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.

Terms	Definition
Aether (also ether)	A medium that was thought to have filled the universe allowing light to propagate through space.
Inertial frame of reference	A frame of reference (or reference frame) that moves with constant velocity or is at rest.
Non-inertial frame of reference	A frame of reference that is accelerating.
Speed of light (*c*)	The speed at which light travels (3×10^8 ms^{-1}). It is constant and is independent of the speed of the source or the observer.
Length contraction	The length of a moving object becomes shorter in the direction of motion relative to a stationary observer.
Time dilation	The time observed in a moving reference frame becomes slower relative to time for a stationary observer.

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

2. Frames of reference:
   https://www.youtube.com/watch?v=mYH_nODWkqk
   Flipping Physics - Skateboarding Frame of Reference Demonstration

3. Speed of light is constant:
   https://www.youtube.com/watch?v=vVKFBaaL4uM
   Veritasium - Can you travel at the speed of light?

4. Simultaneity:
   https://www.youtube.com/watch?v=wteiuxyqtoM
   Simultaneity - Albert Einstein and the Theory of Relativity

5. 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

6. Explaining the twin paradox
   https://www.youtube.com/watch?v=ERgwVm9qWKA
   Physics Girl - Special relativity and the Twin Paradox

7. Examples of Special Relativity: Muon Decay
   https://www.youtube.com/watch?v=IEeOLZmH7IE
   It's Okay To Be Smart - How to see time travel!!!

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

Practice Questions

Useful formulae:

$v = \frac{d}{t}$ (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)	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

Question 1 - Michelson-Morley experiment

Describe the significance of the Michelson-Morley experiment.

The Michelson-Morley experiment attempted to measure the speed of the Earth through the aether. It was designed to measure the speed of light through the aether as the Earth moved in its orbit around the Sun. No motion of the Earth relative to the aether could be detected. This indicated that the aether was not needed as a medium for light to propagate through.

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.

Within an inertial frame of reference you cannot perform any mechanical experiment or observation that would reveal to you whether you were moving with uniform velocity or standing still. To test if you are in an inertial or non-inertial (accelerating) frame of reference you can use:

- A pendulum (or any hanging weight) – In an inertial reference frame, the pendulum will hang directly down. In a non-inertial reference frame, a pendulum will be at an angle, dependent upon the size and direction of acceleration.
- Dropping an object directly down – In an inertial reference frame, the object will appear to fall straight down. In a non-inertial reference frame, it will fall in a slightly different direction, dependent upon the size and direction of acceleration.

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 2.4 seconds to travel to Anthony's cricket bat and return to Bill.

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, travel to Anthony's cricket bat and return to Bill.

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

Julia is stationary and the pitch on the train is moving relative to her. That means she is trying to work out l_v in the length contraction equation. Since $\sqrt{1-\frac{v^2}{c^2}} < 1$ this means that l_v will be smaller than l_o. To make it easy to answer this, remember the phrase - "moving objects are shortened".

To check this we can calculate l_v using the length contraction equation.
The length in the rest frame is l_o = 20.12m. The velocity of the frame moving relative to Julia is $v = 0.9c$. We are trying to solve for l_v:

From the information: $l_o = 20.12$m, $v = 0.90c$, $l_v = ?$

$$l_v = l_o\sqrt{1-\frac{v^2}{c^2}} = 20.12\sqrt{1-\frac{(0.90c)^2}{c^2}}\text{m} = 8.7701\ldots\text{m}$$

Hence the length measured by Julia (8.8 m) is shorter than 20.12 m.

b) Would Julia measure the time it takes the cricket ball to reach Anthony to be longer or shorter than 2.4 seconds?

Similar to above, Julia is trying to solve for t_v, the time it takes an event to occur in a frame moving relative to her. Since $\sqrt{1-\frac{v^2}{c^2}} < 1$, therefore t_v will be bigger thant_o since $\sqrt{1-\frac{v^2}{c^2}} > 1$, which means that the time she measures will be longer. This can be summed up in the phrase - "moving clocks run slow".

To check this we can calculate t_v using the time dilation equation.
The time in the rest frame is t_o = 2.4s. The velocity of the frame moving relative to Julia is $v = 0.90c$.
We are trying to solve for t_v:

From the information: $t_o = 1.2\text{s}$, $v = 0.90c$, $t_v = ?$

$$t_v = \frac{t_o}{\sqrt{1-\frac{v^2}{c^2}}} = \frac{2.4}{\sqrt{1-\frac{(0.90c)^2}{c^2}}} = 5.505...\text{s}$$

Hence the time measured by Julia (2.8 s) would be longer than 2.4 s.

c) 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?

To solve this question, it is best to write down the variables you know and what variable you want to solve for. The length of the pitch in its rest frame is $l_o = 20.12\text{m}$. The velocity of the frame moving relative to Julia is $v = 0.90c$. We are trying to solve for l_v

So: $l_o = 20.12\text{m}$, $v = 0.90c$, $l_v = ?$

$$l_v = l_o\sqrt{1 - \frac{v^2}{c^2}} = 20.12\sqrt{1 - \frac{(0.90c)^2}{c^2}}\text{m} = 8.7701...\text{m}$$

Hence the length of the pitch would be 8.8 m (2 sig. fig.), less than the rest length of the pitch of 20.12m.

Thus, the length measured by Anthony and Bill will be exactly the same as the length that Julia will measure from part a). This is because both frames of reference are moving relative to one-another, meaning that both Julia and the boys are measuring moving frames of reference.

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.

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

In the mission control's reference frame, the spaceship is travelling a distance of 15 ly at a speed of 0.50*c*.
from the information: $v = 0.50c$, $d = 15\text{ly} = 15c.\text{yr}$, $t = ?$

$$v = \frac{d}{t} \Rightarrow t = \frac{d}{v} = \frac{15c}{0.5c}\text{yr} = 30\text{yr}$$

Hence it takes 30 years for the spacecraft to reach Gilese 876d according to the mission control.

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

In the reference frame of the spaceship crew, the crew are stationary while the region outside of the spaceship is moving at 0.50*c* . We know from part a) that the trip took 30 years mission control's reference frame (outside of the spaceship).

From the information: $v = 0.50c$, $t_v = 30$yr, $t_o = ?$

$$t_v = \frac{t_o}{\sqrt{1 - \frac{v^2}{c^2}}} \Rightarrow t_o = t_v\sqrt{1 - \frac{v^2}{c^2}} = 30\sqrt{1 - \frac{(0.50c)^2}{c^2}}\text{yr}$$

$$t_o = 25.9807...\text{yr}$$

Hence it takes 26 years (2 sig. fig.) for the spacecraft to reach Gilese 876d according to the spaceship crew.

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

The distance between Earth and Gilese 876d is 15 ly at rest. Relative frame of reference of the spaceship, the Earth and Gilese 876d are moving at 0.5c, so the distance between the Earth and Gilese 876d will contract.

From the information: $v = 0.50c$, $l_o = 15$ly, $l_v = ?$

$$l_v = l_o\sqrt{1 - \frac{v^2}{c^2}} = 15\sqrt{1 - \frac{(0.50c)^2}{c^2}}\text{ly} = 12.9903...\text{ly}$$

Hence the distance the crew travels has contracted to 13 ly (2 sig. fig.).

Challenge Questions

Question 1 - Jet from a black hole

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.

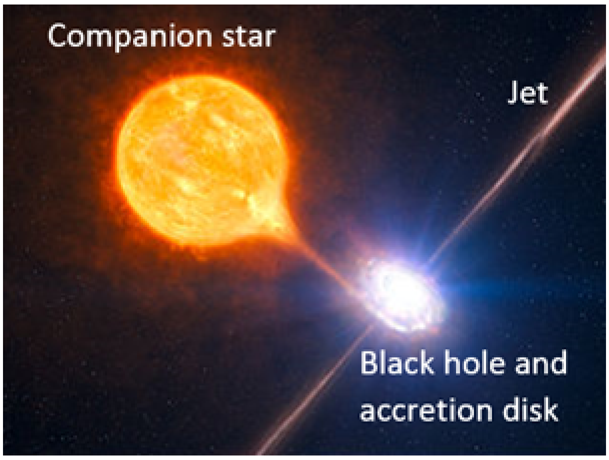


Image reproduced from:
https://commons.wikimedia.org/wiki/File:A_stellar_black_hole.jpg

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.

$f = \sqrt{\frac{c+v}{c-v}}\, f_o$ (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 10^8 ms^{-1}

From the information: $f = 6.67 \times 10^{14}$Hz, $f_o = 5.55 \times 10^{13}$Hz, $v = ?$

We are solving for v:

$$f = \sqrt{\frac{c+v}{c-v}}\, f_o \quad \Rightarrow \quad v = \frac{\left(\frac{f}{f_o}\right)^2 - 1}{\left(\frac{f}{f_o}\right)^2 + 1} c = \frac{\left(\frac{6.67\times10^{14}}{5.55\times10^{13}}\right)^2 - 1}{\left(\frac{6.67\times10^{14}}{5.55\times10^{13}}\right)^2 + 1} c = 0.98$$

This means the material is streaming out of the black hole system at ~99% the speed of light! The fact that this is millions of tons of material demonstrates the extreme type of environments that exist in space and around black holes.

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:

$$E = \frac{mc^2}{\sqrt{1-\frac{v^2}{c^2}}}$$	m is the rest mass v is the speed of the particle c is the speed of light 3.00 x 10^8 ms^{-1}

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

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

$$E = \frac{mc^2}{\sqrt{1-\frac{v^2}{c^2}}} \Rightarrow v = c\sqrt{1 - \frac{(mc^2)^2}{E^2}}$$

$$v = c\sqrt{1 - \frac{(1.673\times10^{-27}\times(3.00\times10^8)^2)^2}{(1\times10^{12}\times1.602\times10^{-19})^2}} = 0.99999955...c$$

Hence the proton is travelling at 0.9999996*c* (7 sig. fig.)

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

In the accelerator's reference frame, the mass of the proton should dilate.

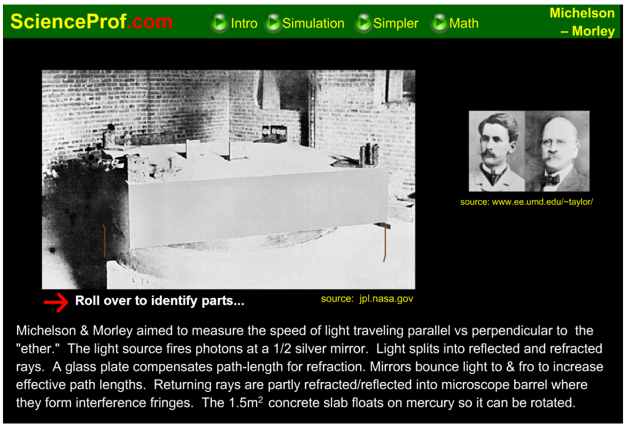
From the information: $v = 0.9999996c$(remember to SAVE the exact value into your calculator), $m_o = 1.673 \times 10^{-27}$kg, m_v =?

$$m_v = \frac{m_o}{\sqrt{1-\frac{v^2}{c^2}}} = \frac{1.673\times10^{-27}}{\sqrt{1-\frac{(0.9999996c)^2}{c^2}}}\text{kg} = 1.8938\ldots\times 10^{-21}\text{kg}$$

Hence, the mass of the moving proton is greater than the rest mass by factor of 6.

Online Interactives

Interactive 1 - Michelson Morley interferometer

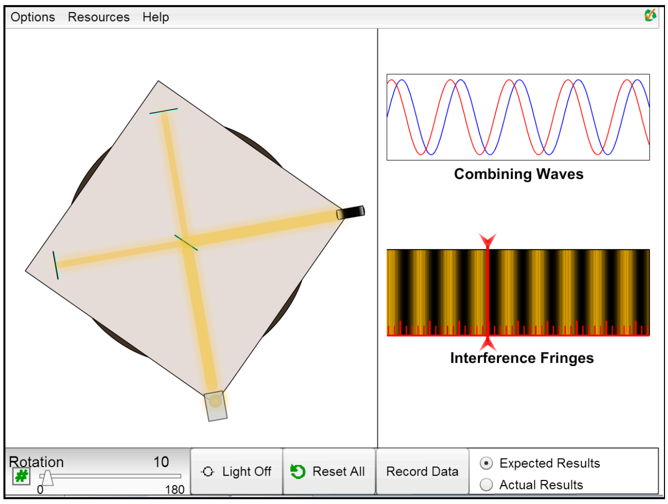


Mmur.net: Michelson Morley Flash Applet
http://www.mmur.net/MichelsonMorley.swf

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.

Interactive 2 - Michelson-Morley experiment



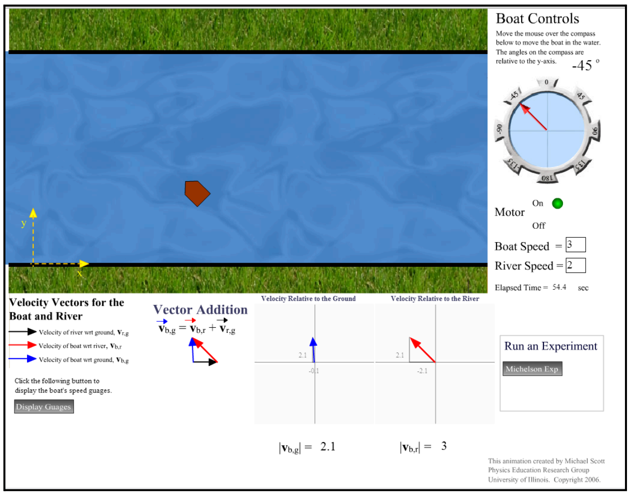
The King's Centre for Visualization in Science, The King's University, Alberta, Canada
http://www.kcvs.ca/site/projects/physics_files/specialRelativity/michelsonMorley/mmExperiment.swf

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.

Interactive 3 - Boat race analogy



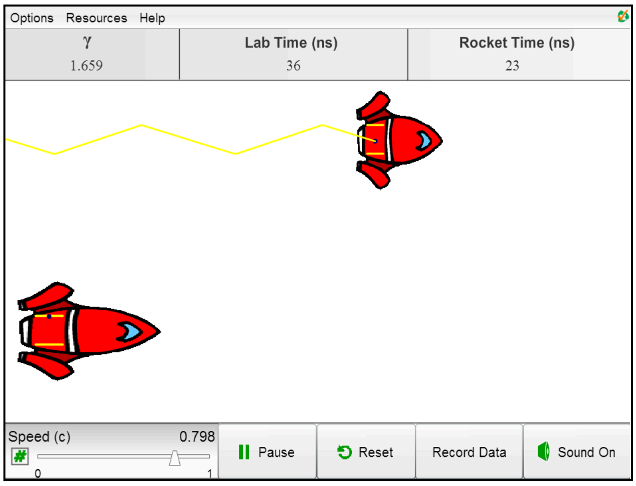
Physics Education Research, University of Illinois, Illinois, United States
http://per.physics.illinois.edu/research/projects/flash/relative_motion_mls.swf

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.

Interactive 4 - Light clock in a rocket



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.

Practical Activities

Activity 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.

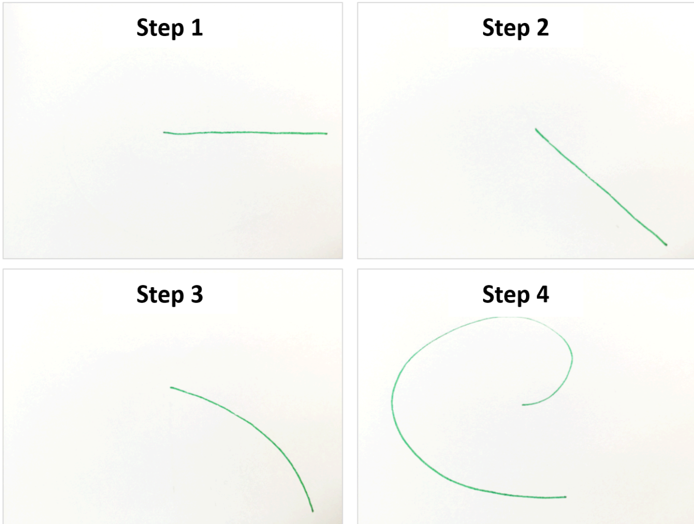
Equipment:
- 1 × microwave oven
- 1 × microwave safe plate (width > 20 cm)
- 1 x microwave safe bowl (larger than the drive mechanism inside the microwave)
- 1 × egg
- 1 × 30 cm ruler
- 1 × pair of oven mitts

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: $v = f\lambda$. 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

Activity 2 - Pen & paper frames of reference

*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?

Teachers notes:

The lines in Step 1 and Step 2 will be in an inertial frame of reference since the lines were drawn on a stationary paper (Step 1) and a paper with constant velocity (Step 2).

Steps 3 and 4 were drawn in a non-inertial frame of reference since the paper was accelerating in Step 3, and in Step 4 the paper had an angular velocity and thus non-inertial (any rotating/spinning object is in a non-inertial frame of reference).

Activity 3 - Pendulum accelerometer

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?

Activity 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.

- https://youtu.be/BnmrFrUkBv0?t=12m23s (watch from 12.23 to 17.40)
  Brian Greene - FABRIC OF THE COSMOS - Part 1/4 : What is Space?

- https://www.youtube.com/watch?v=ejcaz7wXawY
  whentheappledrops - The Time Travelling Muon

- https://www.youtube.com/watch?v=4q2aKjrH3TQ
  Doc Schuster - Relativistic Length Contraction Explains why Muons hit the Surface of Earth

- https://www.youtube.com/watch?v=aRDOqiqBUQY
  Physical Sciences Study Committee - Frames of Reference (1960)

- https://www.youtube.com/watch?v=CYv5GsXEf1o
  Ryan Chester - Ryan Chester Explains The Special Theory of Relativity

- https://www.youtube.com/watch?v=gdRmCqylsME
  NOVA - Hafele–Keating experiment (time dilation on airplanes)

- https://www.youtube.com/watch?v=Bf2B7DN3tqc
  Stephen Hawking - What it takes to Time Travel

- http://www.pbs.org/deepspace/classroom/activity4.html
  PBS Online - Mysteries of Deep Space (Activity: A Classical & Relativistic Trip to a Black Hole)

- http://galileoandeinstein.physics.virginia.edu/more_stuff/flashlets/mmexpt6.htm
  Physics Flashlets, University of Virginia - Michelson-Morley experiment

- http://science.sbcc.edu/~physics/flash/relativity/Michelson%20Interferometer.html
  Faculty of Physics and Engineering, Santa Barbara City College - Michelson-Morley interferometer in motion

- http://gamelab.mit.edu/games/a-slower-speed-of-light/
  MIT Game Lab - A slower speed of light (game). To download a PowerPoint about the relativistic effects of the game click here.

- http://people.physics.anu.edu.au/~cms130/RTR/
  Research School of Physics & Engineering, Australian National University - Real time relativity. For a video preview of this click here.

- https://goo.gl/87tr3w
  Kip Thorne - The Science of Interstellar (book preview)

- https://goo.gl/ZFR8Ty
  Nick Arnold & Tony De Saulles - Horrible Science: Terrible Time (book preview)