- The laws of Newtonian mechanics are only valid in an inertial frame of reference.
- The laws of Newtonian mechanics apply equally in all inertial frames of reference; in other words, all inertial frames of reference are equivalent as far as adherence to the laws of mechanics is concerned.

One final point remains to be made in our review of Newtonian relative motion and frames of reference: there is no such thing as absolute velocity in Newtonian mechanics. Whether you drop a ball while in a vehicle moving with constant velocity east, or in a vehicle moving with a constant velocity west, or in a parked vehicle, the ball moves vertically in the frame of the vehicle. Thus you cannot use measurements of the motion of the ball to help you identify whether you are really moving. In general, for any two inertial frames moving with respect to each other, there is no physical meaning in the question, "Which of these two frames is really moving?"

Special Theory of Relativity

In Chapter 3, we learned how to calculate, by vector addition, relative velocities in moving frames of reference. We have just stressed in our review that Newton's laws of motion apply equally in all inertial frames. We now recall from Chapter 3 that the motion itself has a different appearance, depending on the frame from which it is viewed. For example, if a ball is rolled forward at 10 m/s in a car moving at 30 m/s, its speed is 40 m/s in Earth's frame of reference. Conversely, if the ball is rolled backward at the same speed in the same car, its speed relative to Earth is 20 m/s. Clearly, the speed with which the ball is observed to move depends on the frame of reference of the observer.

LEARNING TIP

Shortcut Symbols
Since the speed of light is a constant, it is given the symbol *c*. Thus, $c = 3.00 \times 10^8$ m/s, so $\frac{1}{2}c$, or $0.5c$, is equal to $\frac{3.00 \times 10^8 \text{ m/s}}{2}$ or 1.50×10^8 m/s.

At the turn of the twentieth century, many physicists wondered whether the same vector-addition rules applied to the motion of light. If light has a speed *c* in a frame of reference of Earth, then would light emitted in the forward direction from a source moving relative to Earth at $\frac{1}{10}c$ have a measured speed of $\frac{11}{10}c$, measured by an observer in Earth's frame of reference? Would light emitted backward from the same source have a measured speed of $\frac{9}{10}c$ in Earth's frame? In other words, would the speed of light, like the speed of a ball rolling in a vehicle, depend on the frame of reference from which it is observed?

The first hint that light was somehow different from other phenomena came in the latter half of the nineteenth century, when Maxwell described light as an electromagnetic wave travelling in a vacuum at 3.00×10^8 m/s. Relative to what frame of reference would the speed of light have this value? Did the calculation presuppose some special, absolute frame?

Up to this time, physicists had always associated waves with a medium through which they travelled. It was natural, then, for them to assume that light must also travel through some kind of medium. Perhaps this medium was the absolute frame of reference in the universe and the speed Maxwell calculated for electromagnetic waves was relative to this frame. The supposed medium, called the **ether**, was thought to allow bodies to pass through it freely, to be of zero density, and to permeate all of space.

ether the hypothetical medium, regarded as not directly observable, through which electromagnetic radiation was thought to propagate

According to classical mechanics, the speed of light measured relative to any frame of reference moving through this ether should differ from 3.00×10^8 m/s by the magnitude of the velocity with which the frame is moving. It was assumed that Earth must be such a moving frame, since Earth is a planet orbiting the Sun. A number of very clever and complicated experiments were designed to measure the speed of Earth through the ether. The most successful of these was performed in 1887 by two Americans, A.A. Michelson (1852–1931) and E.W. Morley (1838–1923). While the details of the

Michelson–Morley experiment can be left to a further course in physics, a brief description of their method and results is necessary for our understanding of special relativity.

In essence, Michelson and Morley compared the relative speeds of light in two perpendicular directions relative to Earth's motion through the ether (**Figure 3**). If Earth were travelling in the ether-absolute frame of reference with velocity $\vec{v}$, then in a frame on Earth the ether would be travelling at velocity $-\vec{v}$, producing an "ether wind." Michelson and Morley expected to find a difference in the measured speed of light dependent on the orientation of their apparatus in the ether wind. Just as the velocity, relative to the shore, of a boat with an outboard motor of constant power varies when the boat is directed first back and forth along the line of the river, then back and forth cross-stream, so the speed of light should differ when it is moving on the one hand back and forth along the line of the wind, and on the other hand perpendicular to the line. To detect the expected small difference in speed, Michelson and Morley used an interferometer, which generates an interference pattern between two parts of a split beam of light.

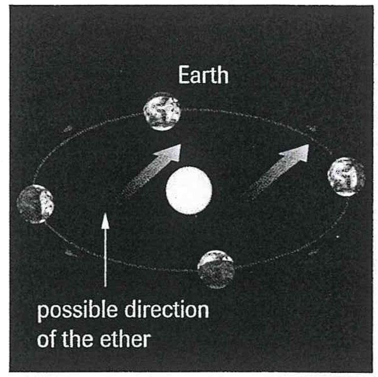

Figure 3
At most points during its orbit, Earth will be moving relative to the ether.

Figure 4(a) shows the setup of the apparatus. (See Section 10.7 for the operation of an interferometer.) The entire apparatus could be rotated to change the positions of the mirrors.

Any small difference in the velocity of light along the two paths would be indicated by a change in the interference pattern as the apparatus rotated. If the apparatus is rotated 90°, the distance L_1 is now perpendicular to the ether wind and the distance L_2 is parallel to it (**Figure 4(b)**). Thus, the time taken to travel these distances should change as the apparatus is rotated. This should produce a phase change in the interference pattern.

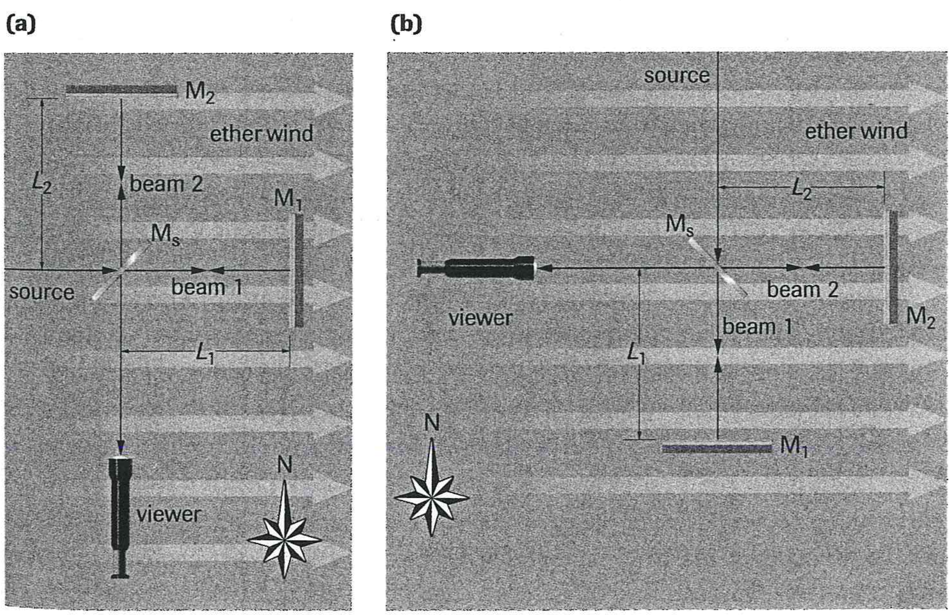

Figure 4
(a) A simplified view of an interferometer place in the hypothetical ether wind.
(b) The apparatus is rotated 90°.

Look this up online as well.

The importance of the experiment lies in its failure to show what was expected. Michelson and Morley performed their experiment over and over at different points in Earth's orbit but continued to get a null result: there was absolutely no change in the interference pattern. The speed of light was the same whether it travelled back and forth in the direction of the ether wind or at right angles to it. The relative velocity of the ether with respect to Earth had no effect on the speed of light. In other words, *the ether does not exist.* This null result was one of the great puzzles of physics at the turn of the twentieth century.

Many explanations were offered for the failure of the interference pattern to change. In 1905, Albert Einstein (1879–1955), then working in Switzerland as a junior patent clerk, proposed a revolutionary explanation in the form of the *special theory of relativity*. His theory rests on two postulates.

> **Special Theory of Relativity**
>
> 1. *The relativity principle:* all the laws of physics are valid in all inertial frames of reference.
> 2. *The constancy of the speed of light:* light travels through empty space with a speed of $c = 3.00 \times 10^8$ m/s, relative to all inertial frames of reference.

The first postulate is an easy-to-accept extension of the idea of Newtonian relativity, mentioned earlier. Einstein proposed that not only Newtonian mechanics but *all* the laws of physics, including those governing electricity, magnetism, and optics, are the same in all inertial frames. The second is more difficult to reconcile in our minds because it contradicts our commonsense notions of relative motion. We would expect two observers, one moving toward a light source and the other moving away from it, to make two different determinations of the relative speed of light. According to Einstein, however, each would obtain the same result, $c = 3.00 \times 10^8$ m/s. Clearly, our everyday experiences and common sense are of no help in dealing with motion at the speed of light.

By doing away with the notion of an absolute frame of reference, Einstein's theory solves the dilemma in Maxwell's equations: the speed of light predicted by Maxwell is not a speed in some special frame of reference; it is the speed in *any* inertial frame of reference.

We have seen that in Newtonian mechanics, while the laws of motion are the same in all inertial frames, the appearance of any one particular motion is liable to change from frame to frame. We shall see in the rest of this chapter that the position for Einstein is similar but more radical: the changes in the appearance of the world, as we move between inertial frames travelling at high speeds with respect to each other, are contrary to common sense.

Note that special relativity is a special case of the more general theory of relativity (not investigated in this text), published by Einstein in 1916. The general theory of relativity deals with gravitation and noninertial frames of reference.

The special and general theories of relativity and their many implications are now considered as much a part of physics as Newton's laws. The difference is this: to comprehend the many ramifications of the theories requires a great deal more mental flexibility and dexterity than was the case with Newtonian mechanics.

DID YOU KNOW?

Invariance or Relativity?
Einstein originally used the name "theory of invariance" and only later the theory of relativity. In a sense, invariance describes the theory better than the word "relativity."

DID YOU KNOW?

Precise Value of the Speed of Light
The speed of light is large but not infinite: $2.997\,924\,58 \times 10^8$ m/s. For the calculations in this text, three significant digits are sufficient in most cases. Thus, 3.00×10^8 m/s is used for the speed of light.

Simultaneity

We begin our examination of the consequences Einstein drew from his two postulates by considering time. In Newtonian mechanics, there is a universal time scale, the same for all observers. This seems right. Surely, a sequence of events that one observer measures to last 2.0 s would also last 2.0 s to an observer moving with respect to the first observer. But it is not always so! According to Einstein, time interval measurements depend on the reference frame in which they are made.

simultaneity the occurrence of two or more events at the same time

Simultaneity, the occurrence of two or more events at the same time, is also a relative concept, and we will make it our starting point, before proceeding to the relativity of a time interval. We will use a thought experiment to show that events that are simultaneous in one inertial frame are not simultaneous in other frames.

An observer O_s, stationary in the inertial frame of Earth, is standing on a railway platform at the midway point between two lampposts, L_1 and L_2 (**Figure 5**). The lampposts are connected to the same circuit, ensuring that, at least from the viewpoint of an iner-