Unit title	The special Theory of Relativity and Time Dilation
Topic	Einstein and relativity concepts such as time, light and gravity
Name and email address of person submitting unit	Not available
Aims of Unit	This unit encourages pupils to think about Einstein's special theory of relativity. It requires pupils to absorb information and relate this to the development of a theory.
Indicative content	Gravity, time, light Relativity and Muons.
Resources needed	The pupils will require access to the paper in either hard or electronic form.
Teachers notes	This is a challenging main task appropriate for pupils who are 16+ the whole task will require at least 50 minutes. This task requires pupils to discuss and digest information and then respond to embedded questions which require calculations. Learning Outcomes All students will be able to discuss some key points of the theory of special relativity. Most students with some help will be able to attempt the embedded tasks within this presentation. Some students unaided will complete the calculations and relate these to observations and theoretical predictions.

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Date:	Topic: The special theory of Relativity and time dilation	Time: 1 hour	Class: 16+

SEN pupils

Gifted and Talented

Class Room Support

Equipment needed for this activity:

Access to the work sheet in either hard copy or electronic form.

Health and Safety:

None

Learning outcomes for this activity

All students will be able to discuss some key points of the theory of special relativity.

Most students with some help will be ale to attempt the embedded tasks within this presentation.

Some students unaided will complete the calculations and relate these to observations and theoretical predictions.

Starter Activity
Main Activity Students will use a presentation which has embedded formulae and questions to investigate Special relativity and time dilation.
Plenary Activity

Reflections on the lesson

The Special Theory of Relativity and Time Dilation

Albert Einstein proposed the special theory of relativity in 1905. At first the scientific community saw little special about it and not much interest was shown. Consequently the theory revolutionised 20th century physics, and 100 years later Einstein's life and work are well known by the general public worldwide.

Einstein's proposal was based on two ideas:

- that the speed of light in vacuum is constant for all observers no matter how they are moving
- that the laws of physics are the same for all systems that move relative to each other at a steady speed.

Einstein used *gedanken* (thought) experiments to develop his ideas, and much is written about how he imagined what things would look like if he could ride on a beam of light. But he also built on and acknowledged the work of others, (Maxwell, Lorentz, Poincare to name a few), like any other scientist. The special theory of relativity is often expressed in terms of mathematical equations outside the grasp of most people, yet essentially it is the concept that is most challenging to students of the theory. On this Einstein believed that the thinking involved was most suited to a child, and said,

"The normal adult never bothers his head about space-time problems. Everything there is to be thought about it……has already been done in early childhood. I, on the contrary, developed so slowly that I only began to wonder about space and time when I was already grown up."

In Einstein's view therefore the concepts, if not the mathematics, of the special theory of relativity should be accessible to students of all ages. This piece of work, including student activity, tackles one consequence of the special theory, time dilation.

Time dilation means that a process that takes a certain time to occur in a moving system is observed to take a longer time by someone outside the system. Accepting Einstein's advice that this concept can be understood using child-like thinking, let's consider the principle using an analogy from the fairground.

Imagine a Ferris wheel moving clockwise at a known steady, slow speed. A girl watching the wheel and her friends in different cars of it, decides she can tell the time by watching the cars pass a fixed point as long as she knows the start time and the number of cars that pass the point each hour. She probably isn't concerned that she sees the cars by photons of light reflected from them, and these travel to her at the speed of light – she doesn't need this idea to tell the time! Scientists say the girl is in *a stationary frame of reference* when she observes the wheel like this.

Now ask yourself what happens if she moves. Let's say she moves in a circle too, inside the wheel but centred at the same point, but she moves slower than the wheel. The cars still pass her, and she still sees them by reflected photons of light moving at the same speed according to Einstein, but the cars will take longer to pass because she is moving. The time that adjacent cars take to pass her has increased because her frame of reference is no longer stationary, and this change affects her method of telling the time. She may think that time is passing more slowly! This is the idea of time dilation.

The mathematical equation used to describe it, (not too difficult to justify, and to be found in any advanced school physics textbook), is

$$\Delta t' = \varphi \Delta t$$

where $\Delta t'$ is time measured in a frame of reference moving with velocity v relative to a stationary one in which the time interval is Δt. The quantity φ is called the Lorentz factor - it is a measure of v relative to the speed of light, c, and

$$\varphi = 1 / \sqrt{(1 - v^2/c^2)}$$

<u>How time dilation explains the paradox concerning muons formed in the atmosphere</u>

Muons are sub-atomic particles sometimes formed in the atmosphere as a result of cosmic ray collisions. They can be detected using balloon flight experiments 2 km above mountain observatories. The paradox is that something like 80% of the muons detected by the balloons are also detected at the observatories, and a few calculations will show you that is well in excess of what classical mechanics predicts.

ACTIVITY:
Muons travel at 0.996c. How long will it take them to travel 2 km? (the speed of light in vacuum, c = 3.0 x 10^8 ms^{-1})
The muons are unstable and decay with a half-life of 2.2μs. How many whole half-lives elapse in the time taken for them to travel 2 km?
Given that in one half-life the muon number decreases to one half of its original value, how many of the original muons will remain after three half-lives?

So measurement shows that 80% of the muons remain to be detected at the observatory – your calculations predict only 12% remain. Quite a discrepancy! However, travelling at 0.996c, special relativity says that the half-life (defined in the muon's moving frame of reference) will be longer if measured at the observatory. A few more calculations will help you to account for the paradox.

ACTIVITY:
Travelling at 0.996c, what is the value for the Lorentz factor, φ, for the muons?
If the muon's half-life is 2.2μs in its moving frame of reference, what will it be in the observatory?
In the 6.7μs the muon takes to travel the 2 km, how many half-lives have elapsed?
In this time, a fraction of a half-life, only about 20% of the muons decay solving the paradox!

So time dilation, a consequence of Einstein's theory, perfectly explains experimental measures of muons created in this way.

Once we can appreciate the idea of time dilation it can be used to realise that it leads to length contraction. A physicist moving in a space laboratory with the muons would measure the 6.7µs travel time recorded in the mountain observatory as 6.7/11.2µs, about 0.6µs. She would then measure the distance the muons travel to be shortened from 2 km to 0.6µs x 0.996c, about 180m. Conversely, a 2000m long object moving towards the observatory at this speed would be measured as 180m long.

Looking at the mathematical form of the Lorentz factor, you should be able to see that unless the speed of an object is significant in comparison with the speed of light, these time dilations and length contractions are insignificant explaining why classical mechanics correctly describes the motions of athletes, cars and Ferris wheels (though the latter acts as a useful analogy!) However, observation involves light, meaning photons travelling at the speed of light, and because time and space are interdependent all measurements of them are relative to the measurer's frame of reference.

Einstein's special theory of relativity led on to his famous equation $E = mc^2$ (and therefore nuclear fission and stellar evolution, as well as t-shirts!) and plenty of other developments in 20th century physics. But it also explained phenomena supposedly understood before this time. For instance, the magnetic forces generated when a current flows in a conductor are a consequence of time dilation, and can only be fully understood using this principle.