

10.1 Postulates of Special Relativity

Section Learning Objectives

By the end of this section, you will be able to do the following:

- Describe the experiments and scientific problems that led Albert Einstein to develop the special theory of relativity
- Understand the postulates on which the special theory of relativity was based

Teacher Support

Teacher Support The learning objectives in this section will help your students master the following student standards:

- (2) Scientific processes. The student uses a systematic approach to answer scientific laboratory and field investigative questions. The student is expected to:
 - (C) Know that scientific theories are based on natural and physical phenomena and are capable of being tested by multiple independent researchers. Unlike hypotheses, scientific theories are well-established and well-tested explanations, but may be subject to change as new areas of science and new technologies are developed.
- (3) Scientific processes. The student uses critical thinking, scientific reasoning, and problem solving to make informed decisions within and outside the classroom. The student is expected to:
 - (D) Explain the impacts of the scientific contributions of a variety of historical and contemporary scientists on scientific thought and society.
- (4) Science concepts. The student knows and applies the laws governing motion in a variety of situations. The student is expected to:
 - (F) Identify and describe motion relative to different frames of reference.

Section Key Terms

Teacher Support

Teacher Support [AL] Discuss the history of the concept of the ether. Explain that it more of a philosophical concept that was important prior to the

development of modern science. It arose from the belief that matter was continuous and vacuums were impossible. Ether was sometimes considered to be one of the elements.

[BL][OL] Mention that electromagnetic waves are unique among wave-propagated energy forms, in that they can travel across empty space. This was difficult to believe and caused scientists to doggedly hang onto the idea that there must be an ether permeating space. Ask students what they know about Einstein and dispel any misconceptions. Explain what *thought experiments* and *postulates* are.

Scientific Experiments and Problems

Relativity is not new. Way back around the year 1600, Galileo explained that motion is relative. Wherever you happen to be, it seems like you are at a fixed point and that everything moves with respect to you. Everyone else feels the same way. Motion is always measured with respect to a fixed point. This is called establishing a frame of reference. But the choice of the point is arbitrary, and all frames of reference are equally valid. A passenger in a moving car is not moving with respect to the driver, but they are both moving from the point of view of a person on the sidewalk waiting for a bus. They are moving even faster as seen by a person in a car coming toward them. It is all relative.

Teacher Support

Teacher Support [OL][AL] Focus students' thinking on the speed of light. Can the students think of anything else that has a maximum allowable value and is also a universal constant? Most constants are just numbers, like the value of pi. Most properties, such as mass and volume, have no fixed upper limit. Why does speed have a limit?

Tips For Success

A frame of reference is not a complicated concept. It is just something you decide is a fixed point or group of connected points. It is completely up to you. For example, when you look up at celestial objects in the sky, you choose the earth as your frame of reference, and the sun, moon, etc., seem to move across the sky.

Light is involved in the discussion of relativity because theories related to electromagnetism are inconsistent with Galileo's and Newton's explanation of relativity. The true nature of light was a hot topic of discussion and controversy in the late 19th century. At the time, it was not generally believed that light could travel across empty space. It was known to travel as waves, and all other types of energy that propagated as waves needed to travel through a material medium. It was believed that space was filled with an invisible medium that

light waves traveled through. This imaginary (as it turned out) material was called the ether (also spelled aether). It was thought that everything moved through this mysterious fluid. In other words, ether was the one fixed frame of reference. The Michelson–Morley experiment proved it was not.

In 1887, Albert Michelson and Edward Morley designed the interferometer shown in Figure 10.2 to measure the speed of Earth through the ether. A light beam is split into two perpendicular paths and then recombined. Recombining the waves produces an interference pattern, with a bright fringe at the locations where the two waves arrive in phase; that is, with the crests of both waves arriving together and the troughs arriving together. A dark fringe appears where the crest of one wave coincides with a trough of the other, so that the two cancel. If Earth is traveling through the ether as it orbits the sun, the peaks in one arm would take longer than in the other to reach the same location. The places where the two waves arrive in phase would change, and the interference pattern would shift. But, using the interferometer, there was no shift seen! This result led to two conclusions: that there is no ether and that the speed of light is the same regardless of the relative motion of source and observer. The Michelson–Morley investigation has been called the most famous failed experiment in history.

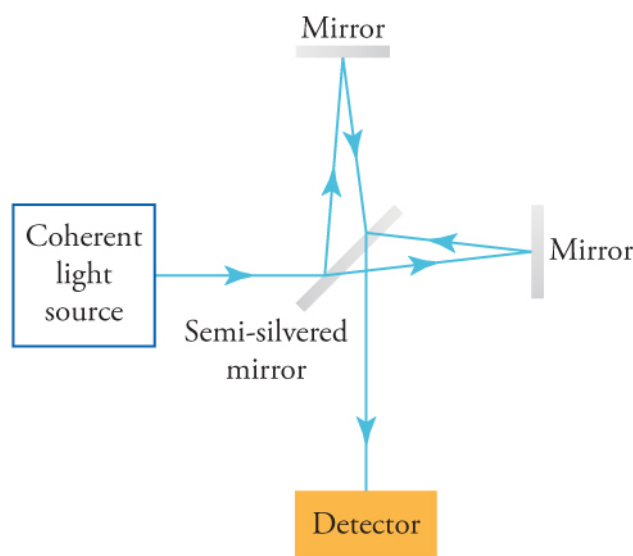


Figure 10.2 This is a diagram of the instrument used in the Michelson–Morley experiment.

Teacher Support

Teacher Support [BL][OL] Explain the geometry of the Michelson–Morley experiment. Explain why failure in this case was actually a success. Discuss how accepting unexpected results is an important ability for scientists. Ask students to memorize the value of the speed of light in m/s to three significant figures.

To see what Michelson and Morley expected to find when they measured the speed of light in two directions, watch this animation. In the video, two people swimming in a lake are represented as an analogy to light beams leaving Earth as it moves through the ether (if there were any ether). The swimmers swim away from and back to a platform that is moving through the water. The swimmers swim in different directions with respect to the motion of the platform. Even though they swim equal distances at the same speed, the motion of the platform causes them to arrive at different times.

Teacher Support

Teacher Support [AL]Be sure students understand that this animation does not explain how light behaves. It shows what Michelson and Morley *expected* to observe. It may work best to just introduce the Michelson—Morley experiment briefly and then watch the animation.

Einstein's Postulates

The results described above left physicists with some puzzling and unsettling questions such as, why doesn't light emitted by a fast-moving object travel faster than light from a street lamp? A radical new theory was needed, and Albert Einstein, shown in Figure 10.3, was about to become everyone's favorite genius. Einstein began with two simple postulates based on the two things we have discussed so far in this chapter.

1. The laws of physics are the same in all inertial reference frames.
2. The speed of light is the same in all inertial reference frames and is not affected by the speed of its source.

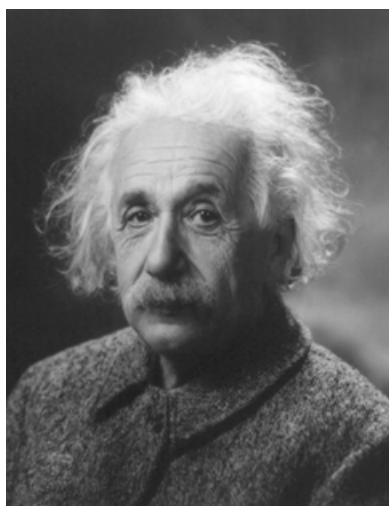


Figure 10.3 Albert Einstein (1879–1955) developed modern relativity and also made fundamental contributions to the foundations of quantum mechanics.

(The Library of Congress)

The speed of light is given the symbol c and is equal to exactly 299,792,458 m/s. This is the speed of light in vacuum; that is, in the absence of air. For most purposes, we round this number off to 3.00×10^8 m/s. The term inertial reference frame simply refers to a frame of reference where all objects follow Newton's first law of motion: Objects at rest remain at rest, and objects in motion remain in motion at a constant velocity in a straight line, unless acted upon by an external force. The inside of a car moving along a road at constant velocity and the inside of a stationary house are inertial reference frames.

Teacher Support

Teacher Support [BL] Ask students to round off the value given for c to 3 significant figures and express in scientific notation. Stress the units of measurements.

[OL] Explain the postulates carefully. Note that, although they both seem true, they lead to problems with the classical mechanics of Newton. Explain the concept of reference frame and ask students to think of examples of reference frames that are moving relative to one other. Use vehicles and celestial bodies. Explain that the understanding of relative motion goes back hundreds of years and did not begin with relativity theory.

[AL] Explain that it is the combination of these two postulates that leads to unusual results that will follow in the next section and that it is the combination of these postulates that forces us to abandon some aspects of Newtonian physics in some scenarios.

Misconception Alert

Note that the very precise value for the speed of light only applies to light traveling through a vacuum and that in all transparent material media it is slower.

Watch Physics

The Speed of Light This lecture on light summarizes the most important facts about the speed of light. If you are interested, you can watch the whole video, but the parts relevant to this chapter are found between 3:25 and 5:10, which you find by running your cursor along the bottom of the video.

[Click to view content](#)

Teacher Support

Teacher Support Only the section from 3:25 to 5:10 minutes is completely relevant to an understanding of the speed of light. If students watch it just after the text above, they will be adequately prepared.

Grasp Check

An airliner traveling at 200 m/s emits light from the front of the plane. Which statement describes the speed of the light?

- a. It travels at a speed of $c + 200$ m/s.
- b. It travels at a speed of $c - 200$ m/s.
- c. It travels at a speed c , like all light.
- d. It travels at a speed slightly less than c .

Snap Lab

Measure the Speed of Light In this experiment, you will measure the speed of light using a microwave oven and a slice of bread. The waves generated by a microwave oven are not part of the visible spectrum, but they are still electromagnetic radiation, so they travel at the speed of light. If we know the wavelength, λ , and frequency, f , of a wave, we can calculate its speed, v , using the equation $v = f\lambda$. You can measure the wavelength. You will find the frequency on a label on the back of a microwave oven. The wave in a microwave is a standing wave with areas of high and low intensity. The high intensity sections are one-half wavelength apart.

- High temperature: Very hot temperatures are encountered in this lab. These can cause burns.
 - a microwave oven
 - one slice of plain white bread
 - a centimeter ruler
 - a calculator
1. Work with a partner.
 2. Turn off the revolving feature of the microwave oven or remove the wheels under the microwave dish that make it turn. It is important that the dish does not turn.
 3. Place the slice of bread on the dish, set the microwave on high, close the door, run the microwave for about 15 seconds.
 4. A row of brown or black marks should appear on the bread. Stop the microwave as soon as they appear. Measure the distance between two adjacent burn marks and multiply the result by 2. This is the wavelength.
 5. The frequency of the waves is written on the back of the microwave. Look for something like “2,450 MHz.” Hz is the unit hertz, which means *per*

second. The M represents mega, which stands for million, so multiply the number by 10^6 .

6. Express the wavelength in meters and multiply it times the frequency. If you did everything correctly, you will get a number very close to the speed of light. Do not eat the bread. It is a general laboratory safety rule never to eat anything in the lab.

Teacher Support

Teacher Support This experiment could be demonstrated to the class if a microwave is available in the classroom. It might be better to let the students do the experiment at home so they can get more of a hands-on experience. Before the lab you might have them watch this video.

To continue the discussion, you could tell them about how light is refracted when it changes speed as it passes from one medium to another. Because light speed in air is slower than in a vacuum, light is refracted as it enters Earth's atmosphere.

This link takes you to a video demonstrating how to measure the speed of light using a microwave, a ruler, and a bar of chocolate. There is also an accompanying article with background information on measuring the speed of light.

Grasp Check

How does your measured value of the speed of light compare to the accepted value (% error)?

- a. The measured value of speed will be equal to c .
- b. The measured value of speed will be slightly less than c .
- c. The measured value of speed will be slightly greater than c .
- d. The measured value of speed will depend on the frequency of the microwave.

Teacher Support

Teacher Support [AL] This will be difficult to grasp completely for some students. The fact that the observers see different things is the result of the two postulates being true. If light speed is a constant and the two frames of reference are both valid, then simultaneity is not the same for all observers. Ask them to try the thought experiment in their own head to grasp what is being shown here. Sometimes students have fun sketching a cartoon that explains or demonstrates difficult concepts. They can then show the cartoon to the class and explain their reasoning.

[OL] If students are struggling with this explanation of simultaneity, let them know that there will be an animation in the next section that should make it clearer.

[OL][BL] Point out that the relationship between special relativity and Newton's mechanics is an excellent example of how science advances. Explain that new theories rarely reverse old theories. It is more common that new theories extend and expand on old theories. Ask students if they can think of other examples from the history of science.

Einstein's postulates were carefully chosen, and they both seemed very likely to be true. Einstein proceeded despite realizing that these two ideas taken together and applied to extreme conditions led to results that contradict Newtonian mechanics. He just took the ball and ran with it.

In the traditional view, velocities are additive. If you are running at 3 m/s and you throw a ball forward at a speed of 10 m/s, the ball should have a net speed of 13 m/s. However, according to relativity theory, the speed of a moving light source is not added to the speed of the emitted light.

In addition, Einstein's theory shows that if you were moving forward relative to Earth at nearly c (the speed of light) and could throw a ball forward at c , an observer at rest on the earth would not see the ball moving at nearly twice the speed of light. The observer would see it moving at a speed that is still less than c . This result conforms to both of Einstein's postulates: The speed of light has a fixed maximum and neither reference frame is privileged.

Consider how we measure elapsed time. If we use a stopwatch, for example, how do we know when to start and stop the watch? One method is to use the arrival of light from the event, such as observing a light turn green to start a drag race. The timing will be more accurate if some sort of electronic detection is used, avoiding human reaction times and other complications.

Now suppose we use this method to measure the time interval between two flashes of light produced by flash lamps on a moving train. (See Figure 10.4)

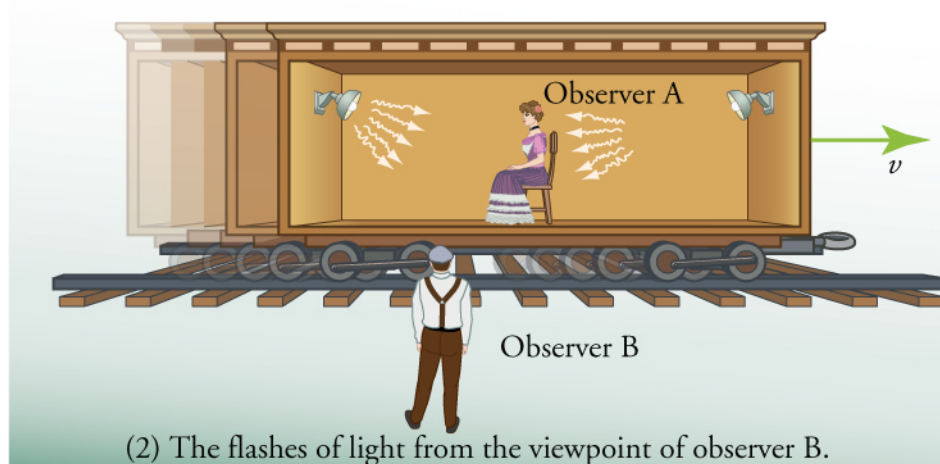
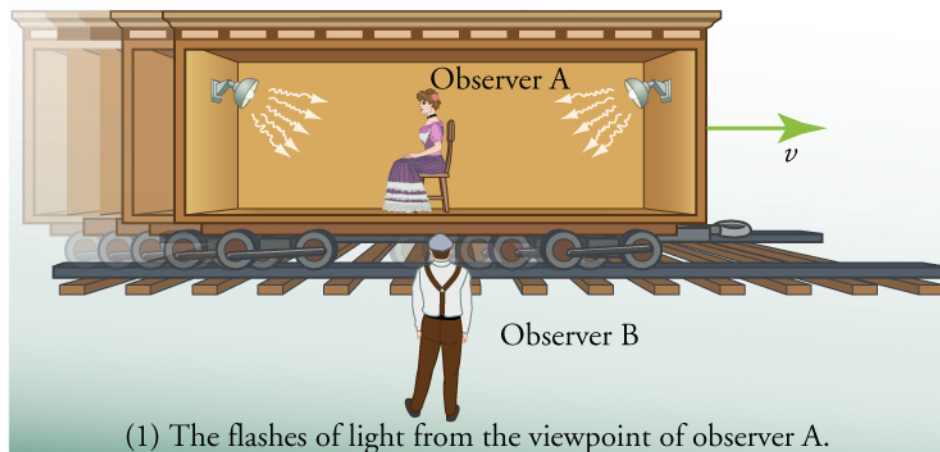


Figure 10.4 Light arriving to observer A as seen by two different observers.

A woman (observer A) is seated in the center of a rail car, with two flash lamps at opposite sides equidistant from her. Multiple light rays that are emitted from the flash lamps move towards observer A, as shown with arrows. A velocity vector arrow for the rail car is shown towards the right. A man (observer B) standing on the platform is facing the woman and also observes the flashes of light.

Observer A moves with the lamps on the rail car as the rail car moves towards the right of observer B. Observer B receives the light flashes simultaneously, and sees the bulbs as both having flashed at the same time. However, he sees observer A receive the flash from the right first. Because the pulse from the right reaches her first, in her frame of reference she sees the bulbs as not having flashed simultaneously. Here, a relative velocity between observers affects whether two

events at well-separated locations are observed to be simultaneous. Simultaneity, or whether different events occur at the same instant, depends on the frame of reference of the observer. Remember that velocity equals distance divided by time, so $t = d/v$. If velocity appears to be different, then duration of time appears to be different.

This illustrates the power of clear thinking. We might have guessed incorrectly that, if light is emitted simultaneously, then two observers halfway between the sources would see the flashes simultaneously. But careful analysis shows this not to be the case. Einstein was brilliant at this type of thought experiment (in German, *Gedankenexperiment*). He very carefully considered how an observation is made and disregarded what might seem obvious. The validity of thought experiments, of course, is determined by actual observation. The genius of Einstein is evidenced by the fact that experiments have repeatedly confirmed his theory of relativity. No experiments after that of Michelson and Morley were able to detect any ether medium. We will describe later how experiments also confirmed other predictions of special relativity, such as the distance between two objects and the time interval of two events being different for two observers moving with respect to each other.

In summary: Two events are defined to be simultaneous if an observer measures them as occurring at the same time (such as by receiving light from the events). Two events are not necessarily simultaneous to all observers.

The discrepancies between Newtonian mechanics and relativity theory illustrate an important point about how science advances. Einstein's theory did not replace Newton's but rather extended it. It is not unusual that a new theory must be developed to account for new information. In most cases, the new theory is built on the foundation of older theory. It is rare that old theories are completely replaced.

In this chapter, you will learn about the theory of special relativity, but, as mentioned in the introduction, Einstein developed two relativity theories: special and general. Table 10.1 summarizes the differences between the two theories.

Table 10.1 Comparing Special Relativity and General Relativity

Worked Example

Calculating the Time it Takes Light to Travel a Given Distance The sun is 1.50×10^8 km from Earth. How long does it take light to travel from the sun to Earth in minutes and seconds?

Strategy

Identify knowns.

$$\text{Distance} = 1.50 \times 10^8 \text{ km}$$

$$\text{Speed} = 3.00 \times 10^8 \text{ km/s}$$

10.1

Identify unknowns.

Time

Find the equation that relates knowns and unknowns.

$$v = \frac{d}{t}; \quad t = \frac{d}{v}$$

10.2

Be sure to use consistent units.

Solution

$$t = \frac{d}{v} = \frac{(1.50 \times 10^8 \text{ km}) \times \frac{10^3 \text{ m}}{\text{km}}}{3.00 \times 10^8 \frac{\text{m}}{\text{s}}} = 5.00 \times 10^2 \text{ s}$$

$$500 \text{ s} = 8 \text{ min and } 20 \text{ s}$$

Discussion

The answer is written as 5.00×10^2 rather than 500 in order to show that there are three significant figures. When astronomers witness an event on the sun, such as a sunspot, it actually happened minutes earlier. Compare 8 light *minutes* to the distance to stars, which are light *years* away. Any events on other stars happened years ago.

Teacher Support

Teacher Support Identify the three variables and choose the relevant equation. In physics, calculations are usually done using units of meters and seconds. Use scientific notation to keep track of significant figures.

Practice Problems

1.

Light travels through 1.00 m of water in 4.42×10^{-9} s. What is the speed of light in water?

- a. 4.42×10^{-9} m/s
- b. 4.42×10^9 m/s
- c. 2.26×10^8 m/s
- d. 226×10^8 m/s

2.

An astronaut on the moon receives a message from mission control on Earth. The signal is sent by a form of electromagnetic radiation and takes 1.28 s to travel the distance between Earth and the moon. What is the distance from Earth to the moon?

- a. 2.34×10^5 km
- b. 2.34×10^8 km
- c. 3.84×10^5 km
- d. 3.84×10^8 km

Check Your Understanding

Teacher Support

Teacher Support Use the Check Your Understanding questions to assess students' achievement of the section's learning objectives. If students are struggling with a specific objective, the Check Your Understanding will help identify which and direct students to the relevant content.

3.

Explain what is meant by a frame of reference.

- a. A frame of reference is a graph plotted between distance and time.
- b. A frame of reference is a graph plotted between speed and time.
- c. A frame of reference is the velocity of an object through empty space without regard to its surroundings.
- d. A frame of reference is an arbitrarily fixed point with respect to which motion of other points is measured.

4.

Two people swim away from a raft that is floating downstream. One swims upstream and returns, and the other swims across the current and back. If this scenario represents the Michelson–Morley experiment, what do (i) the water, (ii) the swimmers, and (iii) the raft represent?

- a. the ether rays of light Earth
- b. rays of light the ether Earth
- c. the ether Earth rays of light
- d. Earth rays of light the ether

5.

If Michelson and Morley had observed the interference pattern shift in their interferometer, what would that have indicated?

- a. The speed of light is the same in all frames of reference.
- b. The speed of light depends on the motion relative to the ether.
- c. The speed of light changes upon reflection from a surface.
- d. The speed of light in vacuum is less than 3.00×10^8 m/s.

6.

If you designate a point as being fixed and use that point to measure the motion of surrounding objects, what is the point called?

- a. An origin
- b. A frame of reference
- c. A moving frame
- d. A coordinate system