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Promoting excellence in higher education

Final Report

TEACHING PHYSICS USING VIRTUAL REALITY

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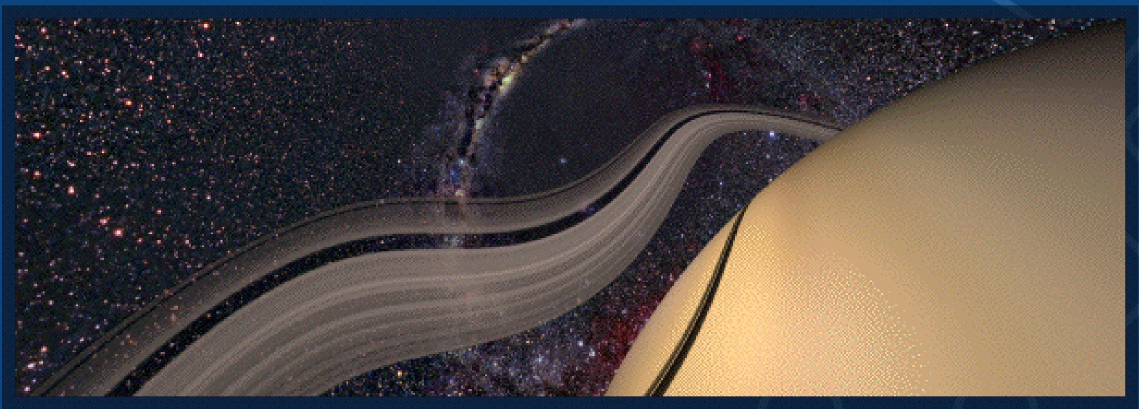
2010

www.anu.edu.au/Physics/vrproject

realtimerelativity.org



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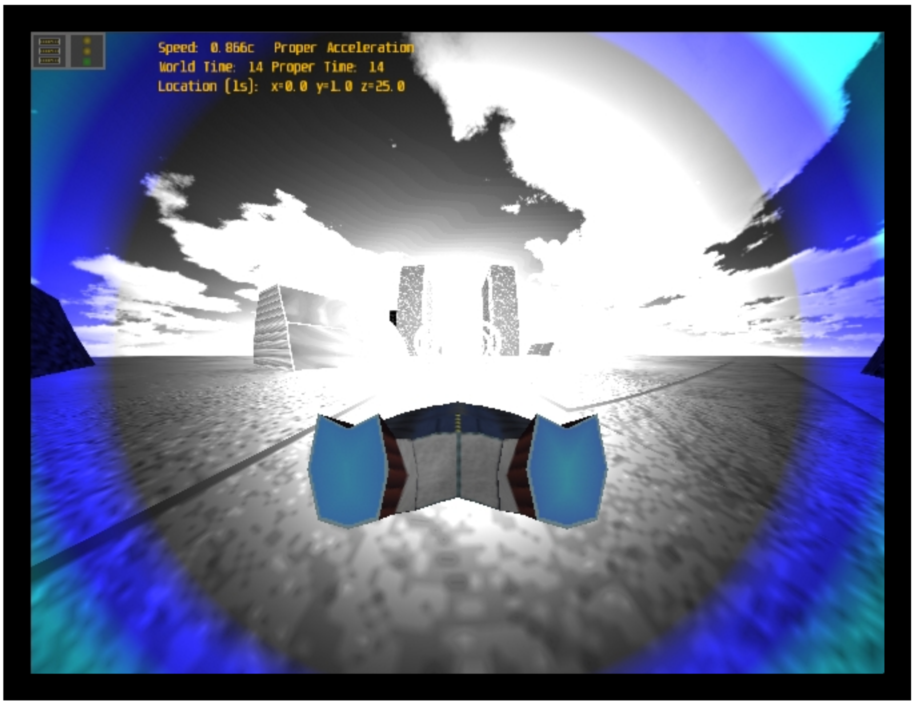


Screenshot from the Real Time Relativity virtual reality software.

Teaching Physics Using Virtual Reality

Craig Savage
Dominic McGrath
Tim McIntyre
Margaret Wegener

Table of Contents

Executive Summary

What it's all about

Amongst the great changes in society is the use of simulations for activities as diverse as public policy making and recreation. These simulations are routinely coupled to sophisticated visual interfaces producing virtual realities. This project has produced examples of how recent developments in simulation technology may be used for learning and teaching physics.

In computer games users must learn to understand and manipulate unfamiliar worlds. But much of physics deals with unfamiliar domains: such as the very fast or the very small. The physics of these domains, relativity and quantum mechanics, is abstract and counter-intuitive. We have found that simulations of these domains can help students learn the physics. The visual learning they enable complements more abstract forms of instruction.

Computer simulations have been used for a long time in physics teaching. They open up complex and realistic scenarios to students and instructors alike. They also allow access to processes which are difficult, or impossible, to observe in the lab. What is new about our approach is the emphasis on immersive, interactive, first-person, game-like simulation. This facilitates student-led discovery learning and gives students another pathway into the physics.

"What is new about our approach is the emphasis on immersive, interactive, first-person, game-like simulation."

What we did

In this project we have concentrated on introductory university physics. Our focus was on the teaching and learning of special relativity. We developed a simulation of a relativistic world called "Real Time Relativity". Around this we created a teaching package including a laboratory manual, background materials, and evaluation instruments. Over 300 students in first year courses at The Australian National University and The University of Queensland used this package.

Student learning as a result of using Real Time Relativity was evaluated using a variety of methods including pre- and post-testing, exams, ethnographic observation, and student interviews. Evaluation results were used to develop the simulation and the teaching package over time, in an iterative cycle.

Using virtual reality.

We applied the lessons learned from Real Time Relativity to the development of a prototype simulation for Quantum Mechanics called "QSim".

What we found

We have accumulated substantial and diverse evidence that one three-hour laboratory based on Real Time Relativity can improve students' understanding of relativity. For example, we found in a blind, randomised trial that students who had completed the lab performed better on the relativity part of the final exam than those who had not. It also improves their attitude towards the topic and their confidence in their understanding.

Real Time Relativity presents the physics of relativity to students in a direct experiential way that complements the traditional abstract formulation based on graphs and equations. Some students identify themselves as "visual learners" for whom a visualisation helps the theory fall into place. Others benefit from the need to actively reconcile their understanding of relativity with what they observe on the screen.

In addition these simulations improve the accessibility of sophisticated physics to introductory students. For example, since Real Time Relativity is based on seeing what the relativistic world looks like, the most natural thing to learn is relativistic optics. This is not usually part of introductory courses. Similarly, QSim is based on quantum dynamics and naturally emphasises time dependence and quantum measurement, which are generally found in advanced courses.

> **“simulations improve the accessibility of sophisticated physics to introductory students”**

Recommendations

1. That higher education institutions embrace the culture of simulation by systematically investing in immersive simulations to enhance education.

2. That virtual realties be incorporated into existing courses through a student-centred process of scaffolded exploration.

3. That consideration is given to the new curriculum possibilities opened up by such simulations.

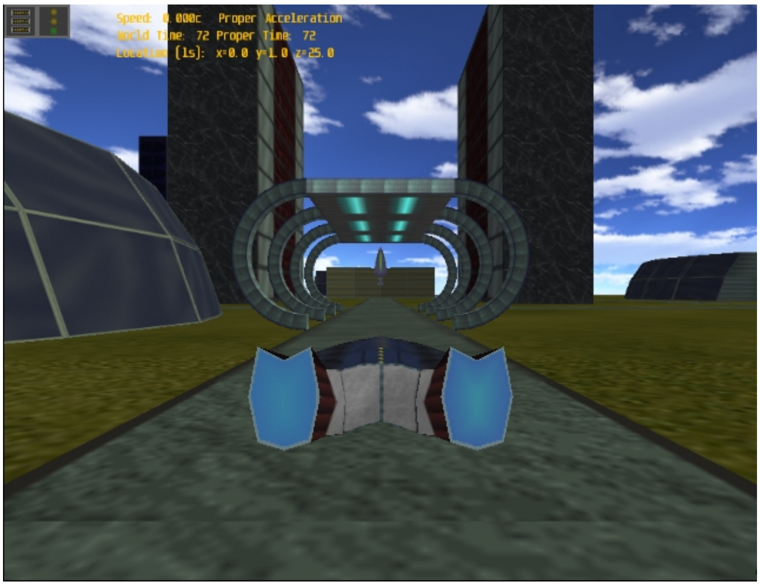


Figure 1. Real Time Relativity screenshot. Spaceship at rest relative to cityscape.

Background

Information and communication technology in higher education

The Information and Communication Technology supported learning and teaching that has been introduced to universities often uses technological approaches that relate more to the generation of teachers than of the students, many of whom have never known a world without computers, the internet, and video games. Students now use technology for a range of purposes that have surpassed support for their study and their lives. Instead it is now a crucial part of their lives, in their communication with each other and in their identity formation and expression - living "virtual lives" through YouTube, MySpace and Second Life. These "virtual realities" have extended the concepts of computer gaming to a point where the users "become" a part of this virtual reality and experience an alternate reality through the technology. They learn about that reality through their experience of it. This "neomillenial" learning style has multiple implications for higher education (Dede 2005; Hort 2007).

To date, higher education has not kept up with these developments in Information and Communication Technology and the ways in which students are using them. Perhaps higher education can benefit from participating in the culture of simulation that is increasingly part of how people work and play (Squire 2006). For example, simulations are now routinely used to inform decision-making in areas as diverse as climate change and economics. Educational research has shown that computer simulations can promote active learning in physics, especially where real laboratories are difficult to provide (Wieman & Perkins 2006). However, the level of sophistication of such simulations has been limited by the available technology, and has generally been restricted to simple demonstrations of theory.

“Perhaps higher education can benefit from participating in the culture of simulation that is increasingly part of how people work and play”

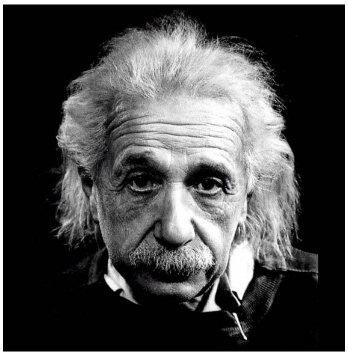
A significant drawback of existing simulations is that they generally lack interactivity. While these simulations promote learning through their capability for visualising abstract concepts, this approach falls well short of the full possibilities of today's technology, which provides for exploration of an immersive, game-like environment with full interactive capabilities. Such an approach has only recently become possible due to the development of the advanced, low-cost, graphics processing units commonly found in today’s personal computers (Owens 2007). This offers the exciting possibility of the routine use of interactive virtual world simulations in higher education. This immersive, interactive, educational mode is already being used in areas for which hands-on training, although desirable, is dangerous or costly. These include training for the military (3Dsolve 2009), and for mass casualty triage (Stanford University Medical Media and Information Technologies 2008). The Australian Learning and Teaching Council has supported the development of an advanced immersive learning environment for process engineering (Cameron 2009, Shallcross 2009). This technology is able to "bring the plant to the student, if you can't get the student to the plant".

Learning

It is widely accepted that people have a variety of learning styles and that different people excel in different styles. One theory is that of “multiple intelligences” (Gardner 1983).

The dominant approach to the teaching of relativity is abstract and equation-intensive. This originates from Einstein's original paper where he discarded the personal observer who collects information from what he/she sees, in favour of more abstract “inertial observers” who use arrays of rulers and synchronized clocks (Einstein 1905). However it has been shown that special relativity can be formulated in terms of an observer's personal visual observations (Komar 1965; Blatter 1988). This provides the scientific underpinning of our specific project to personally engage students with relativity using virtual reality.

Visual understanding has a venerable history in physics. Faraday laid the foundations for electricity and magnetism, and hence for the modern economy, using almost exclusively visual thinking (Koestler 1964). Maxwell completed the mathematical theory of electrodynamics, but was motivated by visual models (Maxwell 1891). Einstein famously started on the intellectual road that led him to relativity by imagining what it would be like to run alongside a ray of light (Calaprice 2000).



Albert Einstein.

Special relativity

The concept of using an interactive virtual world is applicable to a wide variety of topics taught in physics. In this project, the particular topic of special relativity has been chosen as our focus because it is traditionally an area where students struggle to understand concepts. Nevertheless, they find relativity interesting and exciting. Hence one of the roles of relativity teaching is to motivate students to study the subject of physics. Students may, however, be left bemused by the chasm between the theory and their experience. Since the consequences of the theory of relativity are most obvious when travelling at very high speeds (approaching the speed of light), there is no opportunity for students to directly experience relativity. Hence it is often perceived as excessively abstract. Moreover, it contradicts some deeply-held ideas about space and time that have been gained from everyday experience, and students struggle to form an integrated relativistic world-view. As a consequence, students often do not transform their thinking and do not internalise the concepts of the theory.

“Students may, however, be left bemused by the chasm between the theory and their experience”

Although special relativity produced a fundamental paradigm shift in modern physics, Scherr, Shaffer, and Vokos (2002) have found that:

> "... many students who study special relativity at the undergraduate to graduate levels fail to develop a functional understanding."

They identify the reason for this as students having a poor understanding of time in special relativity (Scherr, Shaffer, & Vokos 2001; 2002); students misunderstand fundamental ideas such as: the "time of an event, simultaneity, and reference frame" (Scherr, Shaffer, & Vokos 2002). The use of an interactive virtual reality approach can address these problems, as these ideas have intuitive operational meanings following from the student's interaction with the program. Scherr et al. further conclude that (2002):

> "... a strategy in which the instructor elicits and exposes student beliefs to generate cognitive conflict and then resolves the paradox is inadequate. Our experience indicates that confrontation and resolution must be carried out by the students, not by the instructor, if meaningful learning is to take place."

Mermin (2005), in the preface to his innovative relativity text "It's about time", notes that traditional relativistic pedagogy may make incorrect assumptions about students' prior skills. A central part of traditional pedagogy is comparing descriptions of the same experiment according to differently moving observers. He describes the skills required to do this as "... unused, undeveloped, often nonexistent...". Perhaps a virtual relativistic world would promote the development of these skills by allowing the users to interactively visualise experiments while travelling at any velocity they choose.

“Many students are comfortable discovering the rules of virtual worlds. Can this experience be used for discovering the rules of physics?”

The demonstrably poor grasp of such a central pillar of fundamental physics as relativity is an unacceptable situation. We wished to understand whether an immersive, game-like environment might overcome some of the learning difficulties associated with relativity. In the context of a first-year university physics class, we have asked the question: Can aspects of special relativity be learnt by exploration of a virtual relativistic world? Many students are comfortable interactively discovering the rules of virtual worlds. Can this experience be used for discovering the rules of physics?

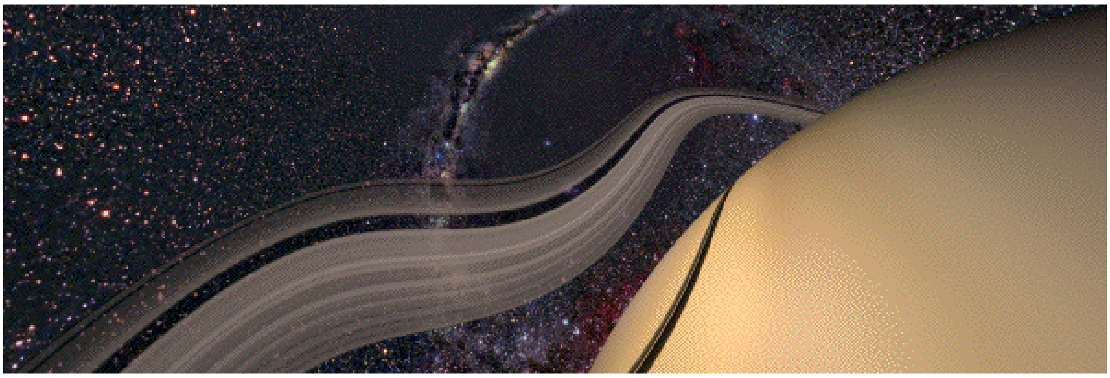


Figure 2. Image of Saturn at a speed of 99% light-speed (with the Doppler and headlight effects suppressed).

Quantum mechanics

The epitome of abstractness for many physics students is quantum mechanics. Indeed there are debates about whether central entities of the theory, such as wavefunctions, are real or not. Creating a virtual world to assist in the learning of quantum mechanics is therefore a greater challenge than doing so for relativity. However the stakes are higher. Quantum mechanics is a central part of twenty-first century technology, through semiconductor devices, and the promise of quantum technologies such as quantum computers. Can the lessons learned from constructing a relativistic virtual reality be applied to quantum mechanics? The technological edge of quantum mechanics is moving increasingly further from the quantum mechanics presented in conventional courses and texts. This is because twenty-first century quantum technology is based on dynamics: and dynamics is hard to do without a computer. Might virtual quantum realities help educators better equip students with what they need to contribute to the quantum technology revolution?

Using virtual reality.

"Might virtual quantum realities help educators better equip students with what they need to contribute to the quantum technology revolution?"

Aims

This project aimed to develop immersive, game-like environments with full interactive capabilities for physics learning and teaching. The simulation software at the core of the project would be embedded in a teaching package, including support materials for using it in courses, and evaluation instruments for measuring its effectiveness. Its effectiveness for improving student learning of relativity would be evaluated using a mixed method approach. The teaching package and the results of its evaluation would be communicated to the physics education community.

Develop a simulation-based approach to science teaching

Virtual realities open up new possibilities for learning and teaching. We aimed to explore and evaluate some of these and produce recommendations for their integration into existing courses.

> **"Virtual realities open up new possibilities for learning and teaching"**

Demonstrate the approach by creating a virtual interactive world defined by the laws of Relativity

The project started from prototype Real Time Relativity (RTR) simulation software that provided proof of concept. We aimed to use an iterative testing and development cycle to evolve RTR and its teaching package. This would require "battle testing" in courses. This would be done by incorporating it as a three-hour laboratory in first-year Physics courses at The Australian National University and at The University of Queensland. In these courses learning behaviours would be observed and learning outcomes measured, with the results fed back into the refinement of the software and teaching package.

Create a teaching package in support of the simulation software

In order to make RTR effective for learning relativity in the context of a university course we needed to develop ancillary materials, such as reference material and a student manual. We also needed to develop evaluation tools to measure student learning. We refer to these as the "teaching package". It was developed in the same iterative cycle as the software.

Evaluate the package's effectiveness in promoting learning

We aimed to provide a rigorous evaluation of the effectiveness of RTR for improving student learning of relativity. Assuming it was found to be effective we aimed to understand why and how it works, that is, to develop an understanding of the ability of a simulation to aid learning.

Develop prototype software in another area of science

We aimed to use the experience of developing RTR to develop a second prototype simulation for learning and teaching science. This would help us to understand better the generality of our approach to simulation-based learning.

Increase awareness in the higher education community of simulations in learning and teaching

We aimed to encourage and facilitate the adoption of simulation-based learning and teaching by universities in Australia.

Products

The project produced two software products: Real Time Relativity (RTR), a special relativity simulator, and QSim, a quantum mechanics simulator, as well as a full teaching package for RTR. RTR is released software, freely downloadable from the Internet, as is its associated teaching package. It has been rigorously evaluated for teaching effectiveness and is the subject of several publications (McGrath et al. 2008, 2009; Savage et al. 2007, 2009). QSim is prototype software that has not been released. Its preliminary evaluation is described in the Learning Evaluation section of this report. The Project web site (http://www.anu.edu.au/Physics/vrproject) contains all of the products.

Real Time Relativity

Real Time Relativity is a computer program that allows the user to fly through a virtual world governed by relativistic physics. The experience is like that of a computer game, flying a spaceship that can travel at relativistic speeds. The user controls a “ship” in 3-D and sees on their screen the view of a “camera” orbiting the ship. The ship may be accelerated and steered, and the camera may be pointed in any direction. Relativistic physics is used to determine how objects in the world frame appear in the flying camera frame.

The student user selects from a number of different "scenarios" or worlds. These are designed with different goals in mind. The "Racing course" scenario is a task-oriented world designed to help students learn in-game navigation. It is typically used early in teaching laboratory sessions. The "Cityscape" scenario consists of buildings, trees and other familiar objects; see Figure 1. This helps students understand the form of relativistic visual distortion, or "aberration" as it is known technically.

The "Solar system" scenario, shown in Figure 2, has photorealistic planets and is the only world containing objects at real world length scales. However, as all planets except Saturn with its rings appear simply as spheres, and spheres remain spheres under relativistic aberration, only Saturn is visually interesting.

Figure 3. RTR screenshot. Ship at rest relative to five clocks in a line.

The "Relativity of simultaneity" scenario (Figure 3) is the only scenario with clocks. It is specifically targeted to studying temporal physics such as time dilation and the relativity of simultaneity.

Other scenarios are primarily for impact: Figure 4 shows how passing through a hollow cube at relativistic speed produces fantastic visual distortions.

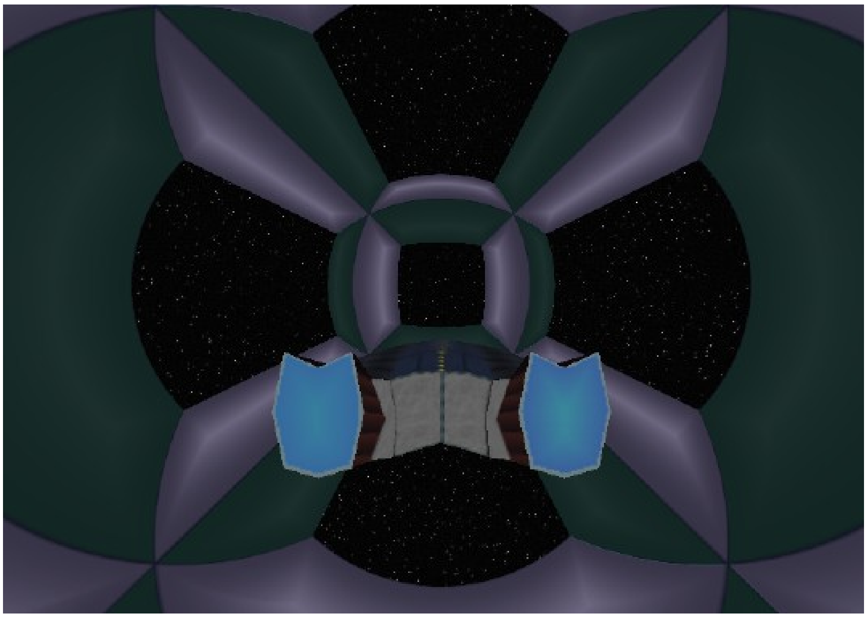


Figure 4. RTR screenshot. Ship passing through a hollow cube at v = 0.968c.

RTR is distributed under the GNU Lesser General Public License. The RTR software comes with a User Guide and a Developer's Guide. The User Guide should be consulted for detailed information about RTR functionality. The Developer's Guide is aimed at those who wish to further develop the software. The source code is available from SourceForge (http://sourceforge.net/projects/rtrelativity).

The Teaching Package for RTR consists of materials to assist in using RTR for teaching relativity. They are:

- A manual for a three-hour lab.
- An educational rationale for the lab.
- Evaluation tools: concept tests and an attitude and confidence survey.
- Lecture notes: all aspects of introductory special relativity, including relativistic optics.
- A link to the website Through Einstein's Eyes (2009): a visually oriented multimedia introduction to special relativity, including relativistic optics.

QSim

QSim is a prototype quantum simulation program whose objective is to give students an experience of a simulated world in which quantum mechanics is dominant. It is written using the same framework as RTR. The initial development work on QSim was done by ANU undergraduate student Byron Vickers using the VPython programming language. QSim has not been publicly released. We have developed a brief User Guide and the 50-minute lab manual used for its initial evaluation.

Quantum dynamics, including quantum measurement, is a relatively neglected part of many introductory quantum mechanics courses and texts. These tend to emphasise time-independent quantum mechanics, with perhaps some time-dependent perturbation theory. However quantum dynamics underpins anticipated 21st century quantum technologies such as quantum computers.

Designing a quantum mechanics simulation requires deciding what will be visualised. We have chosen to visualise the single particle wavefunction. If it is regarded as a mathematical abstraction then we are visualising mathematics. This is quite different to Real Time Relativity, which visualised just what would be seen by the eye, or by a camera. Figure 5 shows the wavefunction as visualised by QSim.

The simulation evolves the wavefunction in time and allows discrete position measurements with variable resolution (Aharanov 2005). The position measurements may be repeated automatically, with a specified frequency and number of measurements, and the results plotted in three-dimensional space.

Something that surfaced in the initial development work was that the quantum Zeno effect (Aharanov 2005; Misra 1977) was apparent to the vigilant observer. This was surprising as QSim was designed for introductory quantum mechanics instruction, whereas the quantum Zeno effect is often regarded as an advanced subject. This is an example of the well-known fact that computers increase the sophistication of subject material that is accessible to students. This has already been encountered with RTR in that it visualises relativistic optics, which is traditionally part of advanced relativity instruction.

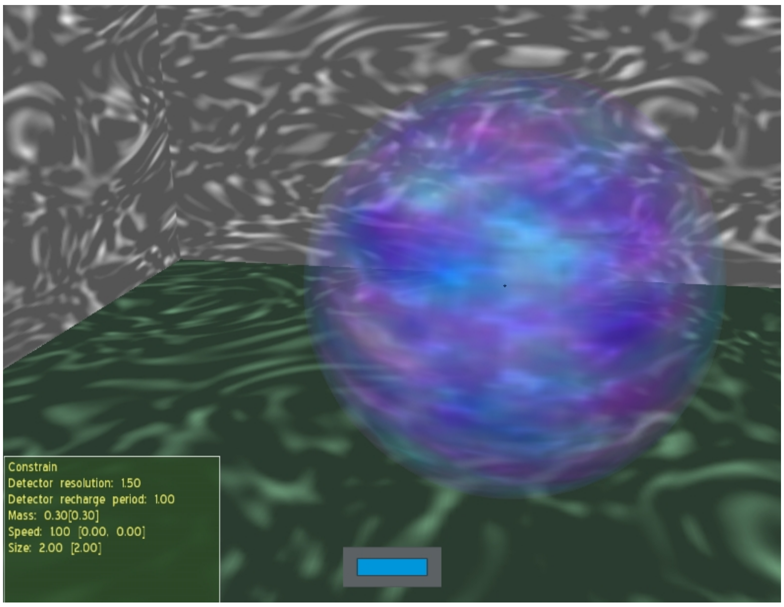


Figure 5. QSim screenshot of a quantum mechanical wavefunction.

Method

Our fundamental method was to use an iterative development cycle: teaching trials *followed by* educational evaluation *followed by* software engineering *followed by* further teaching trials, and repeat.

"Our fundamental method was an iterative development cycle"

The project was supported on three pillars: the underlying relativistic physics, the computer hardware and software to simulate this physics, and the teaching context for the simulation. In the following we describe each of these aspects.

Real Time Relativity was initially developed by ANU undergraduate student Lachlan McCalman as a research project, following an idea of post-doctoral researcher Antony Searle. It built on previous relativistic computer graphics work at ANU, including the Through Einstein's Eyes project (2009; Searle et al. 2005), which used the Backlight program (Savage & Searle, 1999; Backlight 2009). The only other interactive relativistic graphics systems that we are aware of were developed at the University of Tübingen. An early one used parallel CPUs (Weiskopf 2001), and the later one a GPU (Bochers 2005). In the latter the user rides a bicycle through the streets of a virtual city. It has been used in exhibits in German museums (Kraus 2005).

Physics

The relativistic physics explicitly incorporated into Real Time Relativity is: the speed of light, time dilation, aberration, the Doppler shift, and the headlight effect. This is a complete physical basis in that all the other relativistic physics simulated by RTR follows from them. Komar (1965) and others (Blatter 1988) have shown that kinematic aspects of special relativity can be formulated in terms of postulates about a personal observer's visual observations. The two-dimensional screen image is what the person would see, that is, the rays of light reaching the eye at a certain time. In the following it is convenient to think of the user's view as that of a camera.

Relativistic aberration is the dependence of the direction of incoming light rays on the relative motion of the camera and the objects from which they originate. Each camera image pixel is formed by light incident from a particular direction relative to the camera. The relativistic physics problem is to find the corresponding propagation direction relative to the objects in the simulated world. This propagation direction determines what is recorded by the camera pixel. The resulting pixels make up the camera image that is displayed on the screen.

This paragraph, and the following two, describe the approach to calculating the physics of relativistic effects, so are primarily addressed to technically-inclined readers. In relativity a photon is represented by its relativistic energy-momentum 4-vector $P = hf\,(1,\mathbf{n})$ where h is Planck's constant, f is the photon frequency, $\mathbf{n}$ the unit 3-vector in its propagation direction, and c is the speed of light. The propagation direction in the world frame is found by the Lorentz transformation of this 4-vector from the camera frame into the world frame. Its spatial 3-vector component is along the photon's propagation direction in the world frame. A 4x4 matrix represents the Lorentz transformation. It is calculated before each frame is rendered, using the current camera velocity, and is then applied to each camera pixel's photon energy-momentum 4-vector. The spatial parts of these vectors determine the pixel that is to be rendered to the user's screen. Since they are specifically designed to process 4-vectors in parallel, video unit Graphics Processing Units (GPUs) can perform the four-dimensional Lorentz transformation in real time. However, this approach is currently limited to static worlds in which the objects do not move.

The Doppler shift of the photon frequency between frames is given by the ratio of the time components (i.e. the first components) of the photon energy-momentum 4-vector in the frames. However, to determine the effect of the Doppler shift on a general colour requires the intensity spectrum for each pixel. But in computer graphics the spectrum is specified at just three frequencies; red, green, and blue. Hence a simple interpolation is used to generate the intensity spectrum: this is a significant limitation of RTR.

At relativistic velocities aberration concentrates the incident light into a narrow cone centred on the direction of motion. In addition, time dilation increases the photon flux in the camera frame. Overall there is a brightening in the direction of motion, and a darkening away from the direction of motion. The detected photon flux scales as the third power of the Doppler shift (McKinley 1979). There are significant limitations, resulting from computer graphics, on how the resulting large intensity range is rendered to the screen.

Hardware and Software

The computational power required to simulate a relativistic virtual world in real time is provided by Graphics Processing Units (GPUs). A GPU provides the massively parallel processing required to render the visual appearance of the relativistic virtual world. In RTR, to display an 800 by 600 pixel image at 50 frames per second requires about 24 million Lorentz transformations per second. This is well within the capabilities of basic GPUs, and hence in this project the conventional graphics processing limits the overall performance, not the relativistic calculations. GPUs have been following a super Moore's law, doubling in processing power every 6 months, compared to every 18 to 24 months for CPUs (Owens 2007). This is driven by the demand for parallel computing from the gaming community. For example, the Xbox 360 GPU has 48 processors, giving nearly 100 GFlops, compared to a few GFlops for a Pentium 4 computer.

The major step in the software development part of this project was to rewrite RTR to align it with current standards of software design. This made maintenance and further development much easier. We also aimed to develop code that was as independent of the operating system as possible. This should enhance its dissemination by making it possible to produce a version for the Apple OS X operating system, which is popular in educational contexts. It should also facilitate implementation on the new generation of handheld computers, such as the iPhone.

"It should also facilitate implementation on the new generation of handheld computers, such as the iPhone"

The remainder of this section is primarily addressed to technically-inclined readers interested in the approach to the computing necessary in this project. The two-dimensional screen image is created using the computer graphics technique known as environment mapping, which renders the three-dimensional virtual world onto a two-dimensional cube map. A cube map may be visualised as the 360-degree camera view-field mapped onto the interior surface of a cube enclosing the camera. In fact, the cube map is a data structure in which the image pixels are addressed by line of sight direction, rather than by spatial position (NVIDIA Corporation 2004).

A screen update in RTR has four major steps.

1. The camera's position, velocity, and orientation are calculated from the user input.
2. Using this information the video card renders the 3D virtual world to a world frame 2D cube map.
3. The GPU Lorentz transforms the scene into the camera frame.
4. The output is displayed on the screen.

The type of GPU program RTR uses is called a pixel-shader (Neatware 2004). This is a small program that performs per-pixel operations. This is an ideal point in the render pipeline to implement the relativistic optics transformations because the GPU has built-in support for 4-vector arithmetic, making relativistic calculations easy to code and fast to run.

The project team chose to use open source software for the graphics and the user interface: the Ogre open source 3D graphics engine (Ogre 2009) and the CEGUI user interface (CEGUI 2009). With these we achieved our aims and have produced robust and stable RTR software for both Windows and OS X operating systems.

Teaching context

RTR has been implemented in undergraduate university teaching laboratories. Experiments are well-suited to the discovery-based teaching approach we wished to use. Also, laboratories are convenient locations because of the availability of computers there.

Approximately 300 students in first-year physics classes at The University of Queensland (UQ) and The Australian National University (ANU) participated in this project. The courses were: “Electromagnetism, Optics, Relativity & Quantum Physics I”, phys1002, which runs in semesters 1 & 2 at UQ, and “Advanced Physics 2”, phys1201, which runs in semester 2 at ANU. At UQ enrolment numbers are typically 70 in semester 1 and 250 in semester 2. At ANU there are around 70 students. Students were primarily physics majors or engineers. At UQ students spent one week on relativity, comprising three lectures and a tutorial. At ANU students spent three weeks on relativity, comprising nine lectures and three tutorials. At both ANU and UQ students also completed a three-hour RTR lab, which might occur before, after, or during the relativity instruction.

Development cycle

We successfully implemented a development cycle for RTR. The project ran through several iterations of a cycle that involved evaluating students' use of the package then following with development of instructional material and software: refer to Figure 6. The evaluation used a variety of techniques including ethnographic observation, surveys, student focus groups and conventional assessment. These are described in detail in the Learning Evaluation section of this report. Although the iterative development cycle was time consuming and costly, it provided substantial improvements in the software user interface and in the student's learning experience.

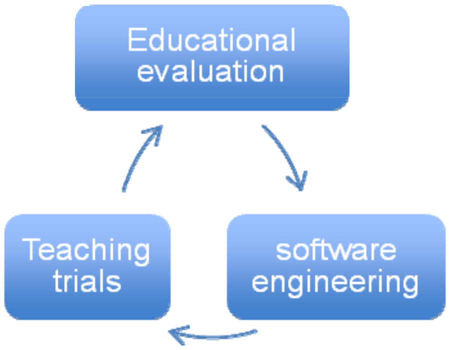


Figure 6. Development cycle for the RTR teaching package.

The evidence gathered from students' use of RTR was used to identify and correct problems and to enhance learning. An example of a software-related problem was the large amount of time students spent positioning the "ship" in order to make an observation they had determined was necessary. We consequently added the capability to move the ship while the simulation was paused. This made observations faster and less frustrating for students. The utility of this capability more than compensated for it being inconsistent with the primary design criterion of maximising realism. This illustrates how student feedback was used to identify where general design criteria were impeding the usability of the simulation.

Our initial teaching strategy was to take maximum advantage of RTR's realism and of students' prior experience understanding virtual worlds. This argued for discovery-based learning in which students were given open objectives and asked to design, and perform, observations to achieve these objectives. For example, in the 2007 lab manual students were asked to: "Verify the Doppler formula". Although this approach worked well for a minority of students, most floundered. Hence a more scaffolded approach was developed. In the 2009 lab manual students were asked to capture a screenshot that illustrated the Doppler effect. This was part of an overall refocusing on concepts rather than quantitative measurement.

"This argued for discovery-based learning"

Learning Evaluation

Central to this project was the evaluation of the effectiveness of Real Time Relativity for the teaching and learning of relativity. Students' attitudes, concept development, and exam performance were evaluated.

During their course that included relativity students typically completed surveys before and after performing their experiments. Pre-experiment surveys were constructed to examine students' views on physics, laboratory experiments, relativity and computing. Post-experiment surveys explored students' views of their learning, concepts, and experience of RTR and its use in comparison with other laboratory experiences. The surveys were developed from survey tools exploring students' attitudes to maths, physics and laboratory activities (Adams, et al. 2006; Cretchley & Harman 2001; Read & Kable 2007). The survey was analysed for validity through student focus groups and checked for internal consistency. Survey forms are available from the project web site: www.anu.edu.au/Physics/vrproject.

Students were observed performing their experiments, and selected students were informally interviewed to elaborate on responses and explain observed behaviours. Informal interviews of laboratory tutors were also conducted. Observation of student activities was conducted by project team member Dominic McGrath, who was otherwise not involved in the physics course. He noted evidence of substantive conversations, times for activities and recurring issues and questions.

Human ethics approval for the evaluation work at both universities was obtained through The Australian National University Human Research Ethics Committee (protocol 2008/318).

Attitudes

After completing the RTR lab 175 students at UQ were asked to respond to the following questions using the Likert scale:
Strongly disagree (1), Disagree (2), Neutral (3), Agree (4) Strongly agree (5).

Question	Result	Mean
I would be interested in using the RTR software in my own time	Neutral	3.0
In other experiments it was easier to connect the theory to what I observed	Neutral	3.1
I learnt more from this experiment than from most others	Neutral-Agree	3.4
Using a relativity simulation is more fun than other experiments	Neutral-Agree	3.5
I would like to use more simulations in my studies	Neutral-Agree	3.6
I would like to learn more about special relativity	Agree	3.7
I found this to be an interesting experiment	Agree	3.9

For each question the mean Likert scale score has an error in the mean of less than 0.2. To assist interpretation, the "Result" for each question is a mapping of the mean score to the word scale. These results indicate a significantly positive attitude towards the RTR lab activity.

One of the origins of this project was the desire to use simulations to make physics less abstract for students. This was tested with an online survey of 54 ANU students, 19 of whom had done the RTR lab and 39 of whom had not. Students were asked: "How abstract is special relativity?" and to choose from one of the options reproduced in the table below:

Response	RTR	No RTR
More abstract than most topics in physics	**58%**	**77%**
No more abstract than most topics in physics	**32%**	**21%**
Less abstract than most topics in physics	**11%**	**3%**

The numbers are the percentage of the responses for that group. Although both groups gave "More abstract …" as the most common response, noticeably fewer did so from the group that had done the RTR lab. This indicates that the lab made special relativity less abstract for students.

"This indicates that the lab made special relativity less abstract for students."

Confidence

Before and after completing the RTR lab 31 students at ANU and 146 at UQ were asked to self-assess their confidence in certain tasks related to using the theory of special relativity. Measured student confidence increased for all tasks. The probability of there actually being no improvement was determined by a paired t-test, and is shown in the following table.

Task	ANU	UQ
Describe the observed changes in shape of an object moving at high speed	<0.1%	<0.1%
Apply aspects of the theory of relativity to solve problems	<0.1%	<0.1%
Predict the change in colour of an object moving at near light speed	0.1%	<0.1%
Explain the theory of special relativity to someone who isn't studying physics	1.0%	<0.1%
Calculate the length contraction of a moving object given a relative velocity	0.9%	<3%

We interpret these results as indicating that the RTR lab improves student confidence in their ability to use the ideas of relativity. Further, this confidence is well-founded, as can be seen from the following sections.

Conceptual Understanding

Evidence of students' conceptual change was gathered through conceptual multi-choice questions and Likert style responses to conceptual statements. These measures consistently indicated improvements in student understanding of relativity after completing the RTR lab. Although the agreement scores changed in the desired direction, the improvement was usually not statistically significant, in that the mean score for the class before and after the lab did not vary by more than the standard deviation of the mean. The notable exceptions were questions to do with simultaneity and time dilation, where for a sample of

28 UQ students the probability of the improvement being due to chance was less than 5% on each of these questions.

Both of the measures used challenged students and required both careful reading and thought. This challenge may be in part responsible for a lower-than-expected response rate and may have influenced the sample of students participating. We need to develop alternate approaches to gathering data regarding conceptual development to maximise participation and opportunity to demonstrate conceptual development. For every item (except a question focusing on length contraction as being optical or physical) more than half the respondents indicated an optimal response in the pre-laboratory measure – reducing the capacity to demonstrate conceptual development. A larger sample size is required to further investigate this.

As an example of the difficult nature of some of these results, consider the results for some multiple-choice questions with four possible answers. A simultaneity question was completed by a sample of 93 UQ and ANU students and a time dilation question by 87 UQ and ANU students. The table shows the percentage of students selecting the correct answer in the pre-lab and post-lab tests.

Simultaneity Question

Correct	Result	Excluding both correct
Pre-lab and Post-lab	54%	
Post-lab only	23%	49%
Pre-lab only	13%	28%
Neither correct	11%	24%

Time Dilation Question

Correct	Result	Excluding both correct
Pre-lab and Post-lab	43%	
Post-lab only	32%	56%
Pre-lab only	13%	22%
Neither correct	13%	22%

The result of most interest for understanding the effectiveness of the RTR lab for learning is the "post-lab only", highlighted in green. This refers to students who got the pre-lab question wrong and the post-lab question right, and who hence might be claimed to have learnt from the lab. The second columns show the results for all students who participated. The percentages in the third columns exclude students who got the question right pre-lab and post-lab, and who hence presumably understood the relevant material before doing the lab. Excluding these students, about half of the remaining students improved. Less than a quarter did not learn from the lab, in that they got both questions wrong. The remaining quarter apparently "unlearnt" in that they gave the correct answer before doing the lab and the wrong answer after doing the lab. What are we to make of this last group? If they were guessing randomly pre-lab and post-lab, there should be three times as many "guessers" getting neither correct - which there are not. This data suggests that some students might be misled by the RTR lab – a possibility that requires further investigation.

Exam results

At UQ in 2008 and 2009, the final exam question on relativity was prepared and marked externally to this study. The exam question was based on material presented in three one-hour lectures and one tutorial session. Students were expected to conduct at least six hours of further independent study. In both years it was found that students who completed the RTR lab performed better on the special relativity exam question.

"students who completed the RTR lab performed better on the special relativity question"

Owing to the rotational structure of the laboratory sessions, students were randomly assigned either to a group that did the RTR experiment or to a control group who did not do the RTR experiment. In 2008, 132 students did the RTR experiment and 50 did not. For these two groups, responses on the final exam were compared. More students in the RTR group performed at a higher standard than those who had not done the RTR lab. While the effect size was small (Cohen's d = 0.33), it was statistically significant ($p<0.05$ by unpaired t-test). The raw data is shown in Figure 7. In 2009 the effect was less significant with $p=0.13$.

A review of the 2008 exam papers did not reveal any significant difference in approach between these groups. Students who completed the RTR experiment were also found to have performed better on a question relating to quantum mechanics but no correlations were found with other topics. This correlation pattern persisted in the 2009 exam.

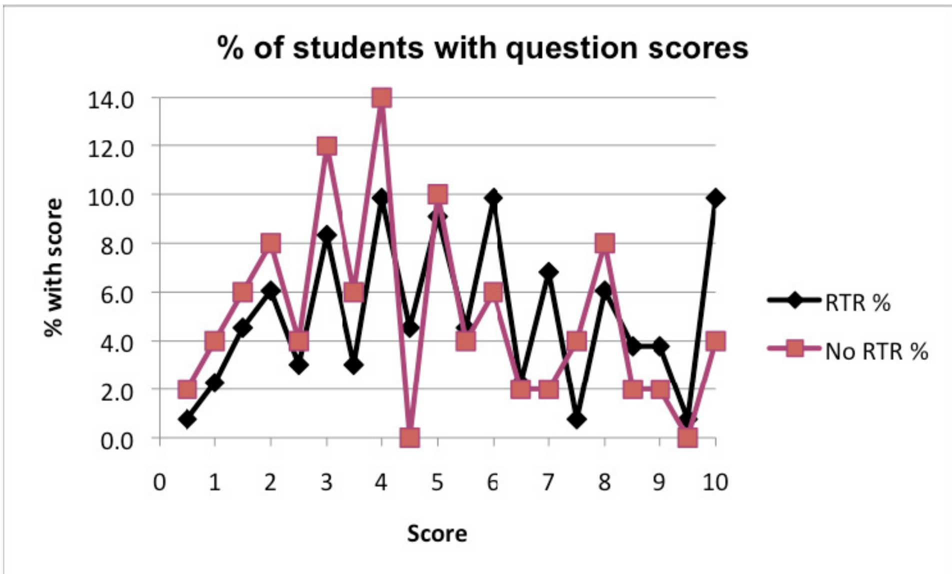


Figure 7. The horizontal axis is the score on the 2008 relativity exam question. It was marked out of 10 in units of 0.5. The vertical axis is the percentage of students in the group with the score. Although the data is quite noisy, the RTR group has a higher percentage of scores of 8.5 or above, and the No RTR group has a higher percentage of scores of 4 or below. The percentage of RTR students with full marks is more than twice that of the No RTR group.

The learning process

We investigated how students learnt from the RTR simulation by analysing open-ended survey questions, observing student behaviour during RTR labs, and running student focus groups.

A common transformative moment for students is when they accelerate towards an object starting from rest. Visually it seems that they are moving backward. This moment of confusion encourages students to question what they are seeing and motivates them to try to understand it. The exploration has begun!

"the exploration has begun!"

The post-lab open-ended survey questions indicated an active learning style in the RTR lab, typical of hands-on experiments. This was reflected in the focus groups. For example one UQ student said:

> "The section where you had to design an experiment about time dilation was useful … you had to design and you weren't just told what to do".

As students worked through the RTR lab a progression from initial confusion, through developing understanding, to connection to theory was commonly observed.

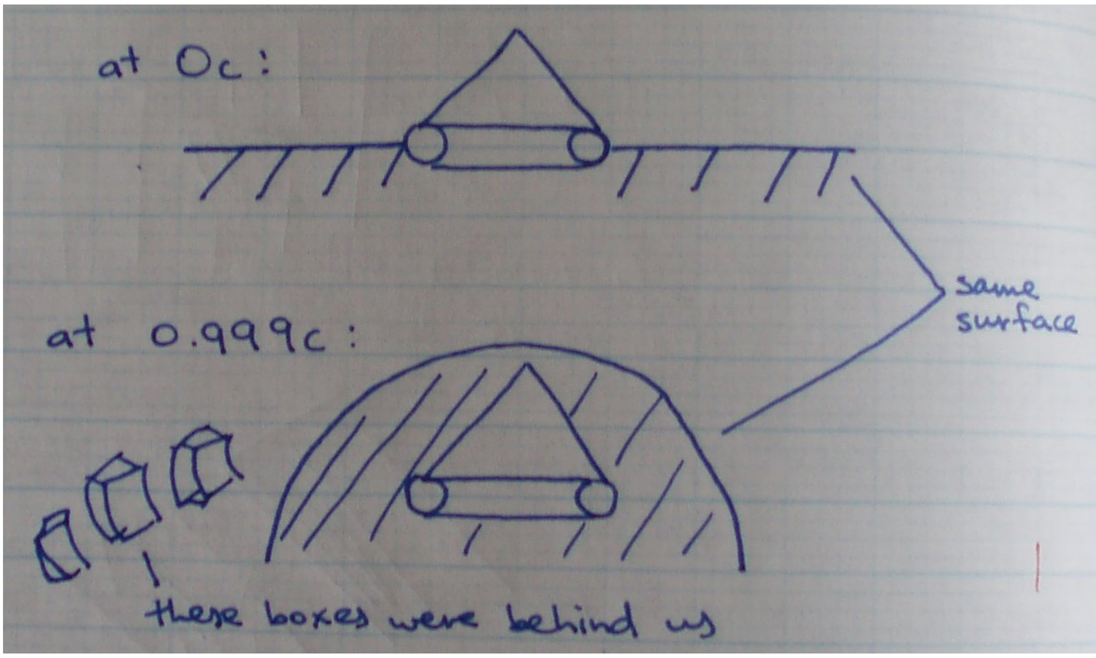


Figure 8. Example of student lab work from UQ, recording observations from the RTR simulation lab.

Responses to post-laboratory open questions about what and how students learned were classified using categories derived from the student responses. The classifications were reviewed and discussed by two members of the project team until consensus was reached. Students identified the most interesting aspect of the RTR experiment to be exploring an individual effect or a selected group of effects of special relativity. Students learned about these effects through "doing" in RTR, "observing" including seeing or watching, tutor-led discussion, and reading supplementary material, demonstrating a predominantly active approach to learning, as shown in Figure 9.

Most responses from students could be classified as typical descriptions of students undertaking hands-on experimental work. Thus virtual reality can be seen to be providing learning opportunities equivalent to other laboratory activities. Students also explicitly identified discussions with their laboratory partners as a way in which they learned.

"virtual reality can be seen to be providing learning opportunities equivalent to other laboratory activities"

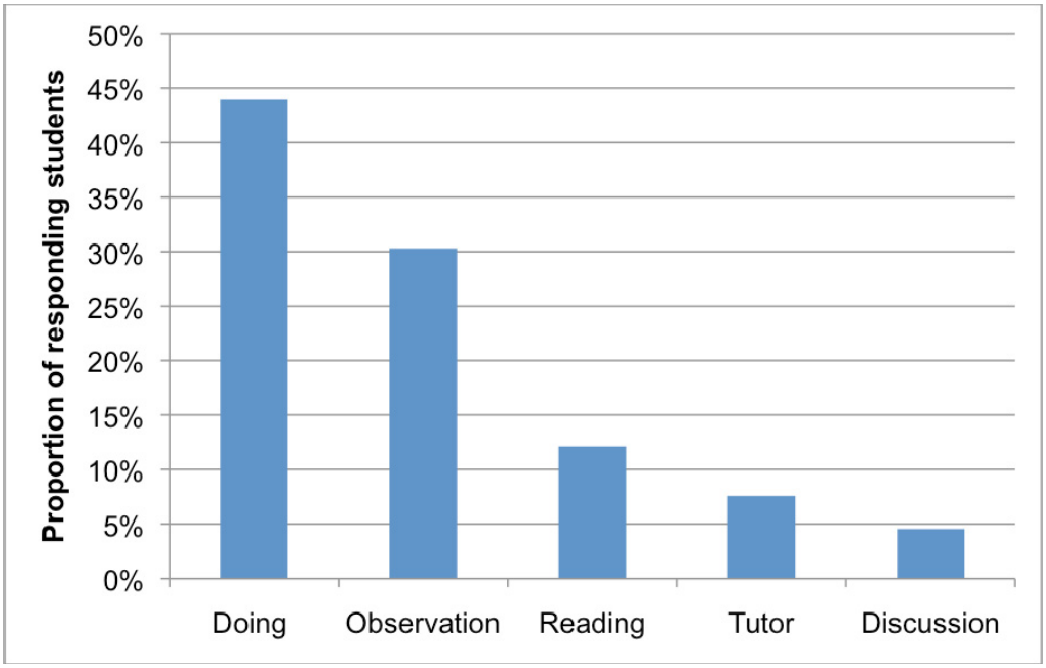


Figure 9. Classified student responses of how students learned the most interesting aspect of activity (n=66, UQ 2009).

Observations of student interaction during the laboratory sessions yielded further insights into the learning process. Students developed deeper understanding by negotiating the theoretical justification for their observations and challenging inaccurate conceptions through debate and experimentation. Most students' initial experience of increasing speed involved moments of:

"Hang on, why are we going backwards?" (UQ student using RTR),

as aberration had a greater effect on perspective than motion. Through a process of testing travel at constant speed, increasing and decreasing speeds, students developed a concept of aberration. Students then had to explicitly connect their experiences to theory by describing how these effects matched the theory of aberration. This matching of observation to labelled effects involved discussion within student groups, testing of concepts and guidance from laboratory tutors.

Instances of "visual learning" were repeatedly reported by students:

> "Real Time Relativity is very useful – many people are visual learners" (post-lab survey, ANU)

"many people are visual learners"

> "it was much easier to learn the concepts (ALL concepts) of relativity when it is seen visually"
> (post-lab survey, UQ)

> "it helped a lot with understanding because you could visualize something, that you have no experience of visualizing in real life"
> (post-lab survey, UQ)

Such evidence suggests that we have been successful in implementing the advice of Disessa (1986):

> "The trick is not to turn experience into abstractions with a computer, but to turn abstractions like laws of physics into experiences."

"The trick is not to turn experience into abstractions with a computer, but to turn abstractions like laws of physics into experiences."

QSim

QSim, our prototype quantum dynamics simulation, has undergone one iteration of our development cycle. Key objectives of the first evaluation were to determine if students correctly interpreted the visualisation and if students felt that it improved their understanding of quantum mechanics.

Six third-year physics students from ANU participated in the evaluation, which consisted of a one-hour structured computer laboratory. There were three activities: free evolution of the wavefunction, position measurement, and the quantum Zeno effect. Students were pre- and post-tested on their confidence that they understood the relevant physics. In open-ended questions they were asked to briefly summarise in writing what they learned in each part of the lab.

On Likert scale questions, all six students rated QSim as either "enormously useful" or "quite useful" as a learning tool. When asked whether QSim improved their confidence in their understanding of specific things such as the Heisenberg uncertainty principle most students selected either "a little" or "significantly", with occasional selections of "a lot" and of "not at all". The overall impression from the surveys was that students felt they had learnt things, but that they weren't quite sure exactly what.

One response to an open-ended request for comments on QSim was:

> "Great idea as it enables the student to clearly visualize something which is so different from classical mechanics. Demonstrates relationships well by allowing you to change variables. Wavefunction looks cool …"

Another student, when asked to comment on how their understanding of the wavefunction had changed, wrote:

> "…Being given a visual representation helps build a mental picture of what is happening in quantum mechanics …"

The importance of visual models for some students is a theme we also encountered in our evaluations of Real Time Relativity: these students might include those who describe themselves as “visual learners”.

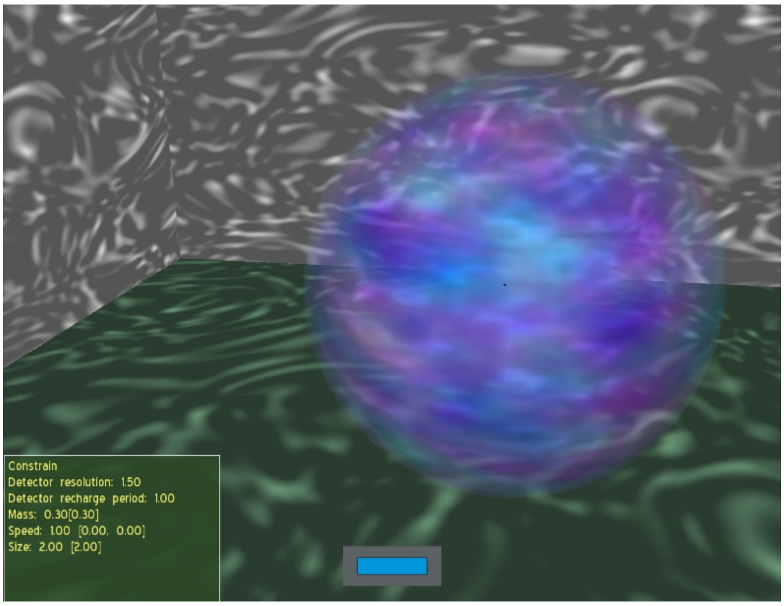


Figure 10. QSim screenshot of a quantum mechanical wavefunction.

Dissemination

A variety of dissemination strategies have been used in order to make the community of physics educators aware of the Real Time Relativity resources. These include: presentations at national and international conferences, seminars, publications, personal contact with physics educators, and a web presence. Publications and presentations are listed in a separate section.

Discussions were held with academics who teach relativity at a number of Australian universities. A recurrent problem was finding suitable computers on which to run the RTR simulation. Although the hardware requirements are quite minimal, they sometimes exceeded those available for university physics teaching, in which budget constraints often lead to purchasing highly stripped-down computers for student use.

One university that successfully incorporated RTR into an existing course is Murdoch University. Dr. C. Creagh used it in course PEC231 Modern Physics, for both internal and external students. Christine Creagh performed an evaluation of nine students in the 2009 course at Murdoch University, and presented the results in a report at an international conference on visualization. This course included distance learning students. She reported:

> "We also used the software and associated learning and teaching material for our external students and it proved to be as valuable for them as it was for the internal students."
>
> (Personal communication, November 2009)

Dr. J. Quinton of Flinders University has used RTR in a first-year laboratory along with other simulation and computation activities. His students reported positively on their RTR experience.

RTR has also been used internationally. Dr. Ian Bearden of the Niels Bohr Institute at the University of Copenhagen has explored student learning using RTR. Dr. Richard Easther of the Physics Department at Yale University is working on a project to interface real-time relativistic simulations with the digital planetarium at Yale's Leitner Family Observatory.

For a computer-based project such as this, internet presence is an important dissemination strategy. The project website went online in March 2008 (http://www.anu.edu.au/Physics/vrproject). As an indicator of activity, in October 2009 it was accessed 115 times and the Teaching Package page of the site was accessed 48 times. As discussed in the Appendix, we estimate that the RTR software was downloaded about 1000 times in the year from November 2008 (realtimerelativity.org). Downloaders self-identified as a broad mix of Australian and international, educators and students.

"Real Time Relativity software was downloaded about 1000 times in the year"

Real Time Relativity is listed as a resource on the Spacetime Emporium which is part of the well-known ComPADRE Digital Library sponsored by the American Association of Physics Teachers, the National Science Foundation, and other organisations (http://www.compadre.org/relativity/items/detail.cfm?ID=3717).

Recommendations

The following recommendations are based on what we have learnt from this project. We regard the supporting evidence in this report as persuasive, especially if universities are seen as an integral part of contemporary society.

They are consistent with recommendation 9 of the 2009 ALTC report "Tertiary Science Education in the 21st Century", by the Australian Council of Deans of Science (Rice 2009): "The ACDS sponsors a project to identify a small suite of exemplars of the use of multimedia and simulation for first year science laboratory teaching and learning".

1. That higher education institutions embrace the culture of simulation by systematically investing in immersive simulations to enhance education.

Real Time Relativity shows how simulations can be used to enhance teaching and learning in higher education. Furthermore, we adapted the lessons of Real Time Relativity to developing a second educational simulation: QSim. The evidence in this report convinces us that there are many opportunities in physics, and in other sciences, to enhance learning with simulations. The work of Cameron (2009) shows that this is also true for engineering.

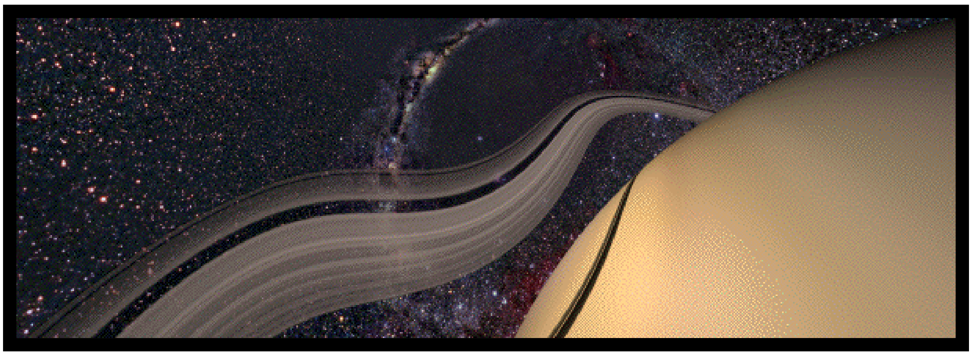
2. That virtual realties be incorporated into existing courses through a student-centred process of scaffolded exploration.

This report shows that simulations can be integrated into existing courses while enhancing open-ended, exploratory style learning. As is known to the education research community, such exploration requires some direction to be most effective for teaching. The mix of freedom and direction may be optimised through a feedback process based on measuring student learning.

3. That consideration is given to the new curriculum possibilities opened up by such simulations.

Computers not only make certain things easier, they make certain things possible. Without them some parts of science are inaccessible to introductory students. Since simulations make new learning possible, we should re-examine the curriculum, and ask what new directions might we move in at the start of the new millennium?

"what new directions might we move in at the start of the new millennium?"



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Antony Searle who provided the computer expertise that has made the entire ANU special relativity visualisation project possible. In particular he had the original idea for Real Time Relativity.

The ANU undergraduate students who contributed to the special relativity visualisation project through the years; especially Michael Hush, Paul Altin and Francis Bennett.

ANU undergraduate student Byron Vickers who developed the prototype of QSim.

Linda Hort at ANU for providing valuable guidance and input in the formative stages of this project.

The Reference Group for their wisdom: David Geelan (UQ), Richard Baker (ANU), Alex Merchant (RMIT).

Portions of this report are quoted from, or adapted from, our publications.

Publications, Presentations and Websites

Publications

Savage, C.M. McGrath, D. McIntyre, T. Wegener, M. & Williamson, M., 2009. Teaching physics using virtual reality. *ICPE 2009 Proceedings*. Available at: http://arxiv.org/abs/0910.5776

McGrath, D. Wegener, M. McIntyre, T. Savage, C. M. & Williamson, M., 2009. Student experiences of virtual reality - a case study in learning special relativity. Available at: http://arxiv.org/abs/0911.0226.

McGrath, D. Savage, C.M. Williamson, M. Wegener M. & McIntyre, T., 2008. Teaching special relativity using virtual reality. *Proceedings of the UniServe Science Symposium on Visualisation and Concept Development, October 2008*. Available at: http://science.uniserve.edu.au/pubs/procs/2008/index.html

Presentations

1. Margaret Wegener and Craig Savage gave a seminar to the Physics Department at the University The University of Western Australia in December 2009.

2. Craig Savage presented a paper at the International Conference on Physics Education in Bangkok, October 2009.

3. Dominic McGrath presented a paper at the UniServe Science Symposium, Sydney, October 2009.

4. Craig Savage presented a poster at the Gordon Research Conference: Visualization in Science & Education - Revealing Nature, Generating Insight, Oxford University, July 2009.

5. Craig Savage gave a seminar to the Physics Department at the National University of Singapore in July 2009.

6. The UQ team presented at the UQ Blended Learning Conference, 18 June 2009 at UQ.

7. Craig Savage gave a “Night Talk” at the Australian Museum in Sydney in February 2009.

8. Margaret Wegener presented a paper to the Education (PEG) stream at the Australian Institute of Physics Conference, Adelaide, December 2008.

9. Dominic McGrath presented an invited paper at the UniServe Science Symposium, Sydney, October 2008.

10. Craig Savage gave a public lecture at the ANU in August 2008.

11. Craig Savage was an invited speaker at the Gordon Research Conference: Computation and Computer-Based Instruction, June 2008, Bryant University, Smithfield, RI, USA.

12. Margaret Wegener presented a paper at the GIREP (Groupe International de Recherche sur l'Enseignement de la Physique) 2008 International Conference / 13th Workshop Multimedia in Physics Teaching and Learning: Physics Curriculum Design, Development and Validation, Cyprus, August 2008.

Websites

1. Project website:
http://www.anu.edu.au/Physics/vrproject
The project website describes the project and contains the following pages:

- Home
- The Project
- The People
- Real Time Relativity
- Teaching Package
- Publications
- Bibliography
- Web Sites
- Get Involved
- Contact us

2. Real Time Relativity website:
realtimerelativity.org
The simulation website describes the software and contains the following pages:

- Home
- Download
- Instructions
- Education

3. The Real Time Relativity source code is available from SourceForge:
sourceforge.net/projects/rtrelativity

4. ComPADRE Digital Library Spacetime Emporium:
http://www.compadre.org/relativity/items/detail.cfm?ID=3717
A digital library of physics education resources sponsored by the American Association of Physics Teachers, the National Science Foundation, and other organisations. A National Science Digital Library pathway.

Appendix: RTR download data

This appendix provides a sampling of information about the downloading of the Real Time Relativity software from the web. We have two kinds of data: from optional self-registration, in which downloaders provide some information about themselves, and from the web server which tells how many times the installer files were downloaded. Comparing this data suggests that about 25% of downloaders choose to register.

In the month of October 2009 the installers were downloaded 223 times (196 Windows, 27 OSX), of which 54 registered.

In the approximately one year period from 15/11/2008 to 9/11/2009 there were 904 registered downloads, suggesting over 3000 downloads in total, or nearly ten per day on average. A burst of 101 registered downloads occurred on 1/11/09, which may have been caused by the posting on the arXiv of one of our papers.

Of the 904 registered downloads, 212 described themselves as "educators" and 511 as "students", the remaining option being "other". Of the 904 registered downloads, 210 described themselves as from Australia.

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