arose • Focus group provided evidence of incorporation of *RTR* into course, and stories of different understanding between students who had and hadn't completed the lab

	• Longer-term considerations, broader course context • Look for indicators of impact on other activities within the course		
S2/2008	• Quantify student confidence with aspects of special relativity and identify specific aspects affected • Identify common misconceptions and identify changes in student conceptions	• Confidence intervals, concept questions and Likert perception questions (pre and post) • Open-response questions (post) • Observation and timing of students undertaking activities • Student focus groups	• Identified most areas as improved - explain special relativity to someone who isn't studying physics, solve problems with special relativity, identify changes to shape and colour - but no statistically significant change with regards to length contraction
S1/2009	• Identify changes in student understanding	• Concept log: a list of statements identifying concepts • Likert perception questions (pre and post) • Open-response questions (post)	• Indicated that *RTR* supports more correct concepts

At this stage in the development cycle, a pre-experiment survey was conducted in order to examine students' views on physics, lab experiments, special relativity and computing. A post-experiment survey explored students' views of their learning, concepts and experience of *RTR* and its use in comparison with other lab experiences. The surveys were developed from existing survey instruments exploring students' attitudes towards maths, physics and lab activities (Adams et al., 2006; Cretchley & Harman, 2001; Read & Kable, 2007). Before they were administered, they were analysed for validity through student focus groups and checked for internal consistency.

The survey results show that students find special relativity more abstract than other areas of physics (70% agree or strongly agree, N = 45), confirming the usefulness of the approach. Students demonstrated enthusiasm for the software, lab experience and subject matter. After using *RTR,* 72% of students indicated they would like to learn more about special relativity, 78% indicated they would like to use more simulations in their studies, and 90% claimed they enjoyed the experience, with only 2% of students surveyed claiming to not have enjoyed the experience. Students generally reported enjoying trying new things on a computer (86% agree or strongly agree), finding simulations to be an effective way to learn (79% agree or strongly agree), and feeling comfortable playing 3D computer games or using 3D simulations (80% agree or strongly agree). A combination of observation and survey data showed that age, gender and prior experience with computers (including VR and 3D gaming) had no significant correlation with students' judgments of their experiences in the lab.

Therefore, we have thorough evidence that we are not introducing an equity problem through a bias against anyone with a lack of confidence in computer use. The survey results confirm that our students do indeed have the characteristics of the audience in mind when the simulation was first conceptualised - the much talked of 'digital native' (Prensky, 2001, p. 1). The survey also shows that a simulation is acceptable to the students, given their expectations of what we do in lab classes.

Students' responses to open-ended questions told us about what they enjoyed about the lab experience as well as about what they believed they were learning. Their responses regarding the former (i.e. enjoyment) were classified into a number of categories, including simply highlighting the *RTR* simulation (31%), emphasising the visual nature of the experiment (52%), and highlighting the conceptual focus of the experiment (14%). For example, one student most enjoyed "thinking about why the effect occurred". As for student responses regarding learning, these showed that their perceptions of what was being learnt were in agreement with our learning aims. These responses were classified as emphasising either the whole of special relativity (31%), a particular aspect of relativity (e.g. length contraction or optical distortion) (48%), or a recognition of the significant difference of travel at near-light speed (21%). An example of a student response in the last category is: "Special relativity is crazy but cool".

Students reported benefits in understanding from undertaking the activities. As indicators of learning, the concept questions demonstrated improvement in some areas, but had a narrow focus and were time-consuming. In the case of the ANU students, who received more instruction (lectures) beforehand, the questions matched the course content too closely, so that students knew the answers before beginning. Hence the concept questions were later abandoned in favour of agreement or disagreement with concept statements on a Likert scale, with the goal of providing a broader and quicker insight into student understanding.

Students using this early version of *RTR* reported user input as the main area in need of improvement. Changes to the user interface that were driven by student feedback were:

- Being able to look around while motion is paused, to make observations easier;
- Offering multiple user-input control options (mouse and keyboard) to further improve the level of student engagement in using the simulation;

and most significantly,

- Switching from a first-person perspective to a third-person viewpoint, with the screen view orbiting a visible ship, to address observed confusion in controlling the view and/or spaceship.

Furthermore, the initial introductory open activity suggested in the lab notes gave rise to unexpected difficulties for students. Students were required to make observations of the visual changes between being stationary and moving at near-light speed with reference to the world of *RTR*. They were overwhelmed by the co-existing effects, and generally could not match specific observations to their constructs of special relativity. 80% of the student groups who were formally observed (N = 20) required tutor assistance to identify the desired phenomena. Mermin (2005) recognises the importance of quickly conveying to students just how strange the effects of movement at high speeds are, as an essential step before students can accept and internalise the concepts of special relativity. To achieve this, and to control cognitive load (Yeo et al., 2004), options were introduced to:

- Toggle the Doppler effect and the headlight effect on or off to avoid obscuring other effects;
- Set the speed of light as infinite (physically unrealistic), effectively enabling a non-relativistic environment, to allow the user to become accustomed to the navigation controls and the virtual world.

Mid-term

In the next round, feedback focussed on more subtle aspects of interacting with the simulation, particularly with respect to information required for assessment tasks. To address these issues, a small level of unrealism was introduced:

- Effects (e.g. the appearance of a clock) and information (e.g. time) must both be visible, so an addition was made to the display to allow the time told by a visually distorted clock to be used.
- In order to gather evidence for their lab reports, many students spent significant time trying to position their ship and rotate their viewpoint for a good screenshot. The awkwardness of these small adjustments led to the addition of a 'ship adjust' control, only enabled when the simulation is paused to make it clearer that it is a fictional device.

Surveys and observations also highlighted the expectations of students as a result of their experiences with other simulation and gaming environments and media tools. Steps were taken to make aspects of the design of the virtual world consistent with those environments and tools so as to align with students' expectations:

- Some students were obviously used to playing flight simulators, where the player pitches downwards by pushing away from him/herself, and vice versa; an option was added so that they could control *RTR* in this way.
- We initially adopted an idiosyncratic convention for toggling between the play and pause modes using an on-screen button. We displayed a 'play' icon (right-pointing triangle) while the game was playing, and a 'pause' icon (two parallel vertical lines) while it was paused. This reversed the usual convention that was familiar to most students from media players such as *iTunes* and *Windows Media Player*. Students found this confusing, and so we switched to the standard convention instead.

Students had difficulties identifying the scale of the *RTR* environment, which was confounded by the reuse of an object in the simulation. One 'Earth' was scaled appropriately, but on the simulation's astronomical scale was so small as to be hard to notice. A second 'Earth' was included as a familiar object to observe distorting effects, but was depicted significantly larger. This scale confusion hindered students' recognition of light delay, so separate scenarios were created to avoid it. This was made possible by adding functionality to *RTR* to modify and build environments, enabling us to design specific experiences targeted to discovery of particular concepts.

Observations revealed that every student group spent time engaged in substantive conversation, as described by Newmann and Wehlage (1993), about the theories and representations of special relativity. For example, students were asked to design and implement a verification experiment within the simulation, and when they were doing this, they were confronted with a pair of clocks with a time difference that changed depending on the location of the observer. Students engaged in negotiation and testing of ideas, using the capability to observe clocks from various locations in time and space. Some student groups required tutor guidance, and significant time and effort; however, all students eventually developed working concepts of the effects of light delay that they then applied to verifying time dilation.

Final product

In refinement of the learning activities, the instructions were changed to have more focus on conceptual development and less emphasis on quantitative verification of formulas. In its final form, a number of individual scenarios within the simulation help achieve a balance between directed activities and open-ended exploration. The revised experiments progress from guided to open activities. Diminishing levels of scaffolding are provided to initially engage and support students in interpreting the world of *RTR*, at the same time challenging them to make significant cognitive steps as they explore and observe effects of special relativity. This supports students' development of understanding of the overlapping effects while leveraging the benefits of the open experimentation that *RTR* affords. The successful time dilation verification experiment was retained. Students were encouraged to consider the accuracy of their measurements, and to critique their experiments.

Outcomes

We have obtained evidence that the *RTR* software and associated learning activities and resources improved with each development iteration, from semester to semester. Figure 3 shows a decreasing trend in the number of suggestions for improvement received in each successive semester. We interpreted this as pointing to a progressive increase in the quality and effectiveness of the teaching package, both in terms of its individual elements and as a whole. The *RTR* interface issues, in particular, had almost disappeared by the end of the last semester. Requests regarding the support materials decreased, although there will always be students who want more guidance and more detail. Consistently, there were small numbers of requests for changes relating to the teaching environment, such as the time allowed and the number of tutors on hand to provide assistance.

Students view the use of *RTR* as a positive learning experience. In general, after having used it, they see relativity as less abstract, are more confident in dealing with the topic, and improve their performance on tests. They believe that they have learnt, and results from our concept tests and from formal examinations show that they indeed have - an optimistic sign that *RTR* can improve students' perceived as well as actual understanding of relativity. The learning outcomes, and how they were measured, are discussed in detail in McGrath et al. (2010) and Savage et al. (2010).

Survey-based self-assessments (the instruments for which are available online at http://www.anu.edu.au/Physics/vrproject/) signified improved student confidence in their understanding each semester; one example is shown in Figure 4. While change in confidence does not directly imply a growth in understanding or learning, it is another indicator of students changing through the experience.

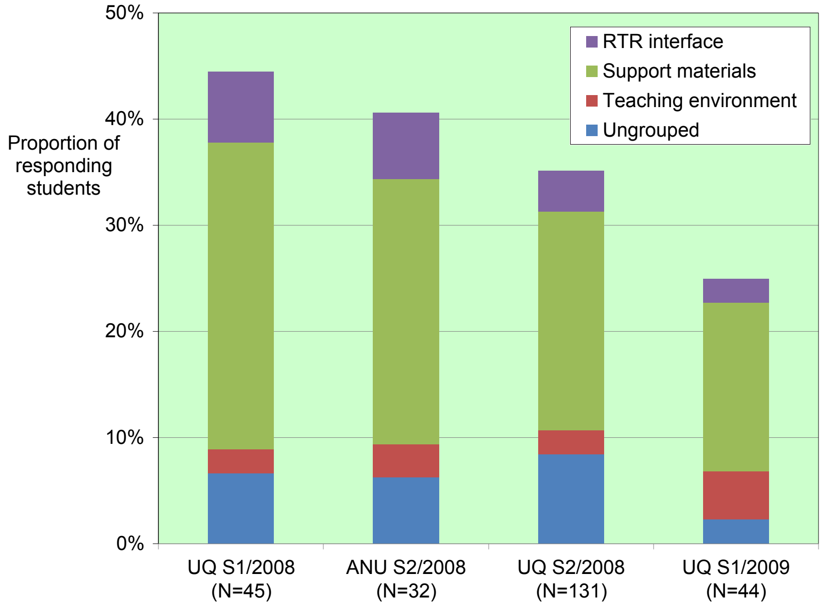


Figure 3: Students' responses to "What aspect of this experiment needs improvement?"

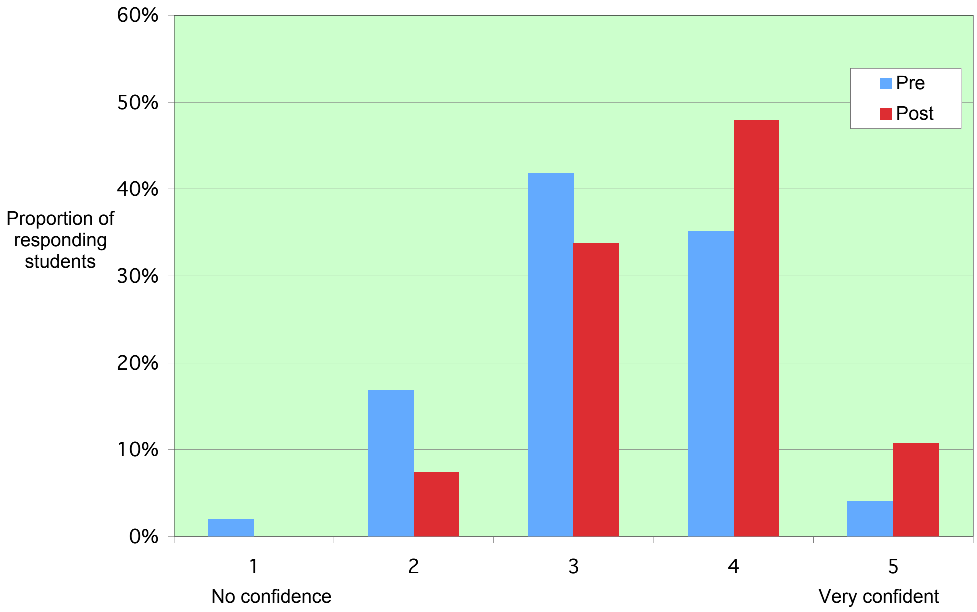


Figure 4: Students' confidence levels in their ability to "Apply aspects of the theory of special relativity to solve problems" (143 responses from ANU and UQ, Semester 2, 2008 and 2009)

Through our evaluative efforts, we have also gained insight into what, and how, students learnt from the *RTR* lab. In response to an open-ended survey question that read, "What was the most interesting thing that you learnt from this experiment, and how did you learn it?" students frequently described active processes that closely parallel doing an experiment in the real world (see Figure 5). Hence the VR can be said to have been a good proxy for a hands-on experiment. The students also acknowledged active thinking, sometimes prompted by the people they were working with. This matched classroom observations in that experimentation and observation were primary, and facilitated through collaboration with lab partners.

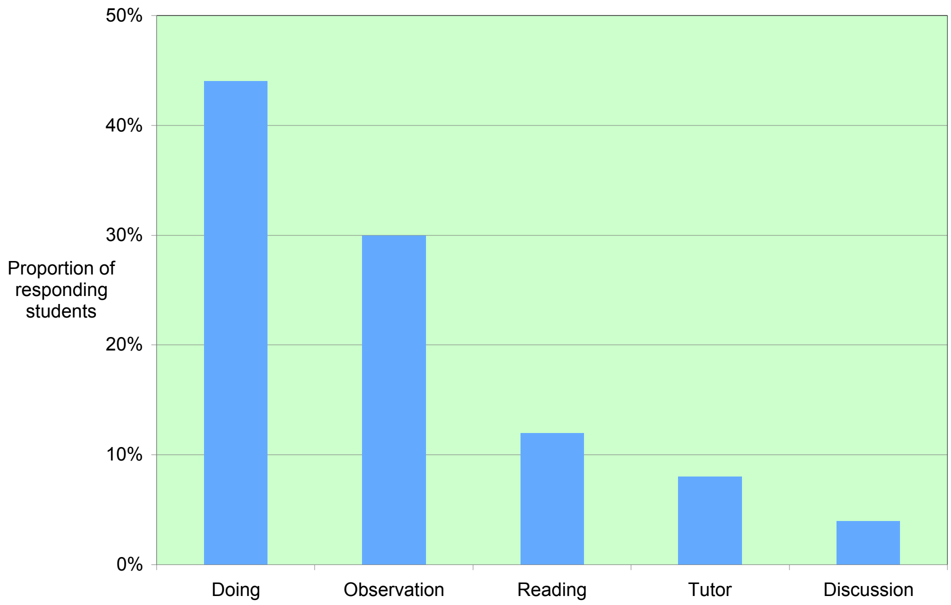


Figure 5: Classified student responses to open-ended question on how students learnt (66 responses from ANU and UQ, Semester 2, 2008 and 2009)

RTR presents relativity in a direct, experiential way that complements the traditional abstract formulation. This helps visual learners, in particular, make sense of the theory. We found evidence that some students subsequently approached relativity in a visual manner, utilising the mental models developed from *RTR* (McGrath et al., 2010). Students developed a usable resource of personal experience. They also behaved more like experts after using *RTR* as, for example, they were better able to use correct terminology specific to the topic.

The difficulty students face in understanding this physics topic, together with the efficacy of our VR-based solution in alleviating that difficulty, is summed up by one student's comment about the final version of the learning experience:

> relativity is confusing. but the lab helped me to understand it ☺

The final product is a mature, robust simulation for special relativity along with supporting learning and teaching materials, all of which are available freely online (http://www.anu.edu.au/Physics/vrproject/) to the wider community.

Lessons learnt from the process of developing the *RTR* teaching package have since been applied to the teaching of another physics topic: To give students an experience of a world in which quantum mechanics is dominant, a prototype simulation, *QSim*, has been created using the same programming framework (Savage, McGrath, McIntyre, Wegener & Williamson, 2009). Tracking the initial stages of our development process, it was reviewed by the project team, then trialled by a small group of students. These students (who had already taken courses on quantum mechanics) interpreted the visualisation as designed, and judged it to be a useful learning tool that enhanced their learning. As with the *RTR*, the students who used *QSim* regularly commented on the importance of visual models to build their conceptual understanding.

Conclusion

We developed the *Real Time Relativity* simulation as part of a teaching package for facilitating learning through guided exploration of a virtual world. What is new is our use of virtual world-based interactive simulations to facilitate student-centred discovery learning, offering students an alternative learning pathway. Our evaluations indicate support for particular learning outcomes using this method, and success in optimising the learning experience for our students. The process we used for developing *RTR* and the related teaching materials yielded an effective and engaging opportunity for students to explore the strange and intriguing world of special relativity.

Our iterative approach and expert assistance (in programming and educational evaluation) contributed significantly to the success of the project. Members of the multidisciplinary, cross-institutional team brought to the project a range of disparate skills. A high level of time commitment is required for developing a teaching package in this way, but this is outweighed by the many benefits, among which is the reliability gained from evaluating use of the package with hundreds of first-year students at multiple Australian universities.

Providing easy and affordable access for both students and educators was a concern throughout the project. Progress in commercially available and mainstream computing technology made the development of the *RTR* simulation possible in the first instance, and the development team worked to minimise technological barriers to its usage.

Interactive computer worlds present immense possibilities for exploring otherwise inaccessible physics. The introduction of students to abstract physics topics such as special relativity in a tertiary education context is well suited to these possibilities. The learning activities we have designed address concerns that abstract physics is often taught with an emphasis on mathematical formulations rather than on its experimental basis, and that students lack direct experience of the concepts. With *RTR*, students learn by immersing themselves in the environment and interacting with it to experience firsthand the physics in action.

The use of VR enables new types of learning that challenge traditional curricula. Special relativity is essentially a visual phenomenon, with the universal constancy of the speed of light at its heart. It therefore makes sense to teach special relativity visually. The visual nature of the simulations naturally highlights certain aspects of the science - what is easy to 'see' with the simulation is different from what is easy to 'see' with a traditional equation-based approach. Involvement in this project has affected our attitudes about what tasks students should do, increasing acceptance of qualitative observations as opposed to solely concentrating on quantitative measurements that fit well within an equation-driven paradigm. Simulations improve the accessibility of sophisticated physics. With *RTR* it is completely natural to learn relativistic optics, which is not usually part of introductory courses. The question of what to teach in introductory physics can be answered both by what is important to know and what is able to be taught; the ubiquity of personal computing power and tools today changes those answers. New curriculum possibilities opened up by VR simulations like *RTR* demand further consideration.

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Authors: Dr Margaret Wegener, Lecturer and First-Year Teaching Director
School of Mathematics and Physics
The University of Queensland, St Lucia, QLD 4072, Australia
Email: m.wegener@uq.edu.au

Dr Timothy J. McIntyre, Senior Lecturer and Head of Physics
School of Mathematics and Physics
The University of Queensland, St Lucia, QLD 4072, Australia
Email: mcintyre@physics.uq.edu.au

Dominic McGrath, eLearning Designer
Teaching and Educational Development Institute (TEDI)
The University of Queensland, St Lucia, QLD 4072, Australia
Email: d.mcgrath1@uq.edu.au

Professor Craig M. Savage
Physics Education Centre, Research School of Physics and Engineering
The Australian National University, Canberra, ACT 0200, Australia
Email: craig.savage@anu.edu.au

Michael Williamson, Software Engineer
Physics Education Centre, Research School of Physics and Engineering
The Australian National University, Canberra, ACT 0200, Australia
Email: michael.williamson@anu.edu.au

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