# 11.1 The Special Theory of Relativity

At the turn of the twentieth century, most of the physics community enjoyed a sense of accomplishment. Newtonian mechanics (also called classical mechanics), based on Newton's laws of motion, provided the principles by which all matter behaved. Physicists expanded these principles to the atomic level and established the idea of energy conservation. Building on James Clerk Maxwell's mathematical description of electric and magnetic fields, physicists successfully unified the subjects of electricity, magnetism, and optics. Maxwell's ideas had an apparent answer to the true nature of light: light is a combination of oscillating electric and magnetic fields.

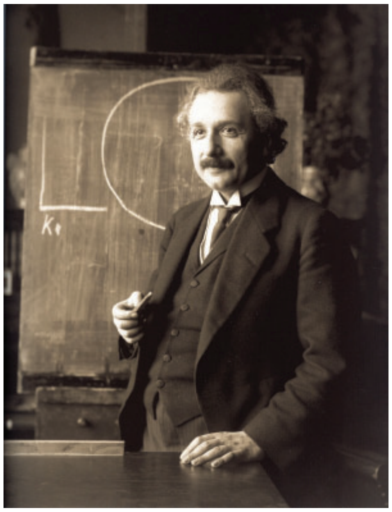

**Figure 1** Albert Einstein's ideas in physics changed our perception of space and time.

At that time, only a few questions remained. The nature of the atom was still unclear. Physicists had observed that light emitted from perfect radiators (called "blackbodies," which you will learn more about in Chapter 12) did not behave as predicted. This gave rise to the so-called blackbody problem. The phenomenon by which metals give up electrons under certain kinds of light also had physicists mystified. Moreover, contrary to Maxwell's assumption that electromagnetic waves, like all waves, needed a medium, there was no evidence to support this. Physicists expected to solve these problems within the framework of familiar physical models and principles. However, new models and principles needed to be developed in order to explain these problems, and these new ideas radically changed the way physicists understood their once-familiar universe. One of the main contributors to these new models was Albert Einstein (1879–1955) (**Figure 1**). CAREER LINK

## The Principle of Relativity

Suppose you are inside a room that has no windows. A billiard table stands near the centre of the room. If you strike the cue ball with the cue stick, you will notice that the ball moves in the direction of the applied force. This is exactly what you would expect to happen, according to Newton's second law of motion ($\vec{F} = m\vec{a}$). Similarly, you observe that linear momentum is conserved when the cue ball collides with another ball. You will also note that mechanical energy is conserved if the collision is elastic. Everything that you observe is consistent with the principles and laws of Newtonian mechanics.

What you do not know is that the room is not simply a windowless room in a building—it is in a railway car that can move on a set of tracks. Now suppose that the railway car starts to move, and for a brief time accelerates from zero to a final constant velocity. You will notice during this time that the laws of motion will appear different in the room. The billiard balls on the table will roll backward on their own, as if acted upon by an unseen force. You may even have trouble walking because of the sensation of a force acting on you. All of this is occurring because everything in the room is accelerating along with the railway car.

By the time the car is moving along a straight, level stretch of smooth track at a constant speed, the conditions in the car are the same as when it was at rest. You cannot feel or hear the motion of the car. The railway car is no longer accelerating, and nothing inside it—not you, not the table, not the balls on the table—is accelerating either. What happens, then, if you hit the cue ball with the stick in exactly the same way as before?

The answer is that the ball moves in exactly the same way. Nothing about the motion of the balls, or any object inside the room, indicates that the room is moving. The reason is that all objects inside the railway car share the motion of the car. The *relative* motion between you and the ball is the same for all constant velocities of the railway car. This includes the special case of zero velocity when the railway car is at rest. In fact, you cannot tell from the motion of any object inside the railway car, including yourself, that the railway car is moving, as long as the railway car does not accelerate.

The railway car in this situation is an example of a frame of reference. Recall from earlier chapters that a **frame of reference** is a coordinate system that you can use to observe and describe motion. In this case, you could measure the motion of the cue ball with respect to the reference frame. In particular, no external force acts on the objects in the frame of reference because the frame (the railway car) does not accelerate. This is the condition described in Newton's first law of motion, or the law of inertia. Any frame of reference that is at rest or moves with a constant velocity is an **inertial frame of reference**.

**frame of reference** a coordinate system relative to which motion is described or observed

**inertial frame of reference** a frame of reference that moves at zero or a constant velocity; a frame in which the law of inertia holds

Within an inertial frame, moving with constant velocity $\vec{v}$ ($\vec{v} = 0$ is a special case of constant velocity), mechanical laws apply in the same way that they would if there were no movement. Would you expect these laws to remain unchanged for an observer in a different inertial frame? As it turns out, there is only one difference between two inertial reference frames. For an observer in one frame, the velocities of objects in the other frame must be added, by vector addition, to the velocity with which that frame moves away from the first observer. This changes the way in which the motion of the object appears to the first observer. An example is illustrated in **Figure 2**. Once corrected, however, by considering the velocities of the two reference frames, the physical results become the same for both reference frames. This situation provides the basis for the **principle of relativity**: for all inertial frames of reference, the laws of Newtonian mechanics are the same. The main idea of the principle of relativity has a long history, going back at least to the work of Galileo in the 1600s.

**principle of relativity** the laws of motion are the same in all inertial frames

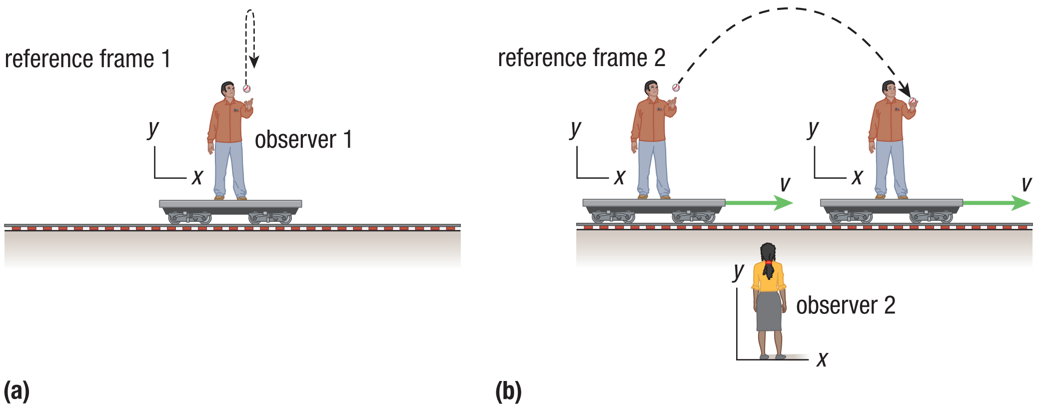


**Figure 2** (a) When observer 1 throws a ball upward, he observes that the ball's motion is purely along the vertical ($y$) direction. (b) When the railway car for observer 1 has a speed $v$ relative to observer 2, the ball appears to undergo projectile motion with a displacement along both $x$ and $y$ in reference frame 2. However, as viewed by observer 1 using his reference frame and coordinates $x$ and $y$, the ball's motion is still purely vertical, as in (a).

Any two cars moving at different speeds on a straight road can each define a different inertial frame of reference. Accelerating objects, such as planets in orbit about their star and satellites in Earth orbit, are not inertial reference frames, but they are reference frames that move with respect to each other. Earth's surface is a non-inertial (accelerating) reference frame because it spins on its axis, rotates about the Sun, moves through the galaxy as a part of the solar system, and so on. However, because the accelerations involved in these motions are small, Earth's surface is very close to being an inertial reference frame. We will use Earth's surface to define an inertial frame of reference throughout this chapter.

## Mini Investigation

### Understanding Frames of Reference

**Skills:** Performing, Observing, Analyzing, Communicating

SKILLS HANDBOOK A2.5

In this activity, you will observe actions at slow, everyday speeds. You will then describe how the laws of Newtonian mechanics change for objects in different frames of reference that move with respect to each other. You will need to work in groups for this activity.

**Equipment and Materials:** small rubber or plastic ball

1. Have one member of the group stand still and toss the ball forward to a second group member. Observe how the speed of the ball depends on the speed with which the ball is tossed.
2. The student throwing the ball now walks slowly forward while tossing the ball to the second student, taking care to throw the ball with the same speed as in Step 1.
3. Repeat Step 2, but with the student walking quickly forward as the ball is tossed.
4. Repeat Step 2, but with the student walking slowly backwards as the ball is tossed.

A. Based on your observations in Step 2, infer how the speed of the ball depends on the speed with which the ball is tossed and the speed of the student tossing the ball. K/U T/I

B. Compare what happened in Step 3 with what happened in Step 2. What can you infer about how the speed of the ball depends on the speed with which the ball is tossed and the speed of the student tossing the ball? K/U T/I

C. Compare what happened in Step 4 with what happened in Step 2. What can you infer about how speed and direction affect the speed of the ball? K/U T/I

D. If you know the speed of an object in one inertial reference frame, can you determine its speed in another inertial reference frame? Explain your answer. T/I A

### Is the Principle of Relativity Universal?

Maxwell's mathematical description of electric and magnetic fields unified the subjects of electricity and magnetism but worked under the assumption that electromagnetic waves needed a medium through which to travel. The medium was called the luminiferous **ether**, or just ether. At the time of Maxwell's theory, physicists thought that ether filled the vacuum of space, had no mass, and had no drag effect on the motions of the planets.

**ether** the proposed medium through which electromagnetic waves were once believed to propagate

For 200 years, physicists knew that Newton's laws of motion remained the same, or were invariant, in all inertial frames. However, electromagnetic waves seemed to be different. As it was then understood, Maxwell's theory stated that the speed of light with respect to the ether was always $c = 3.0 \times 10^8$ m/s. This meant that if you were at rest and observed a light source move relative to the ether, you would measure the speed of light to be different from $c$, depending on where you were standing (**Figure 3**). This is similar to the motion of waves in other media: an observer moving through the medium would measure the velocity of the waves to be different from what an observer at rest with respect to the medium would measure. WEB LINK

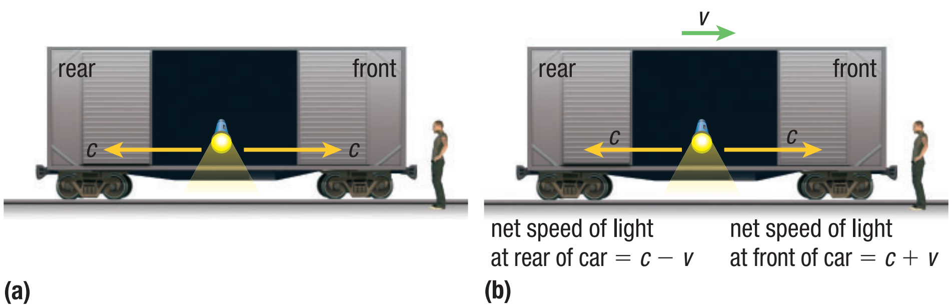


**Figure 3** (a) When the railway car is at rest, the speed of light from the flashlight in both directions is the speed of light with respect to the ether. (b) When the railway car moves at speed $v$ relative to the ether, we would expect a stationary observer in front of the car to measure $c + v$ for the speed of light because it takes less time for light to reach the observer. By similar reasoning, we would expect a stationary observer behind the car to measure $c - v$ for the speed of light because it takes longer for light to reach the observer.

## The Development of Einstein's Postulates

Experimental evidence did not support the idea that the speed of light varied with the speed of the inertial frame. Experiments performed by Michelson and Morley in 1887, and by Trouton and Noble between 1901 and 1903, to try to detect the ether showed no change in the speed of light with the motion of Earth. Ultimately, the results of these and similar experiments suggested that electromagnetic waves do not require a medium in which to propagate, and that the existence of ether could not be proven experimentally.

What were the implications of the absence of ether? For one thing, the motion of the reference frame in which the speed of light was being measured did not seem to affect that measurement. What did these experimental results say about the laws of physics that govern the motion of material objects such as electrons and baseballs?

Einstein was not convinced that electromagnetic phenomena depended on the motion of the reference frame. He examined Maxwell's ideas as applied to a frame-of-reference experiment that required only a magnet and a closed coil of wire. Einstein used a method called a **thought experiment**, which is an experiment carried out in the imagination but not actually performed. A thought experiment examines the logic behind a hypothesis, theory, or principle by analyzing a virtual version of an experiment. The goal of a thought experiment is to illustrate or explore the consequences of a theory. Thought experiments are useful when the actual experiment may be difficult or impossible to perform, or when the researcher wants to emphasize certain details or unusual predictions of a theory. WEB LINK

**thought experiment** a mental exercise used to investigate the potential consequences of a hypothesis or postulate

In the magnet-and-coil thought experiment, Maxwell's theory predicts that when a magnet moves toward a coil of wire, an electric field forms near the moving magnet. This electric field moves charges within the coil, thus inducing an electric current. However, Maxwell's theory also predicts that if the coil moves and the magnet remains at rest, a current exists in the coil, not because an electric field forms, but because the magnetic field exerts a force on the charges in the moving coil.

To Einstein, it seemed illogical that selecting a frame of reference in which either the magnet or the coil is at rest would change the way we understand what is happening. Why would moving the magnet near a coil be different from moving the coil near a magnet? Nothing else in the universe described by physics behaved in this way.

Given this unsatisfactory consequence of classical electromagnetism, as well as the lack of evidence for the ether, Einstein decided to address the problem in the most fundamental and straightforward way possible. He began with the basic assumption that electromagnetism, like Newtonian mechanics, did not change when transformed between inertial frames. That is, the laws were the same in one inertial frame as in another. This meant that basic conservation principles—energy and momentum—held in all frames. Then he proposed two **postulates**, or conditions believed or known to be true at the time. From these, the special theory of relativity was developed.

**postulate** a statement assumed to be true from which a theory is developed

**Postulate 1: The Principle of Relativity**

The laws of physics are the same in all inertial frames of reference. No physics experiment can ever determine whether you are at rest or moving at a constant velocity.

**Postulate 2: The Speed of Light Principle**

There is at least one inertial frame of reference in which, for an observer at rest in this frame of reference, the speed of light, $c$, in a vacuum is independent of the motion of the source of the light.

Postulate 1 states that each inertial observer can consider himself or herself to be "at rest." If nature behaves in a certain way in one inertial frame, it should behave in the same way in all inertial frames. You should not be able to detect inertial motion inside a closed room using experiments of any kind. While not proven directly, this is a reasonable guess.

Postulate 2 is also reasonable. The speed of a wave is always independent of the speed of the source. Sound waves, water waves, and earthquake waves travel at a fixed speed relative to the medium through which they are travelling. In Postulate 2, Einstein assumed that there exists a frame of reference in which light waves behave in the same way as other waves, regardless of whether a medium to carry them actually exists.

Separately, the postulates were not extraordinary. When considered together, however, the two postulates led to an entirely new understanding about our universe. Postulate 1 implies that if Postulate 2 is true in one inertial frame of reference, it must be true in all frames of reference. Essentially, the property of light that is true for all models of waves cannot be true in one frame and false in another; otherwise, the laws of physics of light waves would differ in the two reference frames.

The consequence of this is that the speed of light must be constant and the same in all inertial frames of reference because the laws of physics do not prefer one frame of reference over another. Put another way, the speed of light is the same even when an observer is moving relative to the source of the light. If one observer sees a source of light in motion and another observer sees the source at rest, both measure the speed of the light as $c$. If you move very rapidly toward or away from a flashlight, the speed of light you measure is $c$, not $c + v$ or $c - v$. This result seems absurd, yet it is the logical result of Einstein's postulates.

Einstein published his work in 1905 in a paper titled "On the Electrodynamics of Moving Bodies." This paper was the basis for the **special theory of relativity**.

**Special Theory of Relativity**

All physical laws are the same in all inertial frames of reference, and the speed of light is independent of the motion of the light source or its observer in all inertial frames of reference.

The principle that the speed of light in a vacuum is the same in all frames of reference is an essential feature of the special theory of relativity. In fact, the laws of electromagnetism did not change at all as a result of special relativity, but scientists' understanding of the laws had to change. The laws of physics no longer made sense, and the understanding of space and time had to change. Einstein realized that the simplest and most natural way to develop relativistic physical laws would require a new understanding of space and time. This understanding was not specific to light—it would affect all natural phenomena.

We will consider a number of features of the special theory of relativity. First, the speed of light is much greater than the speeds of objects that you observe from day to day. As a result, in your everyday life, you cannot observe the unusual effects upon space and time hinted at in this section. Another important outcome is that, while advances in experimental techniques at the beginning of the twentieth century made measurements of the speed of light more accurate, it was still difficult to test the results of the special theory of relativity. Einstein used some of these experimental results to draw his conclusions and then relied on thought experiments to test the postulates and complete the theory. Throughout the twentieth century, numerous experiments have confirmed special relativity. For example, global positioning satellite systems would not work accurately if the technology did not take special relativity into account. You will learn more about this in Section 11.2.

# 11.1 Review

## Summary

- A frame of reference is a coordinate system in which we can observe and measure the motion of an object. A frame of reference that moves with a constant velocity—in which the law of inertia holds—is an inertial frame of reference.
- The principle of relativity states that the laws of physics are the same in all inertial frames of reference.
- The ether is a hypothetical medium through which electromagnetic waves were thought to propagate. Tests such as the Michelson–Morley experiment failed to verify that there is an ether.
- Einstein's special theory of relativity is based on two postulates: The laws of physics are the same in all inertial frames of reference, and in at least one inertial frame of reference the speed of light is independent of the motion of the source of the light.
- One result of Einstein's postulates is that the speed of light is the same in all inertial frames of reference, regardless of their velocities.

## Questions

1. A student on inline skates moves with a constant speed along the deck of a cruise ship, which is moving with constant velocity parallel to the shoreline. T/I C
   (a) Identify three distinct frames of reference from which to view the skater.
   (b) Describe the skater's motion in each reference frame.
2. Consider the properties of inertial and non-inertial frames of reference. K/U C
   (a) How does an inertial frame of reference differ from a non-inertial frame of reference?
   (b) Give two examples of each type of frame of reference.
3. Suppose an astronaut in a rocket moving at 0.5*c* along Earth's surface shines a light forward from the rocket. K/U T/I A
   (a) Calculate the speed of the light compared to that of the astronaut.
   (b) Calculate the speed of the light compared to that of Earth's surface.
4. Gabor stands on a cart that moves with a constant velocity. In his frame of reference, he tosses a ball vertically up and down. Lutaaq stands on the ground nearby. She also tosses a ball vertically up and down with respect to her frame of reference. T/I C A
   (a) Explain what the motion of Gabor's ball looks like from Lutaaq's frame of reference.
   (b) Explain what the motion of Lutaaq's ball looks like from Gabor's frame of reference.
5. What feature of Einstein's coil and magnet thought experiment did he find troubling? K/U
6. State the two postulates of the special theory of relativity. K/U C
7. What conclusion results from the combination of Einstein's two postulates? K/U C
8. Explain what a thought experiment is and give an example. K/U C
9. You are travelling in a spacecraft without windows. You are also far from any planets or stars. Describe an experiment that you could perform to determine whether you are in an inertial or a non-inertial frame of reference. K/U C
10. Suppose you are inside a windowless railway car. A billiard table is at the centre of the car. K/U C
    (a) While rolling a cue ball forward, you notice that the ball slows down suddenly, even though you have not applied a backward force on the ball. Explain the motion of the ball in terms of inertial or non-inertial frames of reference.
    (b) While rolling a cue ball forward, you notice that the ball rolls to the right (**Figure 4**), even though you have not applied a sideways force on the ball. Explain the motion of the ball in terms of inertial or non-inertial frames of reference.

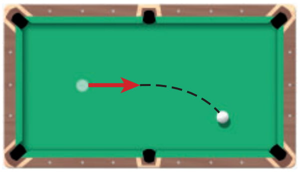

**Figure 4**