

Matter and relativity 2: Introduction to relativity

Components

NAME	DESCRIPTION	AUDIENCE
	<i>Introduction to relativity</i> teachers guide	The teachers guide provides suggestions and strategies for using presentations on relative motion and theories of relativity.
	<i>Relative motion</i> presentation	This presentation introduces students to frames of reference, and demonstrates that all motion is relative.
	<i>Theories of relativity</i> presentation	This presentation describes aspects, and some consequences, of Einstein's special and general theories of relativity.
	<i>Exercises in relativity</i> worksheet	Students explore some consequences of the special theory of relativity. They discover that an object's relative motion causes time, mass and length to change, but these effects only become significant at speeds approaching the speed of light. They also discover why objects with mass cannot reach, or exceed, the speed of light. The worksheet includes both quantitative and qualitative questions to help students construct an understanding of the consequences of special relativity.

Purpose

To describe aspects of the special and general theories of relativity in qualitative terms.

Outcomes

Students:

- describe the evolutionary nature of scientific knowledge;
- describe aspects of the special theory of relativity, including: frames of reference; the effects of relative motion on time, length and mass; and the equivalence of energy and mass; and
- describe aspects of the general theory of relativity, including the effects of gravity on light and spacetime.

Activity summary

ACTIVITY	POSSIBLE STRATEGY
Teacher introduces the concept that all motion is relative, through discussion of the speed of two vehicles relative to each other and to a stationary observer.	teacher-led discussion
Teacher shows the presentation, <i>Relative motion</i> , pausing at the points indicated in the slides for students to discuss questions with others.	think, pair, share
Students note any points they don't understand, and discuss with other students.	students make their own notes: think, pair, share
Teacher and/or other students answer any unresolved questions.	
Students and/or teacher summarise the main points in the presentation.	teacher-led discussion

ACTIVITY	POSSIBLE STRATEGY
Teacher introduces and shows the presentation, <i>Theories of relativity</i> .	
Students note any points they don't understand, and discuss with other students.	students make their own notes: think, pair, share
Teacher and/or other students answer any unresolved questions.	
Students and/or teacher summarise the main points in the presentation.	teacher-led discussion
Teacher discusses areas of interest and/or difficulties students have in accepting these challenging ideas.	
Students complete worksheet, <i>Exercises in relativity</i> . Teachers may choose to use the worksheet as a formative or summative evaluation of students' understanding, or simply to practise applying concepts associated with the special theory of relativity.	individual student work

Teacher notes

The main points covered in the presentation, *Relative motion*, are:

- All motion is relative. Observers may describe the same event differently because of their differing frames of reference.
- Within a frame of reference, there is no measurement you can make that will tell you whether you are stationary or moving with constant velocity.
- Motion can only be described in relation to another object or frame of reference.
- There is no such thing as being 'absolutely' stationary — all objects are in motion relative to some other frame of reference.

The following notes accompany the presentation, *Relative motion*.

SLIDE	NOTES
3	<p>This example should focus students' thoughts on frames of reference.</p> <ul style="list-style-type: none"> • The boy's comment is correct in the frame of reference of an observer standing at a fixed point on Earth. • The girl's comment is correct in the frame of reference of an observer located on the sun or somewhere in space from where she could observe both Earth and Sun. <p>(Note: A 'frame of reference' is an arbitrary set of axes against which the motion or position of an object can be described.)</p>
7	<ul style="list-style-type: none"> • Student discussion should focus on a test that could be performed entirely within the train's frame of reference and doesn't rely on any data from outside sources. For example, they shouldn't describe their train's motion (or lack of motion) relative to an object outside the train, such as a tree or the station. • The trains have constant velocity (including zero velocity). <p>The usual answer is that they could deduce whether their train was moving or not based on their observations of the motion of a falling object.</p>
10	<p>This slide provides an opportunity to discuss what students understand by the statement: 'if you aren't moving relative to the boat'. It may mean that the observer and the boat are both stationary, or that they are moving at the same speed.</p> <p>In both cases, the observer will see the object falling vertically, so the result doesn't tell you whether the boat is moving or not</p>
11	<p>If the object falls along a parabolic path, the object and the observer are in different frames of reference.</p> <p>If the object falls straight down, the object and the observer are in the same frame of reference.</p>
12	<p>The principle of relativity is part of Einstein's special theory of relativity, which only relates to inertial (non-accelerating) frames of reference. A consequence of the principle is that an observer <i>in an inertial frame of reference</i> cannot determine an absolute speed or direction of travel in space, and can only describe speed or direction relative to some other object.</p>

SLIDE	NOTES
15	<p>The example shows that there is no absolute state of rest. While we might think we are stationary within our frame of reference, we are in motion relative to other frames of reference.</p> <p>How fast does Earth rotate?</p> <p>Earth's circumference is approximately 40 075 km and its period of rotation is 24 hours. Relative to an imaginary fixed point at the centre of the Earth, an object at the Equator has a speed of approximately 465 m s^{-1} (or 1670 km h^{-1}). Multiply this figure by the cosine of your latitude to determine how fast the Earth is rotating at your location.</p> <p>How fast does Earth orbit the Sun?</p> <p>Earth orbits the sun at an average radius of 149 597 890 km in 365 days. This is an average orbital speed of $29 806 \text{ m s}^{-1}$ (or $107 300 \text{ km h}^{-1}$).</p> <p>How fast does the Milky Way rotate?</p> <p>The sun is about 28 000 light years from the centre of the Milky Way. It orbits that centre every 225 million years, at an average speed of approximately 230 km s^{-1} or $800 000 \text{ km h}^{-1}$.</p> <p>How fast does the Milky Way move?</p> <p>Our galaxy is moving towards the Centaurus constellation at a speed of over $2 000 000 \text{ km hr}^{-1}$, pulled by an apparent concentration of mass in this region.</p>

The main points covered in the presentation, *Theories of relativity*, are:

The special theory of relativity

- The special theory of relativity is based on two ideas: all observers measure the same speed of light in a vacuum, regardless of their speed relative to the light source; and there is no absolute frame of reference.
- To a stationary observer watching an object travelling at close to the speed of light: time appears to slow down; mass appears to increase, and length in the direction of travel appears to decrease.
- Because all motion is relative, an observer travelling at close to the speed of light (relative to a 'stationary' observer) will see that time, mass and length for a stationary observer have all changed.
- Objects with mass cannot reach or exceed the speed of light.
- Energy and mass are equivalent ($E = mc^2$).

The general theory of relativity

- Space and time merge into four-dimensional spacetime.
- Large masses distort spacetime.
- Gravity results from the distortion of spacetime.
- Gravity causes light to bend towards large masses because of the distortion of spacetime.
- Time runs slower in areas where the gravitational field is stronger.

Einstein versus Newton

- Newton's theories explain motion and gravity under 'normal' conditions.
- Relativity provides better explanations of phenomena that occur when objects travel at speeds close to the speed of light.
- Relativity provides better explanations of phenomena that occur in strong gravitational fields.

The following notes accompany the presentation, *Theories of relativity*.

SLIDE	NOTES
4	<ol style="list-style-type: none"> 1. Light from spaceship B travels to the observer at $c = 3.00 \times 10^8 \text{ m s}^{-1}$. 2. Light from spaceship A also travels to the observer at $3.00 \times 10^8 \text{ m s}^{-1}$. However, some students may incorrectly answer $c + 1000 \text{ km h}^{-1}$. 3. Students who correctly answer questions 1 and 2 should deduce that the observer would see a collision with both spaceships damaged simultaneously by the impact. <p>Students who answer question 2 incorrectly should say that, at the moment of impact, spaceship A is crumpled while spaceship B hasn't yet reached the collision point (because light from spaceship A reaches the observer before light from spaceship B), ie the situation isn't sensible.</p> <p>If light didn't travel at the same speed, regardless of the motion of the emitting body, the Universe wouldn't make sense. Einstein's logical conclusion was that the speed of light in a vacuum is constant and independent of the speed of the emitting body.</p>
5	<p>There is no privileged frame of reference when one is observing and measuring the physical world. No single frame of reference is more valid than any other.</p>
6–9	<p>To observer A in the moving truck, light shines up onto the mirror and reflects along the same path. To stationary observer B, light travels at an angle and follows a longer path due to the truck's motion. Each observation is correct within its frame of reference.</p> <p>Note: It is recommended that discussion of this slide should focus on the constant speed of light. While it is possible to introduce concepts such as time dilation and length contraction, it is not recommended at this stage of the presentation.</p>

SLIDE	NOTES
11–13	<p>A stationary observer watching an object travelling at close to the speed of light would see that time on the object appears to run slower; its mass appears to increase; and its length appears to be shorter. However, an observer travelling at the same speed as the object wouldn't be able to detect any change in time, length or mass.</p> <p>Because all motion is relative, the observer travelling at close to the speed of light would see that time, mass and length, for the stationary observer, have all changed.</p> <p>The worksheet, <i>Exercises in relativity</i>, includes examples to help students understand some of these complex ideas.</p>
15	<p>Infinite energy would be required to make an object with mass travel at the speed of light ($E=mc^2$). Because photons can travel at the speed of light, it follows that they must have zero rest mass.</p> <p>The worksheet, <i>Exercises in relativity</i>, provides examples for students to explore the effect of speed on mass.</p> <p>(Note: Rest mass is the mass of the object when it is at rest relative to the observer. One of the consequences of special relativity is that the mass of an object increases as its velocity increases relative to the observer.)</p>
17	An explanation of how special relativity leads to the equivalence of energy and mass ($E=mc^2$) is provided in the notes following this table.
20	<p>Newtonian physics tells us that objects travel at constant speed in a straight line unless an external unbalanced force acts on them, and that objects attract each other with a force (gravity) that depends on their masses and the distance apart.</p> <p>In general relativity, gravity is a property of the universe rather than of an individual body. Gravity is described in terms of the geometry of spacetime, which is distorted by mass and energy. Whenever an object travels through the universe it follows a path (geodesic) that is curved by any mass in the vicinity. What we feel as the 'force' of gravity is simply the sensation of following the shortest path we can, through curved spacetime.</p> <p>According to general relativity, a force must be applied to an object to prevent it from moving along a geodesic. For example, when we stand still we are no longer moving along the geodesic because the Earth's surface is exerting an upward force on us to prevent the motion.</p> <p>(Note: A geodesic is the shortest route between two points in curved spacetime.)</p>
22	Light from a distant object bends as it travels past a large mass. The bending is caused by the distortion of spacetime. This effect causes observers on Earth to see the object in a different location from its real position.
23	<p>In this photograph there is a massive object, in the foreground, which is distorting spacetime, causing light from a distant quasar to bend around it. This effect causes observers on Earth to see four images of the same quasar. In effect, the massive object is behaving like a convex lens bending light around itself.</p> <p>Analysis of light characteristics and other observational data confirm that A, B, C and D are images of the same object. Reference: http://www.sdss.org/news/releases/20031217.lensing.html</p>
24	The concepts represented in this slide are further developed in the worksheet, <i>Exercises in relativity</i> . The learning object, <i>Satellite clock explorer</i> , and worksheet, <i>Satellite clocks</i> , also provide opportunities for students to explore time dilation due to special and general relativity.
25	For more details on the Australian International Gravitational Observatory, see http://www.gravity.uwa.edu.au .

Image credits

Relative motion

- Milky Way: NASA/JPL-Caltech/R. Hurt (SSC-Caltech)
- Hubble Ultra Deep Field: NASA, ESA, S. Beckwith (STScI) and the HUDF Team

Theories of relativity

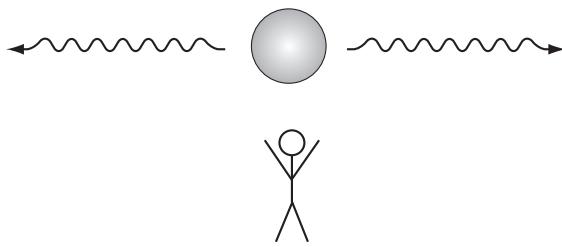
- photo of Einstein in 1905: Albert-Einstein-Archiv, Jerusalem, Lucien Chavan.
- gravitational lensing: NASA, ESA, Richard Ellis (Caltech) and Jean-Paul Kneib (Observatoire Midi-Pyrénées, France)
- Sun: SOHO (ESA & NASA)
- photo of Einstein in 1921: F. Schmutzler
- gravitational lensing of a quasar: Sloan Digital Sky Survey
- GPS satellite: NASA
- Ripples in spacetime: NASA/JPL, Kip Thorne (Caltech) and T. Carnahan (NASA/GSFC).
- International Space Station: NASA Marshall Space Flight Center (NASA-MSFC)
- supermassive black hole: NASA/JPL-Caltech/Tim Pyle (SSC)

An explanation of the energy-mass equivalence principle

Energy-mass equivalence ($E = mc^2$) is often cited as a consequence of Einstein's special theory of relativity, but the connection between these two ideas is not immediately obvious.

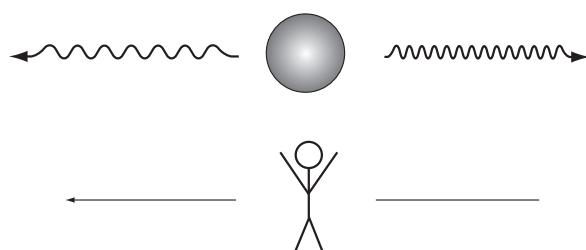
It arose from a 'thought experiment' by Einstein. Some of the most revolutionary ideas in physics originated via thought experiments. These experiments cost nothing at the time, but require billions of dollars of physics equipment to test today!

Imagine an observer (let's call him Sam) watching an object, where neither Sam nor the object is moving relative to the other. Remember, relativity says that we can't tell whether an object is moving or not, just whether it is moving relative to another object or frame of reference.



Sam sees two identical pulses of light emitted by the object in opposite directions at the same instant. You already know that a moving mass has momentum (mass \times velocity), but electromagnetic waves (including light) also have momentum. In this case, the momentum carried by the two light pulses is equal in size, and opposite in direction, so they cancel each other out and the law of conservation of momentum is obeyed.

Now imagine another observer, Samantha, who is moving relative to the object (let's say to the left). Of course, we can equally say that Samantha is stationary and it's the object (and Sam) who are moving to the right.



Like Sam, Samantha also sees two light pulses emitted from the object at the same time. In addition, she sees that there is no change in the speed of the object (therefore no change in its momentum, mass \times velocity). But the two light pulses no longer look the same. The pulse travelling in the same direction as Samantha appears to have a longer

wavelength (it's 'red-shifted'), whilst the pulse travelling in the opposite direction appears to have a shorter wavelength ('blue-shifted').

The two light pulses no longer have the same momentum! The pulse with the shorter wavelength has more momentum than the pulse with the longer wavelength ($P = h/\lambda$). When momentum is added (vector addition) there appears to be a net transfer of momentum to the right. If the object's speed hasn't changed, where has the extra momentum come from?

According to the special theory of relativity, the laws of physics (including conservation of momentum) must hold for both Sam and Samantha as there is nothing special about their two frames of reference.

To solve this problem, Einstein proposed that when the object emits light pulses it loses a little of its mass (and hence a little of its momentum). This is where the extra momentum has come from, and we can see that it is conserved from both Sam's and Samantha's points of view. Knowing the relationship between momentum and frequency, Einstein derived a formula for the amount of mass lost by the object (m) as a function of the energy carried by the light pulses (E) and speed of light (c), or $m = E/c^2$. Rearranging this we get the familiar equation, $E = mc^2$.

Technical requirements

The presentations, *Relative motion* and *Theories of relativity*, are provided in Microsoft PowerPoint and Adobe PDF formats.

The guide and worksheet require Adobe Reader (version 5 or later), which is a free download from adobe.com. The worksheet is also provided in Microsoft Word format.

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