**Special Relativity**

These worksheets are designed to be read by students before viewing a CAASTRO in the Classroom video conferencing session. The ‘Pre-visit activities’ can be completed prior to the conference session and the ‘Post activities’ are provided as suggestions for follow-up activities.

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# **Pre-visit Activities**

## **Glossary**

*The following terms may be cited during the video conferencing session. If students need assistance, refer them to the ‘Revision Videos’ section or any Physics textbook.*

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| **Terms** | **Definition** |
| Aether (also ether) |  |
| Inertial frame of reference |  |
| Non-inertial frame of reference |  |
| Speed of light (*c*) |  |
| Length contraction |  |
| Time dilation |  |
| Mass dilation(also known as relativistic mass) |  |

##

## **Revision Videos**

*The following is a list of useful revision videos. Students can:*

* *Take notes on the videos for themselves; OR*
* *Review one or more of the videos for their classmates as a homework exercise, giving each video a rating and commenting on how well the video communicated the science content.*
1. Ether and the Michelson-Morley experiment:

<https://www.youtube.com/watch?v=7qJoRNseyLQ>

*Neil deGrasse Tyson explains the Michelson-Morley experiment. Excerpt from UNDAUNTED*

1. Frames of reference:

<https://www.youtube.com/watch?v=mYH_nODWkqk>

*Flipping Physics - Skateboarding Frame of Reference Demonstration*

1. Speed of light is constant:

<https://www.youtube.com/watch?v=vVKFBaaL4uM>

*Veritasium - Can you travel at the speed of light?*

1. Simultaneity:

<https://www.youtube.com/watch?v=wteiuxyqtoM>

*Simultaneity - Albert Einstein and the Theory of Relativity*

1. Einstein’s Theory of relativity: Length contraction, time dilation, mass dilation:

<https://www.youtube.com/watch?v=TgH9KXEQ0YU>

*Vinit Masram - Understanding Einstein's Special Theory of Relativity*

1. Explaining the twin paradox

<https://www.youtube.com/watch?v=ERgwVm9qWKA>

*Physics Girl - Special relativity and the Twin Paradox*

1. Examples of Special Relativity: Muon Decay

<https://www.youtube.com/watch?v=IEeOLZmH7lE>

*It’s Okay To Be Smart - How to see time travel!!!*

## **Ask an astrophysicist**

*At the end of the video conferencing session you will be able to ask questions. Think of 3 questions you would like to ask the presenter, either about this topic or their particular research.*

***Question 1***

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***Question 2***

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***Question 3***

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*If there are any questions following the session, or if you did not have time to ask your questions, they can be sent via* [***Twitter***](https://twitter.com/citcvc) *or* ***email****, to be answered by the presenter or the CAASTRO in the Classroom team.*

# **Post-visit Activities**

*To watch a previous CAASTRO in the Classroom video conferencing session on Special Relativity by Joe Callingham of the University of Sydney (27 October 2015) click here:* [*https://youtu.be/C2C-xee6-Gc*](https://youtu.be/C2C-xee6-Gc)

## **Practice Questions**

**Useful formulae**:

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| $$v=\frac{d}{t}$$(speed equation) | $$l\_{v}=l\_{o}\sqrt{1-\frac{v^{2}}{c^{2}}}$$(length contraction) |
| $$t\_{v}=\frac{t\_{o}}{\sqrt{1-\frac{v^{2}}{c^{2}}}}$$(time dilation) | $$m\_{v}=\frac{m\_{o}}{\sqrt{1-\frac{v^{2}}{c^{2}}}}$$(mass dilation) |
| $l\_{v}$ is the length of the object in the moving frame$t\_{v}$ is the time of the object in the moving frame$m\_{v}$ is the mass of the object in the moving frame$l\_{o}$ is the length of the object in the rest frame$t\_{o}$ is the time of the object in the rest frame | $m\_{o}$ is the mass of the object in the rest frame$v$ is the velocity measured in the frame of interest$c$ is the speed of light 3.00 x 108 ms-1$t$ is the time measured in the frame of interest$d$ is the distance measured in the frame of interest |

### ***Question 1 - Michelson-Morley experiment***

Describe the significance of the Michelson-Morley experiment.

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### ***Question 2 - Frames of reference***

Outline the essential aspects of an inertial frame of reference and identify a method to distinguish an inertial from a non-inertial frame of reference.

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### ***Question 3 - Relativistic cricket***

Anthony and Bill are avid cricket fans and are stuck on a train that is travelling at 90% the speed of light. They decide to set up a cricket game in one of the carriages to pass the time. The boys measure out a cricket pitch in the carriage to be exactly 20.12 metres, the standard length. Bill is not very good at cricket so he ends up just throwing the ball straight at Anthony instead of bowling it. The ball is measured to take 1.2 seconds to reach Anthony.

Another cricket fan, Julia, is playing cricket on a field as the speeding train passes. She is envious that she is not playing their game on such a fast moving train! So to ensure that Anthony and Bill are meeting the standards of the International Cricket Council, she measures the length of their pitch and how long it takes the ball to leave Bill's hand and to arrive at Anthony's bat.

1. Would Julia measure the cricket pitch on the train to be longer or shorter than 20.12 m?

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1. Would Julia measure the time it takes the cricket ball to reach Anthony to be longer or shorter than 1.2 seconds?

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1. What length would Anthony and Bill measure Julia's standard cricket pitch to be? Is this the same as what Julia would measure the length of their pitch to be?

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### ***Question 4 - Future space travel***

In the year 3100 a spaceship is travelling at 0.50*c* towards Gilese 876d, one of the closest exoplanets to Earth at 15 light years (ly). The spaceship plus crew have a total mass of 2000 kg.

1. How long would it take for the spaceship to reach Gilese 876d according to the mission control on Earth?

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1. How long would it take for the spaceship to reach Gilese 876d according to the crew inside the spaceship?

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1. What is the total distance to Gilese 876d as measured by the crew inside the spaceship?

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1. Calculate the mass of the spaceship according to mission control.

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1. What would be the mass of the spaceship if it was travelling at 99.9% of the speed of light? Using the results, justify why it is impossible for spaceships to travel at the speed of light.

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## **Challenge Questions**

### ***Question 1 - Jet from a black hole***

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| Most of the known black holes found in the Milky Way have companion stars that orbit around them. A black hole is a region of space-time that even light cannot escape, and a black hole is formed from the explosion of a massive star as it reaches the end of its life. As material is accreted onto the black hole from the companion star it often forms an accretion disc and an outflow of material that can be thought of as a jet. This system can be thought of as the reverse of what you see when you take the plug out of a bathtub, neglecting the added complications of magnetic fields and relativistic particles!The jet coming from a black hole is made up of electrons spiralling in magnetic fields and moving towards the Earth at velocities that are close to the speed of light. As the electrons spiral, they emit radiation in the form of light. | An artist’s impression of an X-ray binary. The X-ray emission originates mostly from thermal processes associated with the accretion disc.Image reproduced from: [https://commons.wikimedia.org/wiki/File:A\_stellar\_black\_hole.jpg](https://commons.wikimedia.org/wiki/File%3AA_stellar_black_hole.jpg)By ESO/L. Calçada/M.Kornmesser (http://www.eso.org/public/images/eso1028a/) [CC BY 4.0 (http://creativecommons.org/licenses/by/4.0)], via Wikimedia Commons |

From experiments on Earth, astronomers know that the frequency of light emitted by such spiralling electrons is $5.55×10^{13}$ Hz. However, they observe that the light coming from the jet is$6.67×10^{14}$Hz. This difference in frequency can be explained by the theory of Special Relativity and the relativistic Doppler effect.

Use the equation for the relativistic Doppler effect (given below) to calculate the velocity at which the electrons in the jet are moving towards the Earth. You may assume that the jet is pointed directly towards us, so you can neglect any directional effects.

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| $$f=\sqrt{\frac{c+v}{c-v}} f\_{o}$$(relativistic Doppler effect equation) | $f$ is the observed frequency$f\_{o}$ is the frequency in the rest frame$v$ is the velocity of the material in the jet$c$ is the speed of light 3.00 x 108 ms-1 |

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### ***Question 2 - Travelling proton***

A proton in a linear particle accelerator is given an energy of 1 TeV. The relativistic total energy is given by:

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| $$E=\frac{mc^{2}}{\sqrt{1-\frac{v^{2}}{c^{2}}}}$$ | $m$ is the rest mass$v$ is the speed of the particle$c$ is the speed of light 3.00 x 108 ms-1 |

The rest mass of a proton is $1.673×10^{-27}$kg, and 1 eV $=1.602×10^{-19}$J

1. Calculate the speed of the proton (in terms of c) correct to 7 significant figures

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1. What is the mass of the proton in the accelerator’s reference frame? (**Hint**: you need to use the answer from part a) )

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## **Interactive Activities**

### ***Activity 1 - Michelson Morley interferometer***

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|  | Mmur.net: Michelson Morley Flash Applet<http://www.mmur.net/MichelsonMorley.swf>*This interactive provides a clear description of the Michelson and Morley experiment including an interactive image of the Michelson-Morley interferometer, a simulation of the experiment showing photons and aether, as well as the mathematical equations intended for calculating the speed of aether wind.* |

**Instructions**:

* On the “**Intro**” tab, move the mouse over the picture of Michelson and Morley’s interferometer to identify the parts of the experiment.
* Click “**Simulation**” tab to rotate the interferometer with respect to the aether wind by clicking and dragging, and observe the expected interference pattern on the right-hand side of the page. To replay the photons, click the **green ▶ button** on the light source.
* Click “**Simpler**” at the top to see a simplified diagram of how Michelson-Morley interferometer works.
* Click “**Math**” to see the mathematical equations that Michelson and Morley intended to use to calculate the speed of the aether.

### ***Activity 2 - Michelson-Morley experiment***

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|  | The King's Centre for Visualization in Science, The King's University, Alberta, Canada<http://www.kcvs.ca/site/projects/physics_files/specialRelativity/michelsonMorley/mmExperiment.swf> *This interactive clearly demonstrates what interference patterns look like and their corresponding wave superpositions. It also compares what Michelson and Morley expected to see and what they actually observed.* |

**Instructions**:

* Click “**START**” and read the “**Instructions**”. Click the **x button** on the top right corner of the instructions box to close it.
* Click “**Light On**” and “**Expected Results**” located on the bottom of the screen
* Click and drag the “**Rotation**” slide bar to rotate the interferometer. To enter a value manually, click the **# button** next to the slider. Notice how the interference pattern and the superposition of waves change with the rotation of the interferometer.
* To turn the aether wind ON and OFF go to “**Options**” and select “**Show Ether Wind**”.
* Move the red slider bar to a feature in the ”**Interference Fringes**”. Click “**Record Data**” and a red star will appear that marks the location of the feature.
	+ Rotating the interferometer shows how much the red star (and hence the interference pattern) has shifted from the original position.
	+ Move the red slider bar to the red dot and click “**Record Data**” to record its new position. Repeat this step several times to measure various shifts in the interference pattern in relation to the rotation.
	+ Go to “**Options**” and select “**Expected Evidence**” to display the data collected
* Select “**Actual Results**” located on the bottom right and rotate the interferometer to see what Michelson and Morley actually observed.
	+ **Note**: there may be a very small shift in the interference pattern when rotating the interferometer.
	+ Repeat the previous step to collect data for “**Actual Results**” then go to “**Options**”
	 and select “**Actual Evidence**” to display the data collected.
* Go to “**Resources**” and select “**Simulate Experiment**” to access further information and suggestions for this activity.

### ***Activity 3 - Boat race analogy***

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|  | Physics Education Research, University of Illinois, Illinois, United States<http://per.physics.illinois.edu/research/projects/flash/relative_motion_mls.swf>*This interactive shows two things:** *How the velocity of a river can affect various velocities of a boat floating on the river*
* *The boat analogy used to explain how Michelson-Morley experiment works*
 |

**Instructions**:

* Change the boat speed and the river speed by typing a number (between 0-6) in the boxes located on the right hand side and click “**Start**”.Move the mouse over the compass located on the top right to move and control the direction (angle) of the boat. Notice how the *speed* of the boat changes relative to the ground and relative to the river by looking at the gauges located on the bottom.
* Select “**Display Vectors**” to observe the *velocity* of the boat changes relative to the ground and relative to the river.
* Select “**Michelson Exp**” located on the bottom right to observe the boat analogy for the Michelson-Morley experiment. Read the scenario and select the outcome of the race.
* Click “**Start**” to begin the boat race. The boat speed and the river speed can be modified by typing a number (between 0-6) in the boxes located on the left hand side prior to beginning the boat race.

### ***Activity 4 - Light clock in a rocket***

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|  | The King's Centre for Visualization in Science, The King's University, Alberta, Canada<http://www.kcvs.ca/site/projects/physics_files/specialRelativity/photonClock/photonClock.swf> *This interactive compares Einstein’s time clock on a stationary and a moving rocket. It explains how time slows down in a moving frame of reference when measured by a stationary observer. It also allows discussion about what happens to time as the rocket travels closer and closer to speed of light.* |

**Instructions**:

* Click “**START**” and read the “**Instructions**”. Click the **x button** on the top right corner of the instructions box to close it.
* Move the slider bar located on the bottom left to select the speed of the rocket (in terms of c). To enter a value manually, click the **# button** next to the slider.
* Click “**START**” to kickstart the rocket into motion. Compare the light clock in the moving rocket (Rocket Time) to the light clock in the stationary rocket (Lab Time).
* Click “**Record Data**” to record the time in the Lab and time in the Rocket. Go to “**Options**” on the top left and select “**Evidence**” to view the table of results.
* Go to “**Resources**” and select “**Sample Problems**” to access problems to solve. The information for “**Problem 1**” and “**Problem 2**” can be obtained by hovering over the “**Sample Problems**” tab and selecting the problems.

## **Classroom Investigations**

### ***Investigation 1 - Measuring the speed of light***

*This investigation uses a microwave oven to calculate the speed of light by measuring the wavelength of a microwave radiation using an egg white. This can be done by using chocolate or cheese slices instead of egg whites.*

**Equipment**:

* 1 × microwave oven
* 1 × microwave safe plate (width > 20 cm)
* 1 x microwave safe bowl (larger than the drive mechanism inside the microwave)
* 1 × egg
* 1 × 30 cm ruler
* 1 × pair of oven mitts

**Method**:

1. Remove the rotating platter and the drive mechanism for the turntable inside the microwave oven. If it is not possible to remove the drive mechanism, place a flat-bottomed microwave safe bowl upside-down over the drive mechanism.
2. Crack the egg and separate the egg white from the yolk. Pour the egg whites onto the microwave safe plate - make sure the egg spreads out to at least a 12 cm diameter.
3. Place the egg white and plate into the microwave oven. If you are using the bowl, carefully place the plate on top of the upside-down bowl.
4. Set the microwave power to medium and the time to 15 seconds. Press start and, watching the whole time, stop the microwave when the egg white is partially cooked in some places and completely cooked in other places.
5. Use the oven mitts to remove the plate from the microwave oven, being careful not to disturb the position of the egg white on the plate. Allow the plate and the egg white to cool.
6. Measure the centre-to-centre distance between two adjacent cooked areas. This is the ½ of the wavelength of the microwave radiation produced by the microwave oven.
7. Measure the shortest and longest edge-to-edge distances between two adjacent cooked portions.
8. Look at the label on the back of the microwave oven or the user’s manual to find the frequency of the microwave radiation produced by the microwave oven.
9. Calculate the speed of the microwave radiation using the wave equation: $v=fλ$. Calculate the error using the shortest edge-to-edge distance (lower boundary) and longest edge-to-edge distance. Compare the results to the actual value of speed of light.

**Adapted from:**

Science Buddies: Hands-on Science Resources for Home and School

<http://www.sciencebuddies.org/science-fair-projects/project_ideas/Phys_p056.shtml#procedure>

### ***Investigation 2 - Pen & paper frames of reference***pen&paper frames of reference.PNG

*This is a simple investigation to determine whether a person is in an inertial frame of reference or a non-inertial frame of reference by using just a pen and paper. Best done as a* ***pair activity****.*

**Equipment:**

* 4 × sheets of A4 paper
* 1 × felt-tip pen or marker

**Method:**

1. Using the pen or marker, have person 1 draw a straight line from the centre of one paper toward the edge. Make sure the pen is moving smoothly at a constant speed.
2. On a separate paper, have person 1 repeat Step 1, while at the same time person 2 moves the paper in one direction at a constant speed.
3. On another paper, repeat Step 2 but have person 2 accelerate the paper (e.g. moving the paper slowly upwards then increasing speed).
4. One the fourth paper, repeat Step 2 but have person 2 spin the paper at a constant speed.
5. Compare each of the drawings. The lines that you see on each paper represent the pathway of the pen in the paper’s frame of reference. What will the pathway in the pen’s frame of reference look like? From the drawings, how would you determine when the papers’ frame of reference is inertial or non-inertial?

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### ***Investigation 3 - Pendulum accelerometer***

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| This is a simple investigation using a pendulum to determine whether a person is in an inertial frame of reference or a non-inertial frame of reference. *Best done as a* ***pair activity****.***Materials:*** 1 × weight
* 1 × length of string (attached to the weight)
* 1 × skateboard or office chair (with wheels)
 | Image from: <https://pixabay.com/en/pendulum-commute-energy-vibration-622706/>  |

**Method:**

1. Attach the weight to the string, making a pendulum.
2. Suspend the pendulum from one hand while sitting on the skateboard/office chair. Observe the position of the pendulum.
3. Repeat Step 2 but with someone pushing the chair so that the chair is moving at a constant speed. Make sure the hand holding the pendulum is kept still during the process. Observe the position of the pendulum.
4. Repeat Step 2 but with someone pushing the chair so that the chair is moving with an increasing speed (accelerating). Make sure the hand holding the pendulum is kept still during the process. Observe the position of the pendulum.
5. Repeat Step 2 but with someone pushing the chair so that the chair is moving fast and then stopping suddenly. Make sure the hand holding the pendulum is kept still during the process. Observe the position of the pendulum.
6. Repeat Step 2 but with someone spinning the chair. Make sure the hand holding the pendulum is kept still during the process. Observe the position of the pendulum.
7. Compare the observations with the position of the pendulum at rest. Which observations show the pendulum at the same position as the rest position?

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### ***Investigation 4 - Bottle accelerometer***

This investigation involves creating an accelerometer using a soft drink bottle, water and cork. The cork will move in the direction of acceleration since the water and cork have different densities.

**Materials:**

* 1 × 2L PET bottle and lid
* 1 × thumb tack
* 1 × 20 cm length of string
* 1 × cork (small enough to fit through the neck of the bottle)

**Method:**

1. Fill the bottle with water.
2. Using the thumb tack, attach the cork to one end of the string.
3. While holding the opposite end of the string, drop the cork into the bottle. Feed most of the string through the neck of the bottle and secure the loose end of the string by screwing the bottle lid over the loose end.
4. Turn the bottle upside-down and the cork should float in the water, without touching the sides of the bottle.
5. Hold the accelerometer at an arm's length and observe the movement of the cork when:
	* walking at a constant speed
	* walking at an increasing speed
	* walking and then stopping suddenly
	* spinning around in a circle.

**Adapted from:**

*Questacon: The National Science and Technology Centre*

<https://www.questacon.edu.au/outreach/programs/science-circus/activities/bottle-accelerometer>

# **Useful Links**

*Below is a list of further links to supporting materials that may assist in teaching this topic.*

## **Additional Videos**

1. Speed of light is constant (watch from 12.23 to 17.40):

<https://youtu.be/BnmrFrUkBv0?t=12m23s>

*Brian Greene: FABRIC OF THE COSMOS - Part 1/4 : What is Space?*

2. Muon decay:

<https://www.youtube.com/watch?v=ejcaz7wXawY>

*whentheappledrops - The Time Travelling Muon*

3. Muon length contraction:

<https://www.youtube.com/watch?v=4q2aKjrH3TQ>

*Looking from a muons perspective*

4. Frames of reference:

<https://www.youtube.com/watch?v=aRDOqiqBUQY>

*Physical Sciences Study Committee - Frames of Reference (1960)*

5. Special relativity explained from a highschool student perspective: <https://www.youtube.com/watch?v=CYv5GsXEf1o>

*Ryan Chester Explains: The Special Theory of Relativity*

6. Time dilation on airplanes:

<https://www.youtube.com/watch?v=gdRmCqylsME>

*NOVA - Hafele–Keating experiment*

7. Stephen Hawking’s Time Travel:

<https://www.youtube.com/watch?v=Bf2B7DN3tqc>

*Stephen Hawking - What it takes to Time Travel*

## **Additional Questions**

### ***Question 1 - A trip to a black hole***

*From Mysteries of Deep Space, PBS Online, Public Broadcasting Service America*

These questions are based on a futuristic exploration of humans to a black hole 10,000 light years away. A great revision for Newton’s Laws of Motion, density, circular motion, laws of universal gravitation, escape velocity and time dilation.

<http://www.pbs.org/deepspace/classroom/activity4.html>

## **Additional Interactive Activities**

### ***Activity 1 - Michelson-Morley experiment***

*Physics Flashlets, Department of Physics, University of Virginia, Virginia, United States*

This interactive is a simple simulation of the Michelson-Morley setup. Students can change the aether speed and observe what effect aether wind would hypothetically have on the speed of light.

<http://galileoandeinstein.physics.virginia.edu/more_stuff/flashlets/mmexpt6.htm>

**Directions**:

* Click the Play ▶ button on the right side to observe the experiment without aether.
* Increase the aether speed on the bottom left to max and click play again.
* Adjust the angle of the aether by clicking the plus (+) or minus (-) buttons on the right and click play.

### ***Activity 2 - Michelson-Morley interferometer in motion***

*Faculty of Physics and Engineering, Santa Barbara City College, California, United States*

This interactive compares the positions of the wavefronts of light in a Michelson-Morley interferometer when stationary to when moving at a certain velocity.

<http://science.sbcc.edu/~physics/flash/relativity/Michelson%20Interferometer.html>

### ***Activity 3 - A slower speed of light (game)***

*MIT Game Lab, Massachusetts Institute of Technology, Massachusetts, United States*

This a downloadable game built to visualise what occurs when travelling at relativistic speeds. These effects include:

* The Doppler effect (red- and blue-shifting of light)
* The searchlight effect (increased brightness in the direction of travel)
* Time dilation
* Lorentz transformation (warping of space at near-light speeds)
* Runtime effect (the ability to see objects as they were in the past, due to the travel time of light).

<http://gamelab.mit.edu/games/a-slower-speed-of-light/>

\*\*CAUTION\*\* May cause motion sickness and epileptic fits

To download a powerpoint presentation about the relativistic effects in the game, click the link below:

<http://gamelab.mit.edu/wp/wp-content/uploads/2012/10/Special-Relativity.pptx>

### ***Activity 4 - Real time relativity***

*Research School of Physics & Engineering, Australian National University, ACT, Australia*

This is a downloadable simulation which involves controlling a spaceship travelling at relativistic speeds. Just like the game in Activity 3, this simulation can be used to observe the Doppler effect, searchlight effect and time dilation.

<http://people.physics.anu.edu.au/~cms130/RTR/>

**Video preview:** <https://youtu.be/eAqmqFDmqQk>

## **Book References**

### ***Book 1 - The Science of Interstellar***

Thorne, K. (2014). *The Science of Interstellar*. New York: W. W. Norton & Company Inc.

**Blurb:** “A journey through the otherworldly science behind Christopher Nolan’s highly anticipated film, Interstellar, from executive producer and theoretical physicist Kip Thorne.”

This book explains the physics behind the extraordinary events and visuals introduced in the movie, *Interstellar*. A fascinating read for anyone who wants to learn more about relativity and cosmology.

 

**Web Source:**

<https://books.google.com.au/books?id=PbWYBAAAQBAJ&lpg=PP1&dq=the%20science%20of%20interstellar&pg=PT521#v=onepage&q&f=false>

### ***Book 2 - Horrible Science: Terrible Time***

Arnold, N., & De Saulles, T. (2014)*. Horrible Science: Terrible Time.* London: Scholastic Children’s Books.

**Blurb:** “Go time-travelling with Terrible Time and discover all the terrifying time facts you've been waiting ages to find out. See what happens if you go too close to a black hole and how flies tell the time!”

This book introduces many strange phenomena in physics and astronomy in a fun and engaging story.

**Web Source:**

<https://books.google.com.au/books?id=pJZ8BgAAQBAJ&lpg=PA141&ots=zcoCm0o-j7&dq=horrible%20science%20special%20relativity&pg=PA140#v=onepage&q&f=false>

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