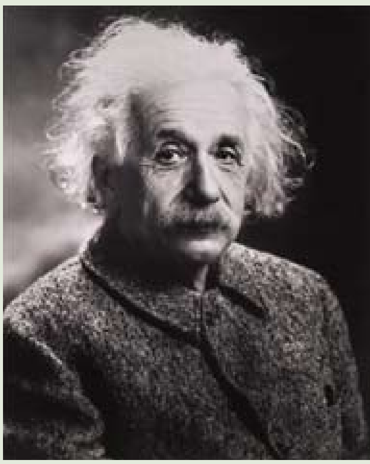
CHAPTER 4

Special relativity

Current and emerging understanding about time and space has been dependent upon earlier models of the transmission of light



Albert Einstein

Introduction

Time runs slower and becomes relative, length contracts and mass becomes greater for fast-moving objects or frames of reference. These strange phenomena may seem to contradict common sense, but they are the consequence arising from the special theory of relativity, proposed by German/US scientist Albert Einstein (1879–1955) in 1905. In this chapter we will analyse in detail the origin, make-up and impacts of the theory of special relativity. The chapter also evaluates the impacts of the theory on re-directing scientific thinking in the 20th century as well as on space travel and exploration.

4.1 The aether model

- ***Outline the features of the aether model for the transmission of light***

Aether was once proposed to be an undetectable (by touch, smell or vision), extremely thin, elastic material that surrounded all matter and at the same time was permeable to all matter on Earth.

The role of the aether

- *The aether was thought to be the medium through which light propagates.*

It was always thought that energy required a medium for transmission and propagation. Just as sound needs a medium such as the air to propagate, the medium for light to propagate was the aether. It was logical to suppose that as all other types of waves need a medium for their propagation (e.g. water waves, sound waves, earthquake waves, waves in springs and strings), so too does light. Light had been shown to have a definite wave nature due to its ability to display interference and diffraction effects, as well as reflection, refraction and dispersion. Maxwell's equations for electromagnetic radiation also showed mathematically how light was a wave. The difficulty for the scientists at the time of the late 1800s was to explain how a wave (light) could travel through a vacuum, unsupported by any medium.

- *The aether was also thought to be the absolute frame of reference to which all motion was compared.*

Long ago, scientists like Galileo realised that all motion is relative (see Chapter 2). However, they believed ultimately that there should be an absolute frame of reference to which all motion could be compared. This absolute frame of reference was the aether. Even Newton suggested the need for an absolute frame of reference when studying motion.

To illustrate this 'absolute frame of reference' concept, consider how the motion of aircraft, ships and cars is measured. The frame of reference used is almost always the Earth's surface, despite the fact that the Earth's surface is subject to the motion of the rotation of the Earth and the orbital speed of the Earth around the Sun. The Earth's surface is very good to use as a frame of reference for the motion of ordinary transport, but becomes less useful to measure the motion of spacecraft or space probes.

Other features of the aether

Not only was the aether extremely thin and transparent, it was also proposed that the aether had a very high elasticity. This property was proposed as the aether had to be a solid to transmit transverse waves—light transverse waves *only* pass through solid—but at the same time sufficiently thin enough to let planets move through it unimpeded. It followed that having a high elasticity meant aether behaved like a solid when it was subjected to instantaneous and varying forces, like that of transverse waves. However, it could be distorted infinitely when it was under a continuous uni-directional force, such as the motion of planets.

TR

Mapping the PFAs
PFA scaffolds H2

The Michelson–Morley experiment

4.2

- ***Describe and evaluate the Michelson–Morley attempt to measure the relative velocity of the Earth through the aether***
- ***Discuss the role of the Michelson–Morley experiments in making determinations about competing theories***
- ***Gather and process information to interpret the results of the Michelson–Morley experiment***

PFA H1

'Evaluates how major advances in scientific understanding and technology have changed the direction or nature of scientific thinking'

PFA H2

'Analyses the ways in which models, theories and laws in physics have been tested and validated'

James Clerk Maxwell had modelled the nature of light (and other yet to be discovered electromagnetic radiation) mathematically. Maxwell believed that there was a need for light to travel through a medium, the 'luminiferous aether'. This would result in the speed of light changing if the aether itself was moving, or being moved through (as is the Earth, at about 30 km s^{-1} as it orbits the Sun), when measured against an absolute frame of reference. Such a requirement would result in the equations themselves changing.

The Michelson–Morley experiment, performed in 1887 and repeated many times since, marked a watershed in modern physics. The experiment attempted to show the existence of the aether by detecting its affect on the speed of light (see page 60). The 'null' result (no change in the speed of light was detected) was met with scepticism by many theoretical physicists at the time.


A. A. Michelson (left) and E. W. Morley

The first implication of this 'null' result was published in 1889. It was proposed that the length of bodies as they moved through the aether may in fact vary. Yet other explanations, using the physics of the time (based on Newton's and Galileo's works) did not stand up to logical argument or made little sense.

Not until Einstein's publication in 1905 of his special theory of relativity did a possible explanation arise. By making space and time relative, the need for the aether dissolved. Einstein's theory explained the results of the Michelson–Morley experiment by saying that the measured speed of light will be the same, regardless of the relative velocity of the source of light and the observer.

Michelson himself did not have confidence in the results of the experiment, and many years later, one of Michelson's colleagues was able to produce a result that showed that the speed of light did indeed vary by up to 10 km s^{-1}, depending on the direction in which it was travelling. This result would seem to go against the special theory of relativity. However, Einstein's relativity, despite its effects not being able to be observed and measured, became widely accepted among the scientific community.

The publication and subsequent widespread acceptance of Einstein's special theory of relativity could not have occurred (or may have been delayed) had it not been for the Michelson–Morley experimental results being debated as widely as they were.

WWW→ **USEFUL WEBSITES**

An overview of the Michelson–Morley experiment:
http://galileoandeinstein.physics.virginia.edu/lectures/michelson.html
http://www1.umn.edu/ships/updates/m-morley.htm
http://www.redsofts.com/articles/read/251/7297/The_Invisible_Ether_and_Michelson_Morley.html
http://www.phys.unsw.edu.au/einsteinlight/jw/module3_M&M.htm
Detailed page for Michelson–Morley and special relativity, with animated explanations:
http://www.upscale.utoronto.ca/GeneralInterest/Harrison/SpecRel/SpecRel.html

The Michelson–Morley experiment

SECONDARY SOURCE INVESTIGATION

PFAs

H1, H2

PHYSICS SKILLS

H13.1A, B, C
H14.1F
H14.3C, D

■ *Gather and process information to interpret the results of the Michelson–Morley experiment*

Hypotheses need experimental evidence, and the aether hypothesis was no exception. In 1887, A. A. Michelson and E. W. Morley set up an experiment in the US, now known as the Michelson–Morley experiment. The aim of the experiment was to prove the existence of aether by detecting the velocity of the Earth through the aether (aether wind) using light as a tool. The apparatus and the set-up of the experiment are schematically represented in Figure 4.1.

Procedure and principle of the experiment

NOTE: For a better understanding of this experiment, we will follow the path of light from label '1' to '5' in Figure 4.1.

1. A light beam is emitted at the light source and travels towards the half-silver mirror.

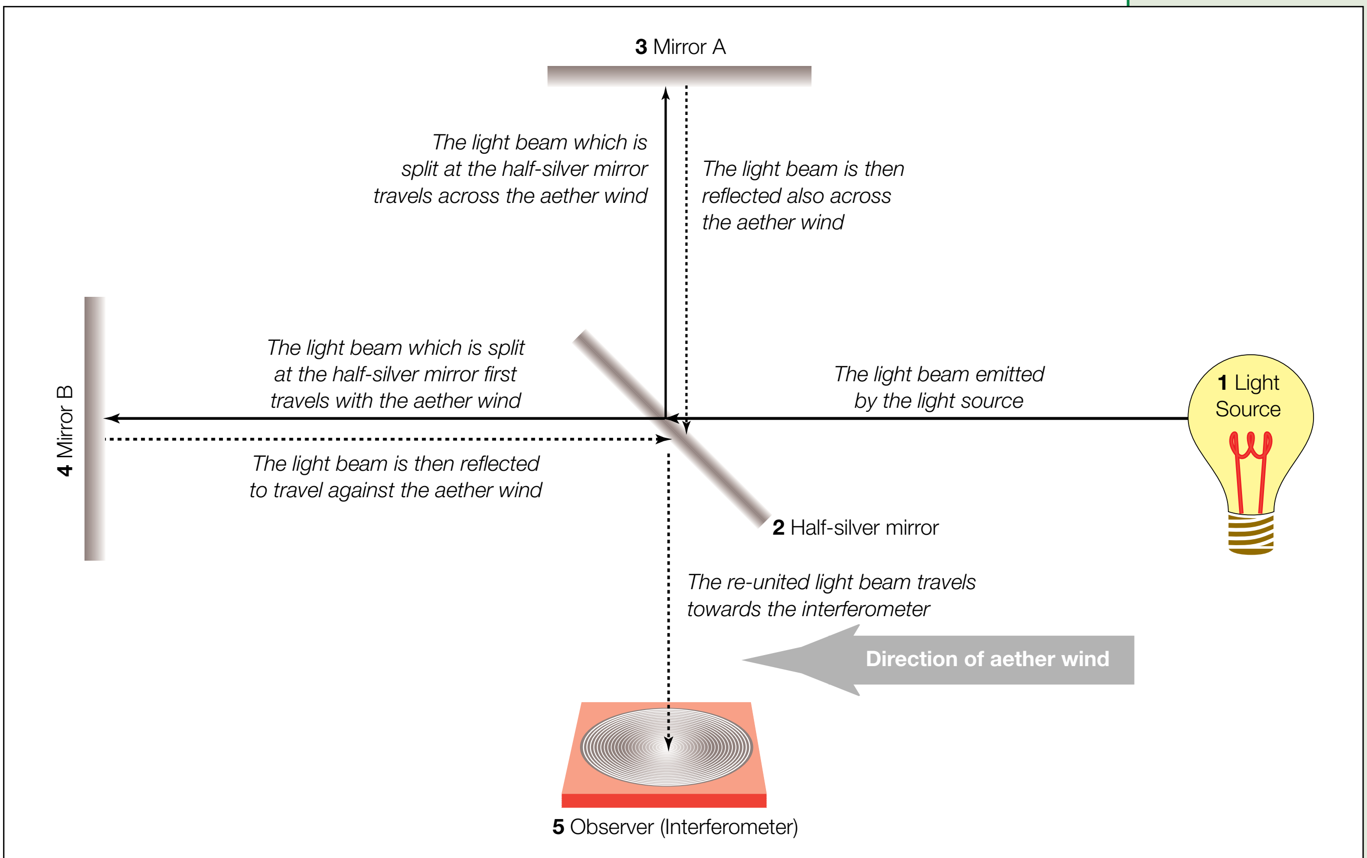


Figure. 4.1 The set-up of the Michelson–Morley experiment

2. The half-silver mirror is a device that splits the light beam into two paths: one that will travel with and against the **aether wind**; the other that will travel across the aether wind. Note that the aether wind is created as a result of the Earth moving through the stationary background aether. The wind 'blows' in the opposite direction to the motion of the Earth.

ANALOGY: When you drive a car through the air, 'wind' is generated. The direction of the wind is in the opposite direction to the motion of the car.

3. One light beam travels across the aether wind to reach mirror A, and then reflects back also across the aether wind.

4. The other light beam travels first with the aether wind to reach mirror B and then reflects back to travel against the aether wind. (If the aether wind is to 'blow' in the opposite direction, then this beam will first travel against the aether wind, then with the aether wind.)

5. The two light beams re-unite at the half-silver mirror and are reflected to the interferometer. If aether exists, then the velocity of the light beam that has travelled with, then against, the aether wind would be affected. However, the velocity of the light that has travelled across the aether wind is affected to a different extent. Therefore, when the two beams re-join, they should be out of phase to each other, and an interference pattern can be observed at the interferometer. However, this is not enough to prove the existence of aether, as the phase difference might be caused by the difference in the length of the two different pathways the light beams have undertaken. Only when the entire apparatus is rotated 90°, and a *change in the interference pattern* is observed, can the existence of aether be proven, since the beam that was once travelling across the aether wind is

now travelling along and against the direction of aether wind and vice versa, showing definitively the phase difference is due to the effect of aether on the velocity of light.

Results of the experiment

When the entire apparatus was rotated 90°, *no change in the interference pattern* was observed. The experiment was carried out at different places at different times; still a null result was recorded.

The null result of the experiment meant that the motion of the Earth through the aether (aether wind) could not be detected. Consequently, the existence of the aether could not be proven. Therefore, the aether model was still lacking experimental evidences.

Simulation Michelson inferometer

Impact of the experiment (evaluation)

The inability to provide evidence for the existence of the aether would mean the aether model was an invalid physics theory. However, because it formed the basis of many physics theories and laws, scientists at the time found it hard to discard the model.

Many proposals were put forward to try to explain the negative or null result of the experiment. For example, it was suggested the Earth carried the aether with it, and thus there was no relative motion (hence, aether wind) detected; also the Michelson–Morley's experiment was criticised as not accurate enough to detect the slight change in the interference pattern. However, these suggestions were simply 'creative', and no physical theory supported them. However, in 1905, the great Albert Einstein proposed a revolutionary theory of his own—**special relativity**—in which he completely abandoned the aether model. The theory not only successfully accounted for the null result of the Michelson–Morley experiment, at the same time it offered people an entirely new perspective of the physics world, as discussed later in this chapter.

NOTE: The best way of explaining the inability to detect something is to say that it does not exist.

An example is shown below to illustrate how a light ray moving directly into and then against the aether wind would have a different average velocity to the light ray moving perpendicularly to the direction of the aether wind.

Two aeroplanes have a race. Both planes can fly through the air at 200 km h^{-1}. Plane 'A' will fly from the start to a point 'X', 400 km to the north. Plane 'B' will fly from the start to a point 'Y', 400 km to the east. The finish is the same point as the start.

If there is no wind blowing, the planes will return at the same time. However, on the day of the race the wind is blowing at a constant 50 km h^{-1} from the north.

$$\text{time} = \frac{\text{distance}}{\text{speed}}$$

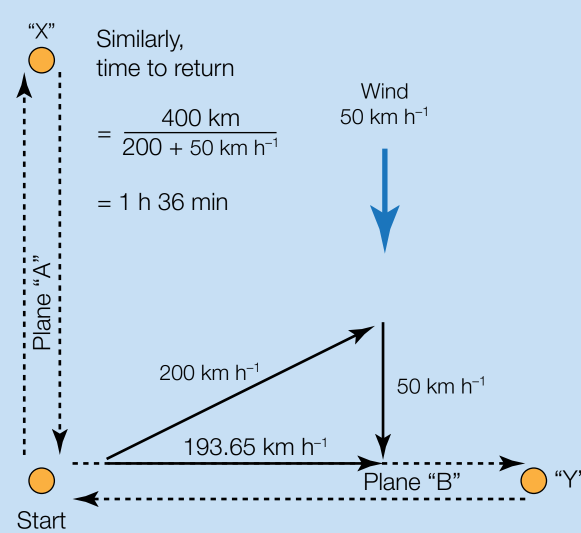
$$= \frac{400\text{ km}}{200 - 50\text{ km h}^{-1}}$$

$$= 2\text{ h }40\text{ min}$$

Similarly, time to return

$$= \frac{400\text{ km}}{200 + 50\text{ km h}^{-1}}$$

$$= 1\text{ h }36\text{ min}$$



Plane 'A' takes two hours 40 minutes to get to 'X', and another one hour 36 minutes to return (with the wind behind it): a total of four hours 16 minutes.

Plane 'B' must head slightly into the wind so that it gets blown back on course, making a speed in both directions of 193.65 km h^{-1}. It takes a total of four hours eight minutes ($\frac{400\text{ km}}{193.65\text{ km h}^{-1}} \times 2$, to the nearest minute).

Plane 'B' wins the race by a significant margin. In the Michelson–Morley experiment, the light ray moving perpendicularly to the aether wind returns faster than the light ray moving directly into and then with the aether wind. As the apparatus is rotated through 90°, this effect would vary, and the interference pattern being observed would appear to change.

See the associated PFA on pages 60–62 information for the implications of this 'null' result.

4.3 Frames of reference

■ *Outline the nature of inertial frames of reference*

Definition

A **frame of reference** is anything with respect to which we describe motion and take measurements.

Galileo and Newton had long ago realised the importance of frames of reference and devised their own theory of relativity. They realised that motion is different when described in relation to different frames of reference. Galileo's analysis of projectile motion is an example of this. They also realised measurements such as velocity are relative depending on the frames of reference used.

For example, when the motion of a car is being described, our frame of reference is usually the ground. Its speed is then measured with respect to the ground, say 60 km h^{-1}. However, if another frame of reference is used, say another car that is travelling in the same direction and at the same speed, then we can say the first car is stationary and its speed is zero *with respect to that frame of reference*. Another example would be a person reading a book at their desk: the person is stationary with respect to the desk, but with respect to the Sun as a frame of reference, the person is orbiting the Sun (being on Earth) with a speed of 30 km s^{-1}.

Types of frames of reference

Inertial

Definition

An **inertial frame of reference** is one that is either stationary or moving with a constant velocity.

In an inertial frame of reference, the **laws of motion** are always valid. No imaginary force needs to be 'made up' in order to explain the motion of objects within inertial frames of reference. Since the laws of motion are true for both a stationary frame of reference and for one that is moving with a constant velocity, there is no physical experiment that can be done within an inertial frame of reference to distinguish whether such a frame is stationary or moving at a constant velocity. To illustrate this, imagine being on an aeroplane that is flying smoothly at a steady speed. The flight steward serves tea and coffee as easily as in a restaurant; a person can walk up and down the aisle as they would in a cinema; and dropping a ball results in it falling vertically under the influence of gravity and no other force. With ear muffs on and the blinds closed, it is not possible to tell whether the plane is indeed in flight or stationary on the ground.

Non-inertial

Definition

A **non-inertial frame of reference** is one that is undergoing acceleration.

For a non-inertial frame of reference, the laws of motion do not hold true. For example, if a tennis ball is placed on the floor of a bus, when the bus *accelerates* forward, the ball rolls backwards. For an observer who is inside this non-inertial frame of reference, no force is observed acting on the ball, yet the ball does not remain stationary. This obviously violates the laws of motion since Newton's first law of motion states that an object will remain stationary or moving with a constant velocity in the same direction unless being acted upon by an unbalanced (net) force. Here, a **fictitious** (fake) **force**, that is, a false backward force, needs to be introduced in order to maintain the validity of the laws of mechanics. The existence of a fictitious force is one of the most distinctive features of a non-inertial frame of reference and allows it to be distinguished from an inertial frame of reference. Such forces are also known as 'inertial forces', centrifugal force being an example.

Non-inertial and inertial frames of reference

FIRST-HAND INVESTIGATION

PHYSICS SKILLS

H11.1B
H11.2E
H11.3A, B
H12.1A, D
H12.2B
H12.3A
H13.1E
H14.1B, E
H14.3B, C, D

■ *Perform an investigation to help distinguish between inertial and non-inertial frames of reference*

As an activity, undertake the following procedure:

1. While walking in a straight line at a constant speed along level ground in the open, throw a tennis ball vertically above you and catch it again. Observe the motion of the ball relative to you, while a stationary observer also observes the motion of the ball. It may be possible to digitally record your observations.
2. Compare and contrast the observations of the motion of the ball made by you and by the stationary observer.
3. Next, again while walking steadily as in step 1, throw a ball vertically above you. This time, while the ball is in the air, stop walking *or* start running forward *or* make a sudden turn. Again, observe the relative motion of the ball with respect to you, and have a nearby stationary observer make their own observation of the motion of the ball relative to them.
4. Compare and contrast the ball's motion as made by the two observers on the two different occasions. Discuss the results in the context of frames of reference.
5. While in a bus or train that is travelling along a straight road or track with a steady speed, drop a ball. Observe the ball's motion and then repeat the experiment while the bus or train is taking off, stopping or stopped. Compare the observations made.

6. Before performing this experiment, carry out a *risk assessment*. This means that: (a) all potential hazards are identified; (b) ways in which these hazards may be minimised or avoided should be written down. As an example, walking over level ground in step 1 is potentially hazardous if there is a ditch, rock or pole which could cause injury. The ground or path should be checked beforehand for such hazards.
7. As a final task, imagine that you are inside a locked shipping container. Devise an experiment you could perform to show you are in an inertial frame of reference. Explain your experiment to the class.

4.4 Principles of special relativity

- ***Discuss the principle of relativity***
- ***Describe the significance of Einstein's assumption of the constancy of the speed of light***

The negative result of the Michelson–Morley experiment was the major inspiration and incentive for Einstein to propose the special theory of relativity. In his theory, Einstein completely abandoned the aether model because he saw it as totally unnecessary. In the absence of this absolute frame of reference, all inertial frames of reference became relative and no one was truer or more correct than another. The absence of the aether (if the results of the Michelson–Morley experiment to detect the effect of the aether wind on the speed of light could be interpreted as being due to the lack of the aether itself) also meant the velocity of light was constant in all directions and under all circumstances. This successfully accounted for the null results of the Michelson–Morley experiment as the constancy of the speed of light led to no change in the interference pattern when the experimental apparatus was rotated through 90°.

The principles of the theory can be summarised into two major ideas:

1. The velocity of light has a constant value of c, regardless of the relative motion of the source and observer.
2. All inertial frames of reference are equal and no inertial frame of reference is truer than others.

NOTE: The velocity of light and other electromagnetic radiation (EMR) is c, which is approximately equal to 3×10^8 m s^{-1}. It is the highest velocity any matter can achieve. In fact, except for light and other EMR, nothing can reach the velocity c.

It is also important to note here that the special theory of relativity *only applies to inertial frames of reference*; it is invalid for non-inertial frames of reference. Relativity which involves non-inertial frames of reference and gravity is dealt with in Einstein's **general** theory of **relativity** (not required by the syllabus).

Example

A star is moving away from the Earth at v m s^{-1}. What will be the velocity of the star's light when it is measured upon reaching the Earth?

(a) c
(b) c + v
(c) c – v
(d) More information needed.

Solution
The answer is (a). The velocity of all EMR, including light, is constant at c, to all observers. It is independent of the relative motion of the source and observer.

4.5 Impacts of special relativity

- ***Identify that if c is constant then space and time become relative***
- ***Explain qualitatively and quantitatively the consequence of special relativity in relation to:***
  - ***the relativity of simultaneity***
  - ***the equivalence between mass and energy***
  - ***length contraction***
  - ***time dilation***
  - ***mass dilation***

H14.1D, F, G, H
H14.2A, B, C
H14.3A, C, D

- ***Solve problems and analyse information using: $E = mc^2$***

$$l_v = l_o \sqrt{1 - \frac{v^2}{c^2}}$$

$$t_v = \frac{t_o}{\sqrt{1 - \frac{v^2}{c^2}}}$$

$$m_v = \frac{m_o}{\sqrt{1 - \frac{v^2}{c^2}}}$$

SR

Worked examples 10, 11, 12, 13

When Einstein's special theory of relativity is referred to by non-scientists, many regard it as something far too difficult to comprehend. However, with a little thought, the theory and its consequences can be seen as logical outcomes of the way in which Einstein regarded the speed of light: that is, the speed of light is a constant no matter how it is measured. In other words, because the speed of light is constant, it follows that many quantities, such as time, length and mass which were once thought to be absolute are now relative.

Because of the very fast speed of light, Einstein used thought experiments to help explain the special theory of relativity. Such 'experiments' can be carried out in the mind of an experimentalist; however, they are not possible to conduct in reality.

Relative simultaneity

Events which are observed to occur at the same time are considered to be simultaneous. However, two observers moving at relativistic speeds (i.e. speeds that are more than about 10% of the speed of light) may not both observe the simultaneous events equally. That is, one observer may regard the events as being simultaneous but the other observer may not.

Definition

Two events that are simultaneous to one observer may not necessarily appear simultaneous to another observer who is in a frame that is moving at a relativistic speed. This is known as **relative simultaneity**.

Consider the following situations (**thought experiment**):

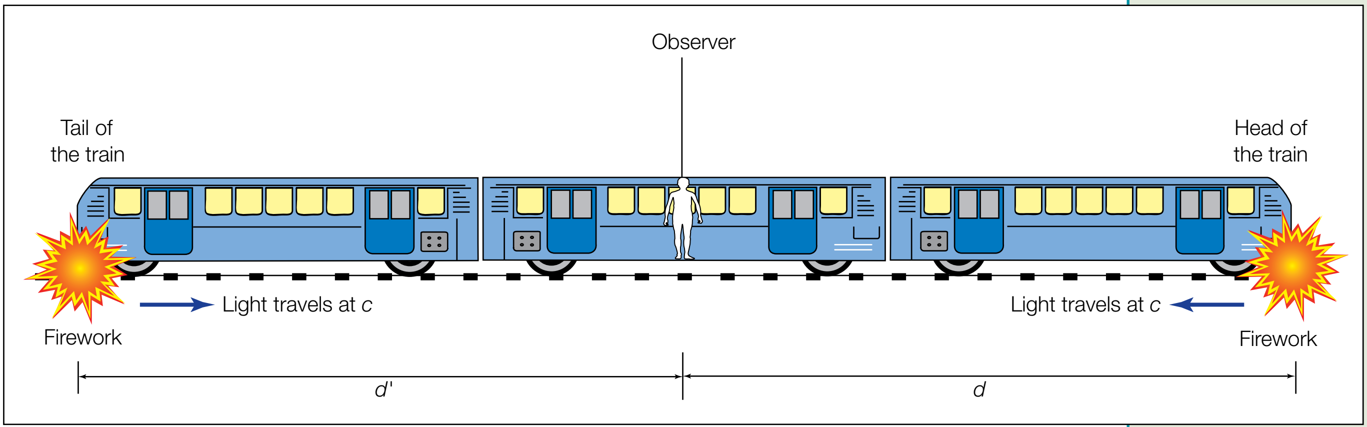
Suppose in a very long train that is at rest, fireworks are launched at both ends of the train at the same time. For an observer standing at the middle of this train as shown in Figure 4.2 (a), the light from both ends of the train will have to travel the same distance (i.e. d = d′) to reach the observer. The time for the light from the head of the train to reach the observer t, will be $t = \frac{d}{c}$ (**s = vt**), and the time for the light from the tail to reach the observer t′, will be $t' = \frac{d'}{c}$. Hence t = t′.

Therefore, light from both ends of the train will reach the observer at the same time; who will consequently conclude that the launching of the fireworks was *simultaneous.*

Now suppose there is another observer who is in the same situation as the observer described above (that is the second observer also stands at the middle and the fireworks are still launched at the same time at both ends). However in this case, the train is moving at a relativistic speed v; that is the second observer is in a *different frame of reference*. This is shown in Figure 4.2 (b)

In this situation, when the light from the front of the train reaches the observer, the observer would have travelled some distance towards the site where the light was emitted. For the same argument, when the light from the rear reaches the observer, the observer would have travelled some distance away from the site where the light was emitted at the end of the train. Consequently the time for the light from the front of the train to reach the observer t, will be $t = \frac{(d - vt)}{c}$, and the time for the light from the rear to reach the observer t′, will be $t' = \frac{(d' - vt)}{c}$. Thus t′ > t (since d is still equal to d′).

Figure 4.2 (a) The thought experiment for the relativity of simultaneity



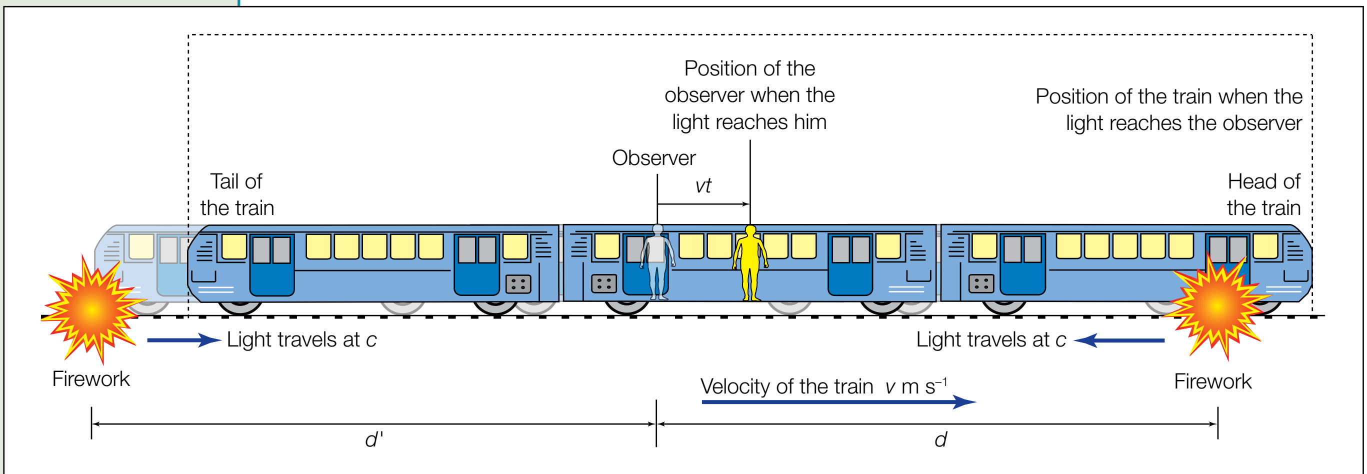


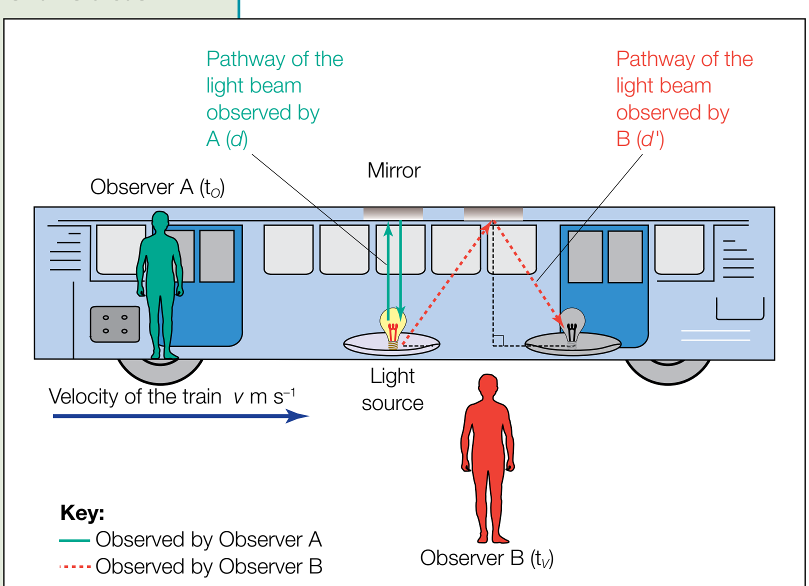
Figure 4.2 (b) The thought experiment for the relativity of simultaneity (different frame of reference)

The conclusion is that the light from the rear end of the train will take longer to reach the observer than the light from the front of the train. The result is that the observer will conclude that the firework at the front of the train is launched first, then later at the rear. Now the two simultaneous events *no longer appear to be simultaneous*.

NOTE: The speed of light is always *constant* despite the two light sources moving in different directions; this is the key to the results in relative simultaneity.

This concept of 'relative simultaneity' demonstrates that even absolutes are now relative and there is no 'better' inertial frame of reference in Einstein's world of special relativity. Students usually find 'relative simultaneity' an abstract concept to appreciate. However, we cannot rely on our common sense when we are dealing with 'relative simultaneity' or more generally, special relativity, simply because they do not occur in everyday life. In order to observe a noticeable effect of relative simultaneity, the velocity of the observer has to approach c and the distance light has to travel needs to be close to infinite. Of course, neither of these happens in everyday situations.

Figure 4.3 The thought experiment for time dilation



Time dilation

Time in Einstein's special relativity also loses its absolute nature and becomes relative. Consider the following situation (thought experiment):

In Figure 4.3, a train is moving to the right at a constant velocity *v* that is close to the speed of light. A light source is placed on the floor of the train while a mirror is fixed onto the ceiling of the train. A light beam is emitted at the light source. Observer A, who is inside the train, will see the light beam going straight up and down. Thus the distance light has travelled will be twice the vertical distance between the floor and the roof of the train, say 2d. (Assume the light source and mirror have no thickness for the purpose of simplicity.)

ANALOGY: If you throw a pen inside a moving train that has a constant velocity, you will see your pen going straight up and dropping straight down into your hand.

On the other hand, Observer B, who is outside the train, will see the light beam travelling forward-upward and then forward-downward as shown in Figure 4.3. The light has to travel diagonally in order to 'catch' up with the moving light source and mirror. Say the light now has to cover a distance 2d′, with d′ being the hypotenuse of the imaginary right angled triangle whose perpendicular height is the distance between the roof and floor, which is d. By Pythagoras theorem, the hypotenuse of a right angled triangle is always longer than the other two sides of the triangle, hence, d′ > d.

Since the light velocity has a constant value of '**c**', then:

- $t_o = \frac{2d}{c}$, where to is the time Observer A measures for the light to travel from the light source to the ceiling and then back. Observer A is stationary relative to the train—the frame of reference, hence, Observer A's time (t_o) is referred to as the **rest** or **original time**.
- $t_v = \frac{d'}{c}$, where tv is the time Observer B measures for the light to travel from the light source to the ceiling then back. Observer B is outside the train and moving relative to the train, hence, the time Observer B measures (t_v) is referred to as the **moving time**.
- Since $d' > d$, then $\boldsymbol{t_v > t_o}$.

The above phenomenon can be generalised to all times, which is then known as 'time dilation' in the theory of special relativity:

Definition

Time dilation can be summarised as 'a moving clock appears to run slower'.

NOTE: Since the time is running slower, the time interval is lengthened, hence, time is dilated.

Time dilation is governed by the equation:

$$t_v = \frac{t_o}{\sqrt{1 - \frac{v^2}{c^2}}}$$

Where:

$\boldsymbol{t_o}$ = the rest ('**o**riginal') time, observed by the person in the moving frame who is *relatively stationary* to the moving frame

$\boldsymbol{t_v}$ = the moving time, observed by the stationary observer who is *moving relative* to the frame of concern, hence, mo**v**ing time

$\boldsymbol{v}$ = the velocity of the frame of concern, measured in m s^{-1}

$\boldsymbol{c}$ = the speed of light, which is approximately equal to 3×10^8 m s^{-1}

$\boldsymbol{t_o}$ and $\boldsymbol{t_v}$ can take any time units as long as they are consistent.

Example 1

Suppose in the thought experiment above, shown in Figure 4.3, the train is travelling at 3.0×10^7 m s^{-1}. If one hour has passed for the stationary observer outside the train, how long has passed for the person on the train?

NOTE: In order to answer time dilation questions correctly, it is very important to identify t_v and t_o correctly.

Solution

For the stationary observer who observes the moving train from outside, there is a relative motion between the observer and the train, and so this observer's time is the moving time, t_v. The observer on the moving train will appear to be stationary relative to the train, therefore, this observer's time is the rest time, t_o.

$$t_v = \frac{t_o}{\sqrt{1 - \frac{v^2}{c^2}}}$$

$$t_v = 1 \text{ hour} = 60 \text{ minutes}$$
$$v = 3.0 \times 10^7 \text{ m s}^{-1}$$
$$t_o = ?$$

$$\therefore\ t_o = t_v \times \sqrt{1 - \left(\frac{v}{c}\right)^2}$$

$$t_o = 60 \times \sqrt{1 - \left(\frac{3.0 \times 10^7}{3.0 \times 10^8}\right)^2}$$

$$t_o = 60 \times \sqrt{1 - (0.1)^2}$$
$$t_o = 59.70 \text{ min}$$
$$= 59 \text{ min } 42 \text{ s}$$

In order to make sure we have done the calculation correctly, we can always check:

One hour has passed for the observer who is stationary, but only 59.70 minutes have passed for the observer on the train. Hence the time for the observer in the moving train (frame) runs slower. This agrees with our definition of time dilation!

Example 2

A super rocket is launched to travel to a star which is 10 light-years away from Earth. If the rocket travels at velocity of 0.94c on average:

(a) How long will a single journey be, as measured by scientists on Earth?
(b) How long will a single journey be, as measured by astronauts on board?

NOTE: Light-year is a distance unit. One light-year is equal to the distance covered by light in one year, it is equal to: $3 \times 10^8 \times 3600 \times 24 \times 365 \approx 9.46 \times 10^{15}$ m.

Solution

(a) $s = vt \Rightarrow t = \dfrac{s}{v}$

$$t = \frac{10 \times (3 \times 10^8) \times (3600 \times 24 \times 365)}{0.94 \times (3 \times 10^8)} \text{ seconds}$$

$$t = \frac{10 \times (3 \times 10^8) \times (3600 \times 24 \times 365)}{0.94 \times (3 \times 10^8) \times (3600 \times 24 \times 365)} \text{ years}$$

$$t = \frac{10}{0.94}$$

$$t \approx 10.64 \text{ years}$$

(b)

$$t_v = \frac{t_o}{\sqrt{1 - \dfrac{v^2}{c^2}}}$$

t_v = time measured by scientists on Earth, since they are moving relative to the rocket = 10.64 years

t_o = time measured by astronaut, as they are at rest relative to the rocket = ?

$v = 0.94c$

$$\therefore\ t_o = t_v \times \sqrt{1 - \left(\frac{v}{c}\right)^2}$$

$$t_o = 10.64 \times \sqrt{1 - \left(\frac{0.94c}{c}\right)^2}$$

$$t_o = 10.64 \times \sqrt{1 - 0.94^2}$$

$$t_o = 3.63 \text{ years}$$

$\therefore$ according to the astronauts, the journey will take 3.63 years.

SR

Simulation: time dilation

Length contraction

Definition

Length contraction is when the length of a moving object appears shorter compared to the length of the object when measured at rest.

Length contraction occurs according to the formula:

$$l_v = l_o\sqrt{1 - \frac{v^2}{c^2}}$$

Where:

$\boldsymbol{l_o}$ = the rest length; it is the length of an object observed when it is stationary, or by an observer who is stationary relative to the object

$\boldsymbol{l_v}$ = the moving length; it is the length observed when the object is in motion, or by an observer who is in motion relative to the object

$\boldsymbol{v}$ = the **relative velocity** of the object, measured in m s^{-1}

$\boldsymbol{c}$ = the speed of light

Again, $\boldsymbol{l_o}$ and $\boldsymbol{l_v}$ can take any length units as long as they are consistent.

NOTE: The phenomenon of length contraction can be proven by using a similar thought experiment used in proving time dilation.

Example 1

A pen is measured to be 15 cm long when placed on the table. How long would it be if it is now moving at a velocity of (a) 340 m s^{-1} (b) 2.7 × 10^8 m s^{-1}

Solution

(a) Since the pen is 15 cm at rest, this is the **rest length** $\boldsymbol{l_o}$. When it is moving, the length it has is the **moving length**, hence $\boldsymbol{l_v}$.

$$l_v = l_o\sqrt{1 - \frac{v^2}{c^2}}$$

l_o = 15 cm

v = 340 m s^{-1}

l_v = ?

$$l_v = 15 \times \sqrt{1 - \left(\frac{340}{3 \times 10^8}\right)^2}$$

$l_v \approx$ 15 cm

∴ the length of the pen when it is moving at 340 m s^{-1} is still 15 cm.

(b) Similarly:

$$l_v = l_o\sqrt{1 - \frac{v^2}{c^2}}$$

l_o = 15 cm

v = 2.7 × 10^8 m s^{-1}

l_v = ?

$$\therefore\ l_v = 15 \times \sqrt{1 - \left(\frac{2.7 \times 10^8}{3.0 \times 10^8}\right)^2}$$

$$l_v = 15 \times \sqrt{1 - (0.9)^2}$$

$$l_v \approx 6.54 \text{ cm}$$

$\therefore$ when the pen is moving at 2.7×10^8 m s^{-1}, its length is measured as being 6.54 cm.

NOTE: The example above illustrates a very important principle. All effects of special relativity (including time dilation and mass dilation) only become apparent when the speed is a significant proportion of the speed of light, that is, a **relativistic velocity**.

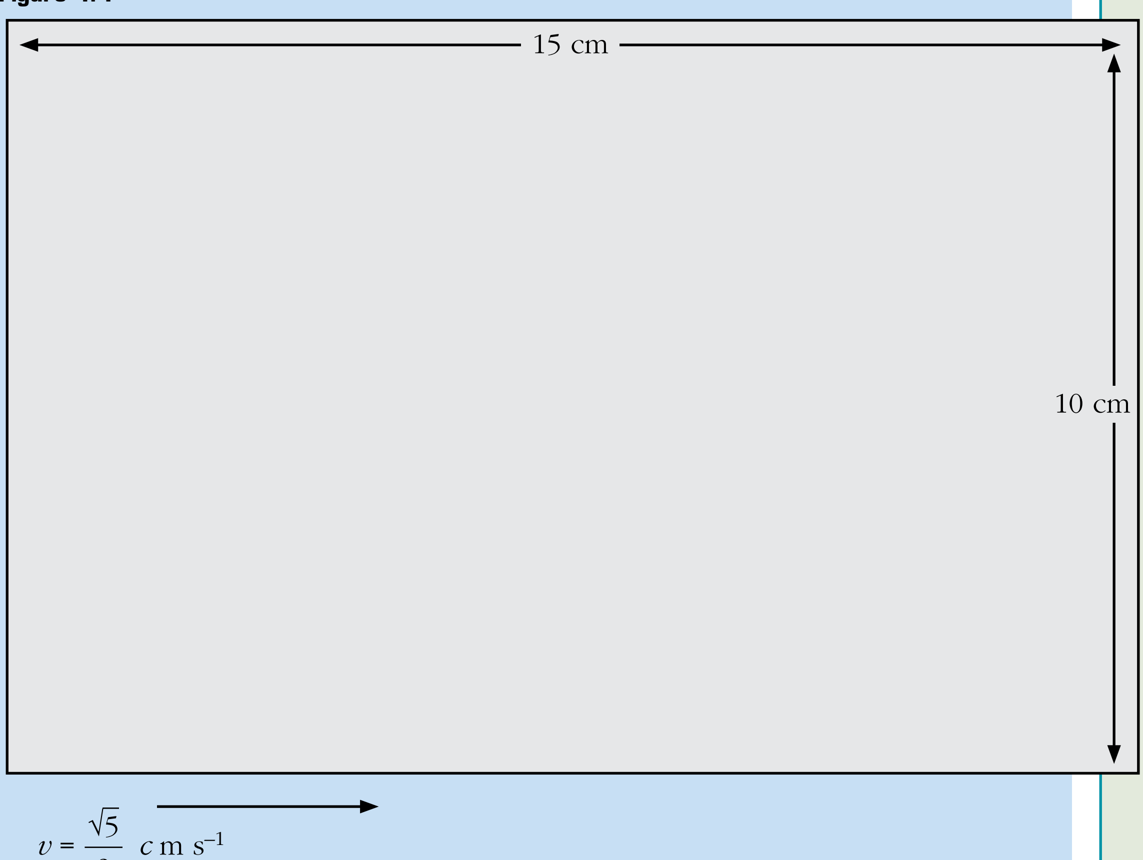
Also, length contraction only occurs in the dimension of the direction of the motion.

The following example illustrates this.

Example 2

For the rectangle below, its length and width are measured to be 15 cm and 10 cm respectively when it is at rest. If it is now moving in the direction shown by the arrow at $\frac{\sqrt{5}}{3}c$ m s^{-1}, what is its length and width?

Figure 4.4



Solution

Only the length is moving in the direction of the motion, hence, it will experience length contraction.

$$l_v = l_o\sqrt{1 - \frac{v^2}{c^2}}$$

l_o = the length of the rectangle when it is at rest = 15 cm

l_v = the length of the rectangle when it is in motion = ?

$$v = \frac{\sqrt{5}}{3}\ c \text{ m s}^{-1}$$

$$\therefore\ l_v = 15 \times \sqrt{1 - \left(\frac{\frac{\sqrt{5}}{3}\cancel{c}}{\cancel{c}}\right)^2}$$

$$l_v = 15 \times \sqrt{1 - \left(\frac{\sqrt{5}}{3}\right)^2}$$

$$l_v = 15 \times \sqrt{1 - \frac{5}{9}}$$

$$l_v = 15 \times \frac{2}{3}$$

$$l_v = 10 \text{ cm}$$

$\therefore$ the length of the rectangle when it is in motion is 10 cm.

The width is not moving in the direction of the motion, therefore length contraction does not apply. The width will still be 10 cm.

Hence the rectangle will become a square, but *not* a smaller rectangle.

Example 3

A UFO that is flying at 4.5×10^7 m s^{-1} is measured to have a length of 30 m according to a stationary observer on the ground. What will be its length measured by a pilot on the UFO?

Solution

The UFO is moving relative to the observer on the ground, so that the length of 30 m measured by the observer is the moving length, hence l_v.

The pilot on the UFO is stationary relative to the UFO so that the length the pilot measures will be the rest length, l_o (even though the pilot is moving).

$$l_v = l_o\sqrt{1 - \frac{v^2}{c^2}}$$

$$\therefore\ l_o = \frac{l_v}{\sqrt{1 - \left(\frac{v}{c}\right)^2}}$$

$l_v = 30$ m

$v = 4.5 \times 10^7$ m s^{-1}

$l_o = ?$

$$l_o = \frac{30}{\sqrt{1 - \left(\frac{4.5 \times 10^7}{3.0 \times 10^8}\right)^2}}$$

$$l_o = \frac{30}{\sqrt{1 - (0.15)^2}}$$

$= 30.34$ m

∴ the length of the UFO as measured by its pilot is 30.34 m.

Mass dilation

Definition

Mass dilation is when the mass of a moving object appears greater compared to the object's mass at rest.

Mass dilation occurs according to the formula:

$$m_v = \frac{m_o}{\sqrt{1 - \frac{v^2}{c^2}}}$$

Where:

$\boldsymbol{m_o}$ = the rest mass; it is the mass of an object measured when it is stationary, or by an observer who is stationary relatively the object

$\boldsymbol{m_v}$ = the moving mass; it is the mass measured when the object is in motion, or by an observer who is in motion relative to the object

$\boldsymbol{v}$ = the **relative velocity** of the object, measured in m s^{-1}

$\boldsymbol{c}$ = the speed of light

Once again, $\boldsymbol{m_o}$ and $\boldsymbol{m_v}$ can take any mass units as long as they are consistent.

Example 1

Electrons have a rest mass of 9.109×10^{-31} kg. If an electron is moving at 6.50×10^6 m s^{-1}, what will be its mass?

Solution

$$m_v = \frac{m_o}{\sqrt{1 - \frac{v^2}{c^2}}}$$

$$m_o = 9.109 \times 10^{-31}$$
$$v = 6.50 \times 10^6 \text{ m s}^{-1}$$
$$m_v = ?$$
$$\therefore\ m_v = \frac{9.109 \times 10^{-31}}{\sqrt{1 - \left(\dfrac{6.50 \times 10^6}{3.00 \times 10^8}\right)^2}}$$
$$m = 9.111 \times 10^{-31} \text{ kg}$$

$\therefore$ this moving electron has a mass of 9.111×10^{-31} kg.

Example 2

(a) The engine of a spacecraft can provide a constant thrust of 2.0×10^5 N. If the spacecraft has a mass of 1.00×10^5 kg at rest, what is its initial acceleration?

(b) What will be its acceleration when its velocity reaches 0.9999999c?

Solution

(a)

$$F = ma$$
$$F = 2.0 \times 10^5 \text{ N}$$
$$m = 1.00 \times 10^5 \text{ kg}$$
$$a = ?$$
$$a = \frac{F}{m}$$

$a = 2.0 \text{ m s}^{-2}$ In the direction of the thrust

(b)

When the spacecraft is at rest, its mass is 1.00×10^5 kg, therefore $m_o = 1.00 \times 10^5$ kg. When it is moving at 0.9999999c, its mass then is the 'moving mass', m_v.

$$m_v = \frac{m_o}{\sqrt{1 - \dfrac{v^2}{c^2}}}$$

$$m_o = 1.00 \times 10^5 \text{ kg}$$
$$v = 0.9999999c \text{ m s}^{-1}$$
$$m_v = ?$$
$$m_v = \frac{1.00 \times 10^5}{\sqrt{1 - \left(\dfrac{0.9999999\cancel{c}}{\cancel{c}}\right)^2}}$$
$$m_v \approx 2.23 \times 10^8 \text{ kg}$$

Then:

$$a = \frac{F}{m}$$

$$F = 2.0 \times 10^5\ N$$

$$m = 2.23 \times 10^8 \text{ kg}$$

$$a = \frac{2.0 \times 10^5}{2.23 \times 10^8}$$

$a = 8.94 \times 10^{-4}$ m s^{-2} in the direction of the thrust

∴ the acceleration when the velocity reaches 0.999 999 9c is as little as 8.9×10^{-4} m s^{-2}

Therefore, as a consequence of mass dilation, as the speed of an object increases, its mass increases; as a result its acceleration decreases if the acting net force remains constant. If this trend continues, the final outcome is that as the speed of the object approaches the speed of light, its mass approaches infinity, and its acceleration approaches zero, as shown in example 3. It follows that under this circumstance, its velocity can no longer increase; hence, the velocity of any object in the Universe will not exceed that of light.

This phenomenon agrees with all the special relativity formulae: since all formulae are related to the $\sqrt{1 - \frac{v^2}{c^2}}$; then if $v > c$, then $\left(1 - \frac{v^2}{c^2}\right) < 0$; and the equations become meaningless.

WWW

USEFUL WEBSITE

The Poul Anderson novel *Tau Zero*, also called *To Outlive Eternity*, is a good fiction story illustrating relativity when *v* is almost *c*. This story can be downloaded from http://www.webscription.net/

The equivalence between mass and energy

In the special theory of relativity, Einstein proposed:

Definition

Enery–mass equivalence is where energy and mass are equivalent and are interconvertible.

This relationship is governed by the equation:

$$E = mc^2$$

Where:

E = the energy, measured in J

m = the mass, measured in kg

c = the speed of light, which is equal to 3×10^8 m s^{-1}

A nuclear explosion at a testing facility in Mururoa, French Polynesia, 1970—energy derived from the loss of mass

This simple equation links mass and energy together, so that mass and energy are no longer independent. This also brings revolutionary changes to the laws of physics. In particular, the law of conservation of energy and the law of conservation of mass are challenged. These laws state neither mass nor energy can be created nor destroyed. However, by Einstein's equation, mass can be created by sacrificing energy, and energy can be created by destroying mass. The consequence is that modifications to these laws need to be made in order to accommodate this relationship between mass and energy. The new law becomes the law of conservation of mass and energy, which states:

Matter and energy cannot be destroyed or created. They can only be transformed.

This energy and mass relationship also opens up a whole new realm of energy study. Since energy is related to mass by a factor of c^2, it follows that if we could convert any mass into energy, then the Earth in fact has an almost infinite amount of energy reserves.

This idea has been extended into nuclear technologies and matter and anti-matter interactions where a small amount of mass is destroyed to create energy. (Nuclear reactions will be discussed in detail in From quanta to quarks.)

Example 1

Assume one small loaf of bread weighs 250 g. If we are able to convert all the mass into energy, how much energy can we produce?

Solution

$E = mc^2$

$m = 0.25$ kg

$E = ?$

$E = 0.25 \times (3 \times 10^8)^2$

$E = 2.25 \times 10^{16}$ J

NOTE: This is approximately the amount of energy a huge power station would deliver in one year; hence, the amount of energy released is enormous.

Example 2

The anti-matter of an electron is called a positron. In simple terms, it is equivalent to an electron carrying a negative charge. When a positron meets an electron, they completely annihilate each other and all masses are converted into energy.

Calculate the energy released when a positron meets an electron so that their masses are totally annihilated.

Solution

Mass of the electron = 9.109×10^{-31} kg

Mass of the positron = 9.109×10^{-31} kg (since they are identical except the signs of their charges)

Total mass annihilated = 1.8218×10^{-30} kg

$E = mc^2$

$E = (1.8218 \times 10^{-30}) \times (3 \times 10^8)^2$

$E \approx 1.64 \times 10^{-13}$ J

4.6 The modern standard of length

■ *Discuss the concept that length standards are defined in terms of time in contrast to the original metre standard*

In 1793 the French government decreed that the unit of length shall be one ten-millionth (i.e. 10^{-7}) of the distance from the north pole to the equator, passing through Paris. This distance was to be called the metre. Three platinum bars were made based on the survey. Although it was found that the surveyors had made an error in their measurements, these bars served as the standard for length rather than the original definition. A platinum-iridium alloy bar replaced the original standard bars in 1889.

The need for a more accurate standard of length led to the formal adoption in 1960 of a definition of the metre based on a wavelength of radiation from kryton-86, specifically being 1 650 763.73 wavelengths of a particular emission line measured in a vacuum. This change made the standard more precise than previously, but with the need for an even more precise standard, it was changed in 1983. The new standard, still in use today, is based on the definition of time, a very precisely known standard, being defined as 9 129 631 770 oscillations of the Cs-133 atom. Using this precise definition, the present definition of the metre is *the length of the path travelled by light in a vacuum during the time interval of 1/299 792 458th of a second*. This definition itself assumes that the speed of light is exactly 299 792 458 metres per second. Thus the metre can be determined experimentally.

It may be that a further redefining of the metre will be required at some point in the future. The present definition does not take into account certain relativistic phenomena, including time dilation, as well as how the speed of light is affected by the strength of the gravitational field through which it is travelling. The need for an even more precise standard for length will drive any changes.

Evidence for special relativity

SECONDARY SOURCE INVESTIGATION

PFAs

H1, H2

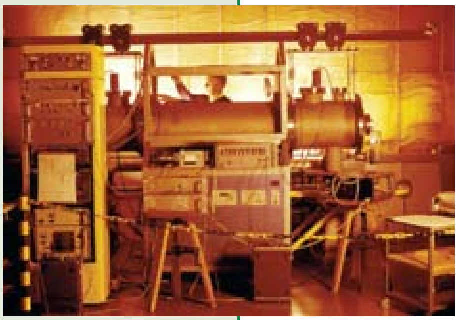
PHYSICS SKILLS

11.1, 12.3, 12.4, 13.1, 14.1, 14.5

■ *Analyse information to discuss the relationship between theory and the evidence supporting it, using Einstein's predictions based on relativity that were made many years before evidence was available to support it*

Just like the aether model, Einstein's special theory of relativity also needed supporting experimental evidence. Unfortunately, highly advanced instruments were required in order to detect accurately the minute changes in time, length and mass at low speeds. Speeds that were close to the speed of light, which would otherwise produce obvious relativistic changes, were impossible to achieve, and this is true even with our current technology. This made verifying the theory an extremely difficult task. In fact, Einstein proposed his special theory of relativity as early as 1905, but it was not until a few decades later that strong and convincing evidence was made available to prove the validity of the theory.

Some experimental evidence for special relativity are described below.

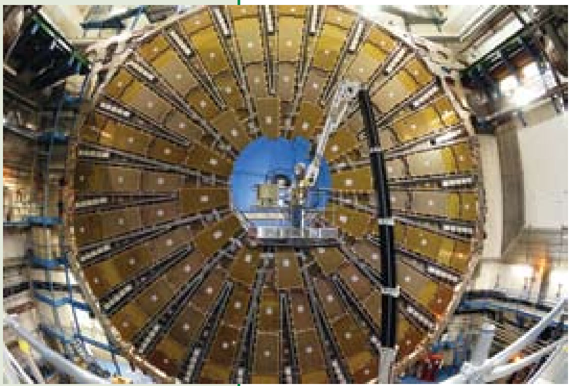


Atomic clock

Atomic clocks

Atomic clocks are extremely accurate and sensitive clocks that can measure time down to—and more precisely than—one billionth of a second.

The experiment involves two synchronised atomic clocks. One of the atomic clocks is put in a jet plane, which is sent off to fly at a very high speed for a period of time, while the other one is left on Earth (stationary). When the jet plane returns, the time of the two atomic clocks are compared. It is found that the two clocks are no longer synchronised; the time of the clock placed in the jet plane runs slower, as predicted by Einstein, hence, time is dilated.



A muon detector

Muons

Muons are one type of subatomic particles. They are formed in the upper atmosphere as a consequence of the interaction between the atmosphere and cosmic radiation. Muons are unstable and are subjected to natural decay. They have a very short half-life, about two micro-seconds. Although they travel at a very high velocity, with this short half-life it is impossible for any muon to reach the Earth's surface, since the distance from the upper atmosphere to the Earth's surface is large and all muons would have decayed before they could reach it. However, with the aid of advanced instruments, scientific laboratories have detected the presence of muons.

This comes as no surprise according to the special theory of relativity. Since muons are travelling at a relativistic velocity, their time will be dilated as measured by a stationary scientific laboratory; that is, muons' extremely short half-life of two micro-seconds (as measured when they are at rest) will be lengthened significantly, long enough for them to reach the surface of the Earth. The fact that muons are detected at the surface of the Earth provides very strong evidence for the validity of special relativity.

NOTE: The other way to explain this phenomenon is that as muons move down at a very high velocity, the distance before them appears to move at a relativistic velocity relative to them. Consequently, the distance they have to travel will contract, short enough for the muons to reach the Earth's surface within the limit of their lifetime.

4.7 Limitations of special relativity and the twin paradox

What is the twin paradox?

Consider two identical twins who have just celebrated their 21st birthday. One of the twins is put on a spacecraft and takes a long return trip to a distant star at a speed close to *c* while the other remains on Earth.

The Earth twin sees her own state as stationary while the space twin rockets off; thus she sees the time in the spacecraft ticking more slowly than time on Earth (observing time dilation). Hence the Earth twin concludes that the space twin will age less and will be younger upon her return.

However, from the space twin's perspective, she is at rest, while the Earth twin moves away at a relativistic speed.

Thus the space twin concludes the Earth twin's clock is running slower and will therefore expect the Earth twin to age less and be younger upon their reunion. However, they cannot both be younger than each other, hence, the paradox emerges!

ANALOGY: If you are in a moving train, you will think you are stationary, but everything outside is moving.

How is the paradox solved?

The paradox is resolved when we take into account the limitation of special relativity: special relativity is *only valid* for inertial frames of reference.

The Earth twin, who is at rest, remains in the same **inertial frame of reference** throughout, therefore her conclusion is always valid. The space twin however is not always in an inertial frame of reference, as the space twin has to accelerate to move away from Earth, make turns and decelerate to come back. Thus during these periods of acceleration, the space twin occupies a **non-inertial frame of reference**. Consequently the space twin's conclusion is fallacious.

NOTE: To produce a correct analysis of the time events from the point of view of the space twin, we must incorporate the effects of acceleration on time. As it turns out if we apply the time dilation formula from the theory of **general relativity** (which students do not need to know in this course), the answer will show the space twin returns younger, which is in agreement with the conclusion made by the Earth twin using special relativity.

What does the 'twin paradox' show?

Since only the statement made by the Earth twin is valid whereas the one made by the space twin needs to be disregarded, the 'twin paradox' is not a true paradox, but rather a stimulus that illustrates the limitation of special relativity.

Thought experiments and reality

■ ***Analyse and interpret some of Einstein's thought experiments involving mirrors and trains and discuss the relationship between thought and reality***

SECONDARY SOURCE INVESTIGATION

PFAs

H1, H2

PHYSICS SKILLS

11.1, 12.3, 12.4, 13.1, 14.3

Most of Einstein's theories are based on abstract thought experiments. For instance, the idea of time dilation and relative simultaneity are deduced based on thought experiments involving trains, light and mirrors. Although the thought experiments do not lack logic, they deviate quite a lot from reality because:

- Trains or spacecraft cannot travel at relativistic velocities.
- Even if a train does travel this fast, it is then impossible for an observer outside the train to observe anything and make any accurate measurements for the events happening in the train.
- In the time dilation thought experiment, it is impossible in reality to see the single light beam travelling up from the light source and then reflecting back from the mirror. We will just see the whole train light up.
- In the relative simultaneity thought experiment, in order to observe any noticeable effects, the train needs to be infinitely long, this cannot be achieved in reality at two levels. First, it is simply impossible to construct such a train. Second, even if such a train is made, the observer will not be able to see the light flashes from the sources placed at both ends of this train. This is because the infinitely large distance will result in the light intensity dropping to zero before reaching the observer.

Note that only the logic is valid in thought experiments—the experiments themselves cannot be reproduced in reality. Nevertheless, thought experiments are significant as sometimes they are the only way we can deduce important scientific theories. Can you come up with some thought experiments?

4.8 Implications of special relativity for future space travel

- ***Discuss the implications of mass increase, time dilation and length contraction for space travel***

Impact of mass dilation

As we have discussed earlier, the increase in mass as the speed of a spacecraft approaches c means that it becomes more difficult to further accelerate the spacecraft once its velocity becomes relativistic. This factor limits the speed of the spacecraft, with the maximum speed being one that is slightly under the speed of light even in an ideal situation (e.g. very powerful engine).

Unfortunately, compared to the vastness of the Universe, this speed is extremely small. Consequently space trips will take an extremely long time. For example, a trip to our closest star Alpha Centauri C will take 4.3 years even when travelling close to the speed of light.

Impact of time dilation

As we have seen in the time dilation section, time in the moving frame appears to run slower. Hence if a spacecraft can travel at a relativistic velocity, then its pilots' time will run significantly slower, therefore they will age much less compared to people on Earth. This means the extremely lengthy space travel as observed by the people on Earth (say, 4.3 years) will be reduced considerably according to the pilots (0.61 years if $v = 0.99c$). This allows the pilots to make prolonged space travel within their lifetime.

Also, when they return, they will see their children and probably grandchildren to be older than they are. More years have passed on Earth than they have experienced. They are able to 'see the future'.

Impact of length contraction

When a spacecraft is moving through space, relative to the pilots on the spacecraft, the space in front of the spacecraft is moving towards them. This means that the distance of the journey will appear shorter to the pilots than that being measured by people on Earth. Consequently, it will take the pilots a shorter time to reach their destination. However, it should be noted here that the pilots' time is at the same time running slower, as measured by an external 'stationary' observer.

NOTE: Once again, this shows length is related to time.

CHAPTER REVISION QUESTIONS

1. Aether was once a very significant part of most physics theories.
   (a) Outline why aether was important for physics theories.
   (b) List three properties of aether.

2. Michelson and Morley were determined to find evidence for the existence of aether.
   (a) With the help of a diagram, outline the method they used to try to detect the presence of aether. Specifically comment on why they had to rotate their apparatus by 90°.
   (b) What was the result of their experiment, and how could this be interpreted?
   (c) What were the consequences of the results of their experiment?

3. A student decides to carry out a pendulum experiment that she did in a school laboratory in a train that is travelling steadily at 20 m s^{-1}. How would the results compare to those obtained in the school laboratory? Explain your answer.

4. (a) Define the term 'non-inertial frame of reference'.
   (b) Give two examples of non-inertial frames of reference.
   (c) You are going to perform a simple experiment to confirm the two examples named in part (b) are non-inertial frame of references; briefly describe the procedure and results of the experiment.

5. Johnny is running at 5 m s^{-1}.
   (a) If he is going to throw a tennis ball at 10 m s^{-1} in the same direction as he is running, what will be the velocity of the ball with respect to the ground?
   (b) What will be the velocity of the ball relative to him?
   (c) If he is carrying a torch and is shining a beam in the same direction as he throws the ball, what will be the velocity of this beam of light relative to the ground?
   (d) What will be the velocity of the light relative to the torch?

6. Would a person in a rocket that is accelerating upwards be able to use special relativity to predict length contractions?

7. Discuss the concept of relative simultaneity. Briefly comment on the consequences.

8. As mentioned in the chapter, muons have a half-life of approximately two micro-seconds. What will be their half-life as measured by an Earth laboratory, if the muons are travelling at $0.99c$?

9. Suppose a super plane is to make a journey from town A to town B, 3400 km apart. If the plane travels at $0.3c$ throughout the journey:
   (a) How long will the journey be according to a resident in town B?

(b) How long will the journey be according to the pilot of the plane?
(c) What is the distance between town A and B according to the pilot?
(d) If the pilot is able to call the resident in town B, they will disagree with each other both in regard to the time elapsed and the distance of the journey. Who is correct? Justify your answer.

10. A spherical UFO with a radius of 50.0 m flies past the Earth at a velocity of 2.7×10^8 m s^{-1}.
(a) Determine its height and width as measured by observers on the Earth.
(b) If a human being can live for 100 years on the surface of the Earth, how long will they live for according to their relatives on the Earth when they travel inside this UFO?

11. Determine the mass of a moving hydrogen ion, travelling at 4.0×10^7 m s^{-1}.

12. A super aircraft has a mass of 30 tonnes (including full load of fuel) when it is parked at the airport. When it reaches and is flying at its maximum speed, its mass is 31 tonnes (including the fuel). Calculate its maximum speed.

13. It is true that all scientific theories need to be proven or validated by experiments. Describe one experiment which was conducted in an attempt to validate Einstein's special theory of relativity.

14. There are many obvious links between the relativistic effects described in special relativity.
(a) How can the concept of equivalence between mass and energy be linked to the concept of mass dilation?
(b) How can the concept of time dilation be linked with the concept of length contraction?

15. What are thought experiments? How do they differ from reality?

16. Evaluate the implications of special relativity on space travel.

SR

Answers to chapter revision questions