M.8.2 Einstein's Theory

M.8.2.1 Galileo's Principle of Relativity

Newton's laws are valid in **inertial frames of reference**; that is frames of reference in which an object is at *rest* or moves with a *constant velocity*. The results of an experiment that was carried out in a stationary frame of reference would be identical to the results obtained in a frame of reference that was moving with a uniform velocity.

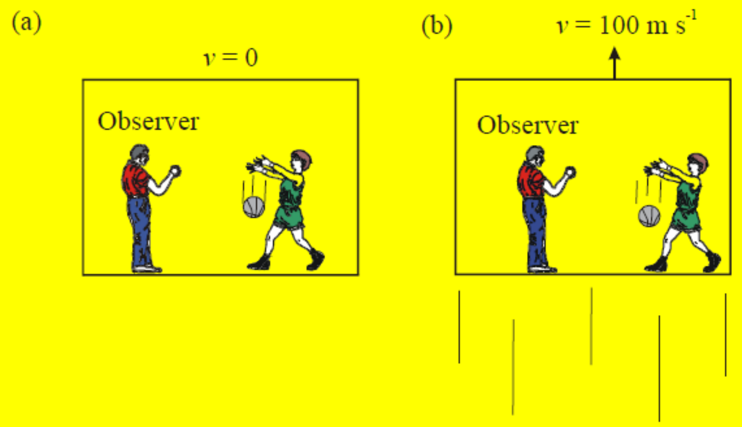


Figure 7.1(a) The observer and experimenter are both stationary, so this is an inertial frame of reference. (b) The observer and experimenter are both moving with constant velocity, so this is an inertial frame of reference. Identical data would be collected in both situations.

Similarly, if this experiment was *observed* by someone in an inertial frame of reference, the results would still be identical.

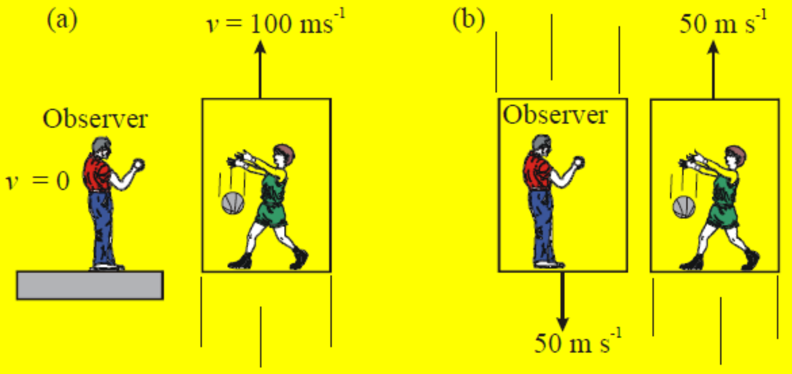


Figure 7. 2(a) The observer and experimenter are both in inertial frames of reference. (b) The observer and experimenter are again both in inertial frames. Identical data would be collected in both situations.

Clearly, it doesn't matter whose inertial frame of reference we take our measurements from - the results will be the same.

Since an object at rest or moving with a constant velocity is moving according to Newton's First Law or Galileo's Law of Inertia, the principle describing this behaviour is often referred to as the **Galilean principle of relativity**.

- Principle of Galilean Relativity – the laws of mechanics are the same in all inertial frames of reference.

M.8.2.2 James Maxwell and The Speed of Light

In 1864, **James Maxwell**, a brilliant theoretical physicist, produced **four equations** that form the basis of all electrical and magnetic interactions. Maxwell predicted that electromagnetic waves would **travel through a vacuum** at **3.0 × 10^8 m s^{-1}**. At the time it was accepted that waves needed a medium to travel through. Maxwell said that space was filled with a substance called the aether. Einstein later determined the aether to be unnecessary.

A problem with Maxwell's equations was that they predicted that the **speed of light would be the same for all observers**. According to his equations, it did not matter whether the light source was moving towards you, was stationary or was moving away from you - the measured speed of light would always be 3.0 × 10^8 m s^{-1}. This seemed to contradict the principle of Galilean relativity.

Two important aspects arising from Maxwell's equations were:

- light is an electromagnetic wave that travels at 3.0 × 10^8 m s^{-1} in a vacuum.
- the speed of light is the same for all observers, regardless of their state of motion. (experiments by physicists such as Michaelson and Morley supported this notion)

M.8.2.3 Einstein's Solution

In 1905, Albert Einstein published the Special Theory of Relativity. This theory was based on two simple postulates:

- **Postulate I**: the laws of physics are the same in all inertial (not accelerating) frames of reference.
- **Postulate II**: the speed of light in a vacuum has a constant value for all observers, regardless of their motion or motion of the source. $c = 2.99792458 \times 10^{8}\ m\ s^{-1}$

These two postulates seem to throw up some baffling contradictions. For example, if an astronaut in a rocket is travelling with a speed v towards a distant light source such as a star, you would expect, according to postulate I and our old Newtonian ideas, that the speed of this light relative to the astronaut would be c + v.

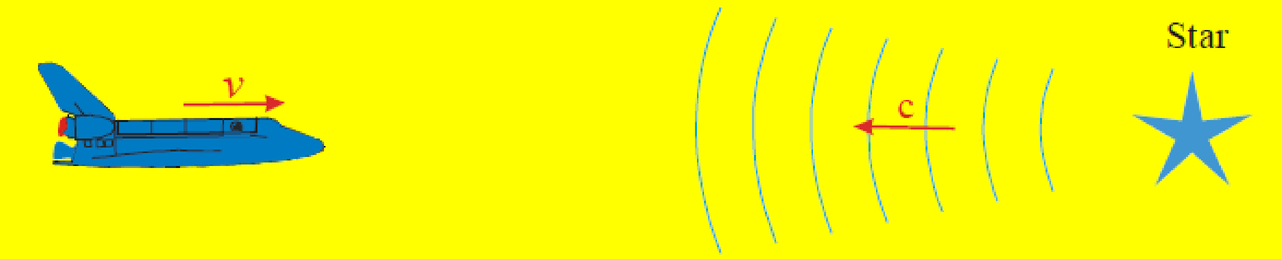


Figure 7.8 Einstein said that the speed of this starlight relative to the astronaut is c. To understand why this is so, it is necessary to think differently about the nature of space and time.

At the same time, postulate II is saying that the speed of the light relative to the astronaut is simply c. To overcome this apparent paradox, Einstein made some radical proposals about the nature of space and time.

According to **Newton's** postulates, quantities such as **space and time** were **absolute**. They did not change as the speed or position changed. Newton's laws are based upon these assumptions and work very well in most situations. Einstein proposed that Newton's laws and the absolute nature of space and time were fundamentally flawed and that it was necessary to change the way that quantities such as **length**, **mass** and **time** were viewed. **Einstein** suggested that **space and time were not absolute quantities**. Their values could change depending on their frame of reference.

To illustrate the consequences of accepting the two postulates he put forward, Einstein discussed a simple thought experiment. It involves a train, moving at a constant velocity.

Amaya and Binh have boarded Einstein's *Gedanken* train and Clare is outside on the platform (refer to Figure 6.1.6). This train has a flashing light bulb set right in the centre of the carriage. Amaya and Binh are watching the flashes of light as they reach the front and back walls of the carriage. They find that the flashes reach the front and back walls at the same time, which is not surprising. Outside, Clare is watching the same flashes of light. Einstein was interested in when Clare saw the flashes reach the end walls.

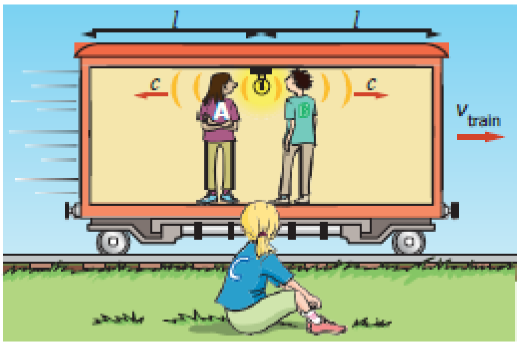


FIGURE 6.1.6 Amaya and Binh see the light take the same time, $\frac{l}{c}$ seconds, to reach the front and back walls.

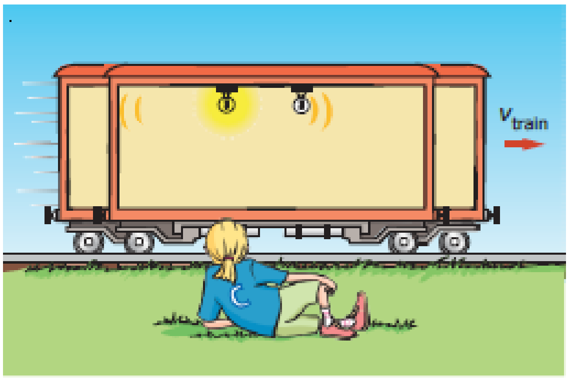


FIGURE 6.1.7 Clare sees the light reach the back wall first, and then the front wall.

If Clare sees the light travelling at the same speed in the forward and backward directions, she will see the light reach the back wall first (refer to Figure 6.1.7). This is because that wall is moving towards the light, whereas the front wall is moving away from the light, and so the light will take longer to catch up to it. This is against the principles of Newtonian physics. Amaya and Binh saw the light flashes reach the ends of the carriage at the same time; Clare saw them reach the walls at different times.

The idea that two events that are **simultaneous** (occur at the same time) for one set of observers but are not simultaneous for another is hard to comprehend.

Einstein said that the only reasonable explanation for how two events that were simultaneous to one set of observers were not simultaneous to another, is that time itself is behaving strangely. The amount of time that has elapsed in one frame of reference is not the same as that which has elapsed in another.

Einstein suggested that time and space are interrelated. This four-dimensional relationship, which includes the three dimensions of space and the one dimension of time, is called **spacetime**. Special relativity is all about spacetime.

James Clerk Maxwell predicted that light was an electromagnetic wave that propagated with a velocity of approximately 3×10^8 m s^{-1} through a medium called 'aether'.

Example 11 (2004 Sample Q10, 2 marks)

Explain why Maxwell's predictions appeared to contradict the 'principle of relativity'.

In 1861 James Clerk Maxwell proved that light was an electromagnetic wave with a speed of 3×10^8 m s^{-1}. Following Maxwell's predictions, physicists had some concerns.

Example 12 (2004 Pilot Q2, 2 marks)

Which one or more of the statements (**A – D**) below outlines one of these concerns?

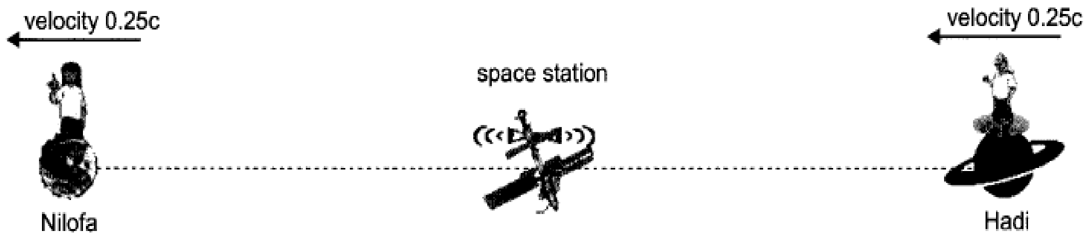
A. All waves propagate in a medium, but there was no medium in empty space.

B. Unlike the speed of other waves, experiments showed that the speed of light did not depend on the observer or source speed.

C. If light was a wave, it would not diffract.

D. The speed of light predicted by Maxwell did not agree with the measured speed.

A space station is emitting light from lasers fixed to it. Nilofa and Hadi are situated on two planets that are at rest relative to each other. They measure the speed of the light emitted from the lasers on the space station. Hadi is travelling towards the space station with a speed of 0.25c. Nilofa is travelling away from the space station with a speed of 0.25c. The speed of light through space is c.



Example 13 (2006 Q6, 2 marks)

Which of the statements (**A - D**) below gives the correct values for the velocity of light as measured by Nilofa and by Hadi?

A. Nilofa measures c and Hadi measures c.

B. Nilofa measures c and Hadi measures 1.5 c.

C. Nilofa measures 1.25 c and Hadi measures 0.75 c.

D. Nilofa measures 0.75 c and Hadi measures 1.25 c.

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