Teaching ideas for Option A: Relativity

There is much that this topic can do for promoting the excitement and interest in studying physics. In line with our knowledge of the nature of science, this topic contains apparent inconsistencies that need explaining, imaginative thinking to find the explanations and considerable creativity in the formulation of new theories. Although the concepts in this topic are difficult for many to cope with, an understanding, even a rudimentary one, will take students a long way to realising just how powerful our ideas in physics are and where these ideas are likely to lead us in our future learning about the world and universe we live in.

Some useful points to consider are:

- The justification for students learning about relativity is clear: there are so many aspects of our learning, and our models to explain them, that have required knowledge of relativity, from ideas about magnetism, through global positioning systems, production of energy by nuclear fission and fusion, observations of muons in the atmosphere, to using a synchrotron at the European Organization for Nuclear Research (CERN) to smash protons into each other.
- The introduction of relativity into our knowledge of physics was an excellent example of a paradigm shift in learning and knowledge.
- The gamma factor and the Lorentz transformation are much used in several areas of current physics research and show how important they have been in the design and implementation of cutting-edge research projects.
- The additional HL (AHL) material, for HL students only, looks at how Einstein considered energy and momentum in relativistic terms. This gave rise to the understanding that energy and mass are two different manifestations of the same phenomenon. It also looks at some of the ideas in general relativity, such as the bending of light and the application of relativity to black holes.

Ideas for teaching the topic

- A good approach to this conceptually demanding topic is to tell a story: the story of how we have come to accept the ideas of relativity into our present-day understanding of physics. Historical, or chronological, developments allow students to develop their own understanding in a way that reflects how physicists learnt from the time of Galileo and Newton in the 17th century, through the mid to late 19th century, and up to modern times.
- Faraday, in the 1830s, had already shown that a changing magnetic flux induced an electric field. In the 1860s, Maxwell had taken this concept and combined it with the idea that a changing electric field will induce a magnetic field, to show that if both of these changing fields are present at the same time (i.e. when a charged particle is made to accelerate) they will self-propagate, and produce an electromagnetic wave. Maxwell’s classical derivation of the speed at which these waves would move showed that this speed is determined only by the permeability and permittivity of the medium through which they move and is not dependent on any kind of relative motion. This is the basis of the axiom that the speed of light is invariant. This idea is a strong one for teachers to use with students, because it gives a very firm foundation for why this axiom has been adopted.
- Maxwell himself did not really believe what he had proposed and suggested that there had to be some kind of medium (called the ‘aether’) that carried these electromagnetic waves. This suggested that a motion relative to the aether would result in a perceived speed at which electromagnetic waves moved that could be different for different relative motions. This led to the famous Michelson–Morley experiment. When the results of this experiment showed no difference observable in the speed of light in two perpendicular directions, Einstein scrapped the aether idea and concentrated only on Maxwell’s famous equations.

Copyright Cambridge University Press 2014. All rights reserved.

- When Einstein proposed the two postulates, that the speed of light is invariant and that the laws of physics are the same for every inertial frame of reference, the implication of these immediately suggested that time itself must be relative. This is a good point at which to introduce the idea of frames of reference: that is, observers and all their measuring instruments form a frame of reference from which they make their measurements. If the observer is not accelerating, this frame of reference is called an inertial frame, and the usual Galilean transformation to describe what one observer measures compared to what another observer measures can be derived. The important point of Galilean relativity is that time is measured to be the same by any observer. (Newton thought this to be true too.) This will allow students to perform simple calculations of relative motion. A good YouTube video to help reinforce this is: http://www.youtube.com/watch?v=uMaFB3jM2qs. This video also supports the earlier ideas about the importance of Maxwell's equations and the need for the Michelson–Morley experiment.

- Now is a good time to introduce the Lorentz transformation. It is perhaps easiest to do this with time. The classic way of deriving the dilation of time (with a vertical beam of light and a horizontally moving train or bus) will be an easy idea for students to understand and requires only knowledge of Pythagoras and right-angled triangles. Once students have understood the gamma factor, combining this with the invariance of the speed of light will show that the gamma factor also applies to length. A good video to help with this is: http://www.youtube.com/watch?v=aZrjMmMBa_8, which leads nicely to the twin paradox.

- There are two good examples of how the Lorentz transformation affects our perception of events when particles travel at speeds approaching the speed of light.

  The first of these is the lifetime of muons. These particles are produced in the atmosphere and have a lifetime (i.e. the time before they decay) of about 2.2 μs. A simple calculation of how far they travel during their lifetime suggests that they will not make it to the ground. However, because they are travelling at appreciable fractions of the speed of light, we perceive their 'clocks' to run slowly compared to our 'clocks', allowing them more time to exist, and so they do reach the Earth and we can detect them. The muons 'think' that the distance between them and the Earth is shorter than we think it is, because of the length contraction caused by the relative motion of the Earth to them, and so in their short lifetime they can travel far enough to reach the ground on the Earth.

  The second example, although not really any different in terms of physics, is the lifetime of particles produced in the Large Hadron Collider at CERN. As particles are accelerated to speeds above 90% of c, we perceive their lifetimes as becoming longer, whereas the particles would 'perceive' the distance they have to travel as being shorter.

  Both of these examples will help with the important idea that events that are simultaneous for an observer and that occur in different locations will not be simultaneous for another observer who is in a different frame of reference. This leads to the idea of a proper time interval.

- This will be a good time to get students practising how to add relativistic velocities. The equation for this is in the data booklet for students.

- At this point it will be worth consolidating the idea of frames of reference with that of the Lorentz transformation so that students will begin to appreciate what these tell us about light. Einstein had pondered, in one of his typical 'gedanken experiments', what it would be like to ride on a beam of light. What the Lorentz transformation tells us is that the photons have clocks that have stopped and that distances in the direction of motion of a photon become zero. This is a nice way to explain to students why photons last forever or why a photon can travel across the universe in no time in its own frame of reference!

Copyright Cambridge University Press 2014. All rights reserved.

- Now it is time to introduce the idea of a spacetime (or Minkowski) diagram, so that students can see a way of representing the position of an object, in one or more than one dimension, as a function of time. In some spacetime diagrams, time *t* is plotted on the *y*-axis, but the syllabus states that sometimes the *y*-axis may be a *ct*-axis rather than a *t*-axis. This is because it is sometimes desirable to re-scale the *y*-axis by multiplying by *c*, giving all of the units that this will be measured in relative to the speed of light. In this case, the path of a photon would be a diagonal line at 45^o to the *x*-axis, giving the gradient of this line, *c*, an effective value of 1.

- Students should become familiar with the idea of a world line as a line on the spacetime diagram that shows how a particle moves in space and time. This line is usually a curve whose gradient is linked to the velocity of the particle. Students should understand that a steep line represents a slow speed and that the less steep the line is on the spacetime diagram, the faster a particle is moving. Now, particles moving at a constant velocity (as the syllabus suggests will be the case) will have their own spacetime diagrams that have axes that are at an angle to the axes representing the observer's frame of reference. In a similar way, if an event is to occur that begins at the origin of the spacetime diagram, then the future event cone of this will be a cone outside which it is not possible to go. Whatever a particle's world line is going to be, it will have to be a line that occurs within this future light cone.

- For the AHL material in Subtopic **A.4**: Relativistic mechanics, relativistic expressions can be derived for momentum and energy using the gamma factor that will allow students to solve problems relating momentum, rest energy and total energy. This will reinforce the idea that a constant force on a particle will result in an acceleration that decreases in time until it is zero. It also allows students to become more familiar with using units of MeVc^{-2} for mass and MeVc^{-1} for momentum. The conservation of momentum and the conservation of energy within relativistic circumstances should be considered.

- In Subtopic **A.5**: General relativity, you could look at the application of general relativity to the bending of light and to black holes. Both of these ideas rely on the equivalence principle: that gravitational effects and inertial effects are indistinguishable. This makes accelerating a frame of reference equivalent to having a frame of reference that is at rest in a gravitational field.

- The ideas of general relativity could be approached by considering how the ideas can be tested. This fits in well with the Nature of science, as all scientific claims must be able to be tested. There are two tests necessary in this topic:

  (i) That light (and radio waves) is bent by the gravitational fields produced by large masses. This was verified in 1919 by Dyson, Eddington and Davidson. Students should be aware of the observations that this group of scientists made.

  (ii) That gravitational fields produce gravitational red shifts. Because general relativity predicts that time becomes dilated in the presence of gravitational fields, the frequency of a photon of radiation will be observed to be different for an observer outside the field as it is for an observer inside the field. This was verified by the Pound–Rebka–Snider experiment using gamma rays emitted by radioactive iron. Using the energy conservation idea from earlier in the topic, students should be able to show that the shift in frequency, Δf, of a gamma ray emitted from a height, *h*, above the Earth's surface is given by $\Delta f/f = gh/c^2$. The slowing down of time by gravitational fields has also been shown to occur using atomic clocks in satellites orbiting the Earth.

- The last section of work in this topic requires students to look at black holes. Students should be taught how to derive the Schwarzschild radius for a black hole (some may have already done this in the AHL Topic **10**: Fields) and use this to calculate its size.

- The time dilation caused by the gravitational field of a black hole shows students that the presence of the mass of the back hole distorts not only the space around the black hole, but

Copyright Cambridge University Press 2014. All rights reserved.

also time. Using the equation given in the data booklet, students should be able to calculate the time delay that observers will receive between two signals sent, say, 1 second apart, if they are sent from near to the Schwarzschild radius, noting that at the radius, this time delay will be infinite, decreasing as the distance away from the radius increases.

Practical activities

- Simple Galilean relativity can be demonstrated with students observing each other while moving around. If students move only with constant velocity relative to each other, it should be easy for them to work out how to find the velocity observed by one student is related to the velocity observed by another.
- It is always going to be difficult to suggest practical activities for a topic such as relativity. However, if you are lucky enough to have a version of the Michelson–Morley experiment, this will be a good demonstration for students to see. There is a good simulation of what Michelson and Morley had expected to see on the following website:

  http://galileoandeinstein.physics.virginia.edu/more_stuff/flashlets/mmexpt6.htm
- Some other useful websites and videos are available on:

  http://www.youtube.com/watch?v=uMaFB3jM2qs (a good introduction to Galilean relativity)

  http://www.youtube.com/watch?v=aZrjMmMBa_8 (useful for time dilation derivation and the Lorentz transformation)

  http://www.phys.unsw.edu.au/einsteinlight/ (a site that students might like to investigate independently).
- Please see the available practical notes for further ideas.

ICT

- A number of online simulations will be helpful in teaching this topic. Some useful ones are listed above, although there are many others that you may prefer to use.

Common problems

- The concept of a proper time interval is something that students may find difficult. You should emphasise that a proper time interval occurs when two events occur in the same place. An observer who sees these two events occurring in different places (because the observer's frame of reference is moving relative to the one in which the two events occurred) will measure a different time interval that is given by $t' = \gamma t$.

Theory of knowledge (TOK)

- The way in which Einstein changed our way of looking at physical quantities (such as distance and time) has had a profound effect on the way we look at everything now. Will there be another paradigm shift as huge as this one? And if there is to be one, in which area of our learning will it be?
- A hundred years or so ago, scientists had put together a good overall picture of how physical systems behaved, but they had become content that their picture was all-encompassing. This contentment created complacency in learning and it required a truly innovative, creative and somewhat reactionary character, Einstein, to make us look at things differently and search for a new way of painting our picture. How much more physics might there be for us to learn and understand now? How is our picture going to change in the next hundred years?

Copyright Cambridge University Press 2014. All rights reserved.

- Einstein's work with the cosmological constant was abandoned as a blunder. Many years later it was shown to be correct. Are there other examples that show earlier discarded ideas to be valid much later?
- Wheeler's work on black holes was very much inspired by his intuition (so it has been said). How important is intuition in the creativity of science?

International-mindedness

- The international variety of scientists that have, together, tested and verified the theories of relativity is a wide one. This reminds us that scientific endeavour frequently ignores national and cultural boundaries and borders.

Copyright Cambridge University Press 2014. All rights reserved.