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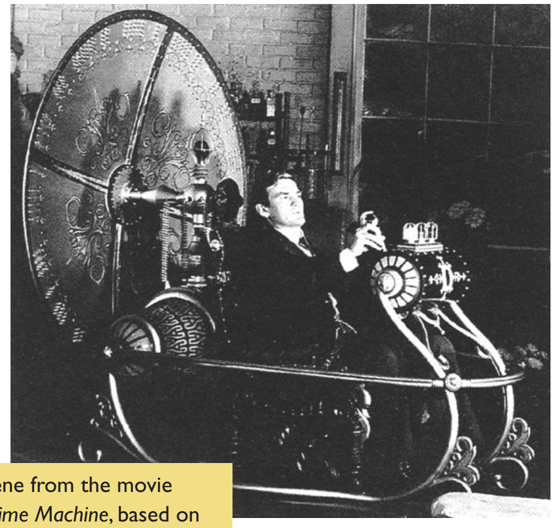
CHAPTER 27 Relativity



A scene from the movie *The Time Machine*, based on the 1895 novel by H.G. Wells.

In H.G. Wells's classic novel *The Time Machine*, the hero invents a device that transports him hundreds of years into the future. As fantastic as this sounds, a time machine is possible. As we shall see in this chapter, all that is required is a spaceship capable of moving at a speed close to the speed of light. If you traveled for a few years in such a spaceship and then returned to earth, you would find that many more years had elapsed on earth. If you were traveling fast enough, perhaps hundreds or even thousands of years would have passed. Although extremely high-speed, long-distance space travel is not yet practical, someday it may be. An astronaut might blast off from the earth in a spaceship that takes her to distant regions of space, reaching speeds approaching the speed of light. The astronaut, still young, might return to earth hundreds of years later. However, unlike the Wells story, she would never be able to go back to the past or to those she left behind. Time travel is apparently limited to a one-way trip—into the future, never into the past.

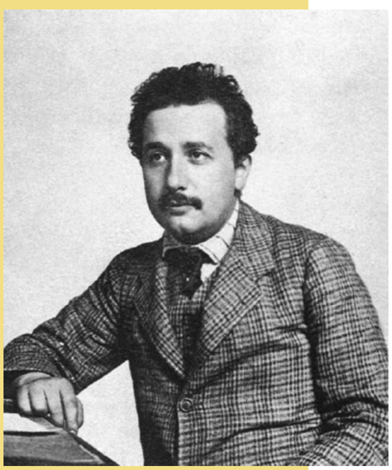


Fig. 27–1 Albert Einstein in 1905.

We can predict today the possibility of time travel, based on work first published in 1905 by a man who was then an obscure Swiss patent clerk. The man was Albert Einstein (Fig. 27–1), and his work was the theory of relativity—a theory that was to make him the most famous scientist of all time. As much as any athlete or film star, he was a great celebrity of his day. His name became synonymous with genius. Einstein's life is described in an essay at the end of this chapter.

Although Einstein's insights were brilliant, his ideas did not arise in a vacuum. In a sense they were the natural result of the kinds of questions that were being asked at the turn of the century. However, we shall not discuss this historical background of relativity theory here. In this way we can present without interruption the essence of Einstein's ideas, so that you can better appreciate their logical simplicity and beauty.

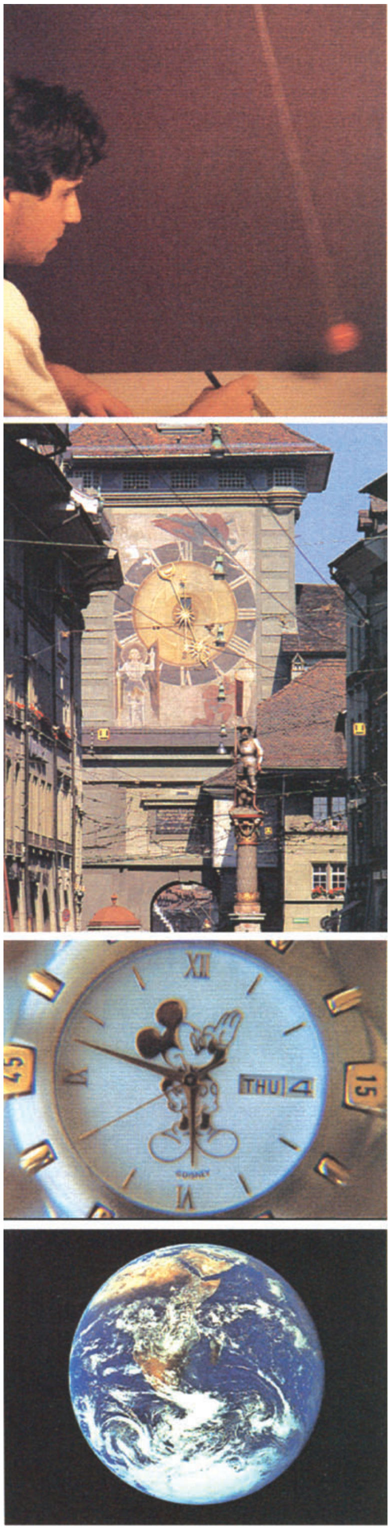


Fig. 27–2 Various clocks: a simple pendulum being used to mark time, a pendulum clock in Berne, Switzerland, a quartz wristwatch, earth clock.

27–1 Measurement of Time; Einstein's Postulates

The Nature of Time

What is time? Physicists, philosophers, and poets have all struggled with this question. Simply defining time as "duration" or "period" does no good, since such a definition merely substitutes for time another undefined quantity. Comedian Woody Allen jokingly defined time as "nature's way of keeping everything from happening at once." Of course, we all have a sense of what time is, though we may not be able to express it in words. In the *Principia,* Isaac Newton wrote: "I do not define time, space, place, and motion, since they are well known to all." However it is important that we examine more carefully the meaning of time, so that we do not harbor false or misleading concepts. Newton himself believed that "absolute, true, and mathematical time, of itself, and from its own nature, flows equably without relation to anything external… ." We shall see that such a concept of absolute time is unfounded. Einstein showed that time is relative, not absolute.

The concept of time as it is used in physics always relates to measurement with a clock. Suppose, for example, a certain plane arrives at an airport at 4:00 P.M. Saying that the time of arrival is 4:00 P.M. means simply that the arrival of the plane is simultaneous* with a clock reading 4:00. **The time of any event is given by the reading of a nearby clock, simultaneous with the event.**

Clocks are generally based on some kind of repetitive or periodic motion (Fig. 27–2). Old-fashioned pendulum clocks count oscillations of a pendulum. A modern quartz wristwatch measures time by counting the oscillations of a quartz crystal. The quartz watch is more accurate than a pendulum clock because the period of oscillation of the quartz is more regular than the period of the pendulum. The most accurate clocks are atomic clocks, which are based on the period of the electromagnetic radiation emitted by an atom. Motion of the earth and moon provides a kind of natural clock, with time units of days, months, or years. And the human body is also a natural clock, with various natural cycles or intervals: the heartbeat, circadian rhythms (cycles of about 1 day, such as the sleep cycle), monthly menstrual cycles, and even lifetimes.

Measuring the time of a very distant event is not as direct as for a nearby event, since observation of the event requires light, which travels at a finite speed.† When you look up at the night sky, you see light from stars at various distances. For example, you may see the stars Sirius and Betelgeuse simultaneously. This does not mean that the light from these stars is emitted simultaneously. Astronomers have determined that the distances to these stars are approximately 9 light-years and 490 light-years respectively; that is, light from Sirius takes 9 years to reach earth, and light from Betelgeuse takes 490 years to reach earth. The light you see coming from Betelgeuse was emitted 481 years earlier than the light from Sirius, though you see the light from each at the same instant!

We compute the time of distant events based on the known speed of light and the place where the event occurred. We can use that computation to coordinate clocks at very distant locations. For example, an astronaut on the moon can synchronize her clock by communicating with earth via visible light or other electromagnetic radiation

*When we say that the plane's arrival and the clock's reading are simultaneous, you know what that means. The idea of simultaneous events at the same place is a basic undefinable concept; that is, we cannot define this concept in terms of anything more basic.

†The earth is small enough that we can witness any event on earth with almost no delay time. Light can travel half way around the world in less than 0.1 s. For example, we can witness on television a political uprising in Beijing, China, as it is occurring, by means of electromagnetic waves bounced off of communication satellites.

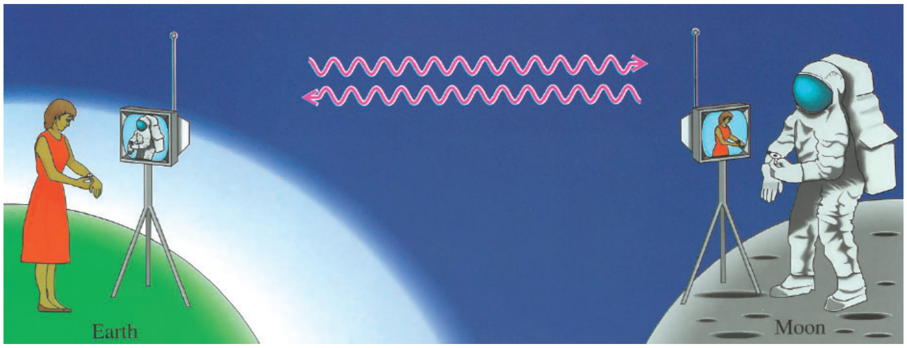


Fig. 27–3 Observers on the earth and the moon synchronize their watches by means of electromagnetic signals. Compared to the speed of light, the observers are nearly at rest with respect to one another.

(Fig. 27–3). In principle, one could set up a system of synchronized clocks throughout the universe. If these clocks are at rest relative to one another at known locations, they form a reference frame for observing events throughout the universe. **The time of any event, relative to this reference frame, is defined as the reading of one of the reference frame's clocks close to the event.**

The next question that arises is whether systems of clocks in relative motion at very high speed can be synchronized so that passing clocks always agree. The answer is no, as we shall see in the next section. But to arrive at this conclusion we must first introduce Einstein's postulates.

Einstein's Postulates

Einstein based his theory of relativity on the following two postulates:

I **The principle of relativity: All laws of physics are valid in any inertial reference frame.**

II **Light always travels through a vacuum at a fixed speed *c*, relative to any inertial reference frame, independent of the motion of the light source.**

Meaning of Einstein's First Postulate

An inertial reference frame is any reference frame in which the principle of inertia, Newton's first law, is valid. As discussed in Chapter 4 (Section 4–3), the earth's surface is approximately an inertial reference frame. Any reference frame moving at constant velocity with respect to the earth is also inertial. Suppose you are in a plane moving at a constant velocity of 1000 km/h westward. According to the principle of relativity, all the laws of physics work for you, just as they would on the ground. It follows that if the plane's windows were covered there would be no way to discover your motion by means of any experiment confined to the plane. For example, if you were to perform a free-fall experiment, you would measure the same gravitational acceleration as though you were at rest with respect to the earth. Other experiments in mechanics, electricity, optics, and so forth would all give the same results as though performed at rest on the ground, if in all these experiments there were no interactions with anything outside the plane. The principle of relativity implies that absolute motion is meaningless. Only relative motion has meaning. Thus, for example, it is just as valid to use the reference frame of the plane and describe the plane as being at rest and the earth as moving at 1000 km/h eastward.

Accelerated reference frames are not inertial. The laws of physics do not work in such reference frames. For example, you can easily detect a plane's motion at takeoff and landing, when it is accelerating. You can feel the force on your body producing the acceleration.

Meaning of Einstein's Second Postulate

Einstein's second postulate is at first hard to accept. According to this postulate, if we observe light from *any* inertial reference frame, the light travels at a fixed speed $c = 3.00 \times 10^8$ m/s no matter how fast the source of the light may be moving. For example, suppose that a spaceship (A) is passing the earth at a speed of 2.00×10^8 m/s and emits a laser pulse directed at the moon (Fig. 27–4). According to Einstein's second postulate, the laser light travels from the spaceship to the moon at a speed of 3.00×10^8 m/s —not at a speed of 5.00×10^8 m/s! This means that the pulse is received on the moon, 3.84×10^8 m away, after a time delay of $(3.84 \times 10^8\text{ m})/(3.00 \times 10^8\text{ m/s}) = 1.28$ s. This time interval is measured by synchronized clocks on the earth and the moon.

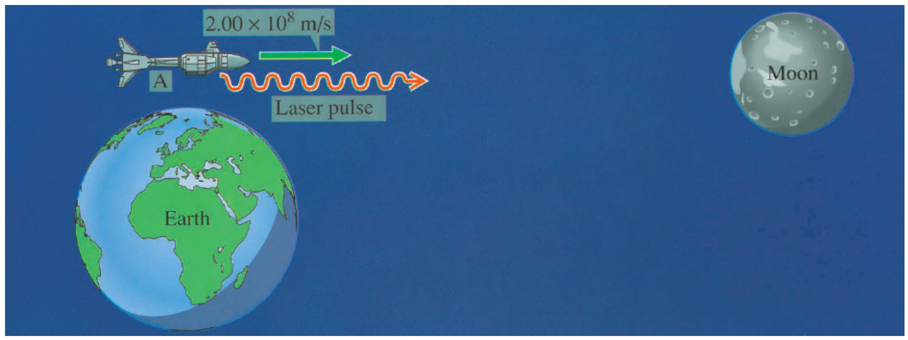


Fig. 27–4 A pulse of light is emitted from a laser on a spaceship as it passes the earth at a speed of 2.00×10^8 m/s.

The really amazing thing about the motion of light is that it moves at the same speed relative to *any* inertial reference frame. Suppose, for example, the light pulse is observed by an astronaut who also happens to be passing the earth but moving in the opposite direction at a speed of 1.00×10^8 m/s in spaceship B, as shown in Fig. 27–5. According to Einstein's second postulate, the laser pulse travels at a speed of 3.00×10^8 m/s, as seen by the astronaut on ship B. The laser pulse moves at the same speed (3.00×10^8 m/s) relative to the earth and relative to each of the spaceships, despite the fact that the spaceships are moving relative to the earth. Obviously the equations for determining relative velocities, presented in Chapter 3 (Section 3–4), are not valid for light. (And these equations are invalid for any bodies moving at speeds comparable to the speed of light, as we shall see in Section 27–4.)

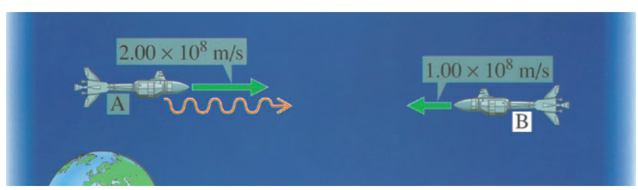


Fig. 27–5 Spaceship B, relative to the earth, travels at a velocity of 1.00×10^8 m/s directed toward the left. This ship is an inertial reference frame. Therefore the laser pulse emitted by ship A travels at a speed of 3.00×10^8 m/s, relative to B.

By way of contrast with the behavior of light, consider how sound waves travel when the source of sound is moving. The speed of wave propagation is independent of the motion of the source of the sound. However, the speed is not the same in all reference frames. Sound waves move through a medium at a fixed speed *relative to the medium.* Sound travels through air at a speed of 340 m/s, relative to the air, even if the sound source is moving through the air. For example, as illustrated in Fig. 27–6, sound from a race car engine moves at 340 m/s relative to the air (and relative to a stationary observer), even though the car (A) is moving at 70 m/s. However, the speed of sound is different when measured by an observer moving relative to the air. If car B approaches car A at a speed of 50 m/s (relative to the ground and the air), the sound wave moves relative to B at a speed of 390 m/s (Fig. 27–7).

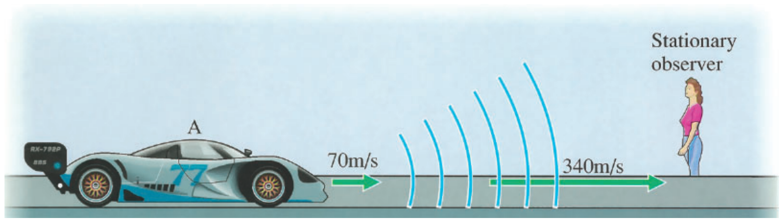


Fig. 27–6 Relative to a stationary observer, sound waves emitted by a moving race car (A) travel at a speed of 340 m/s, independent of the speed of the car.

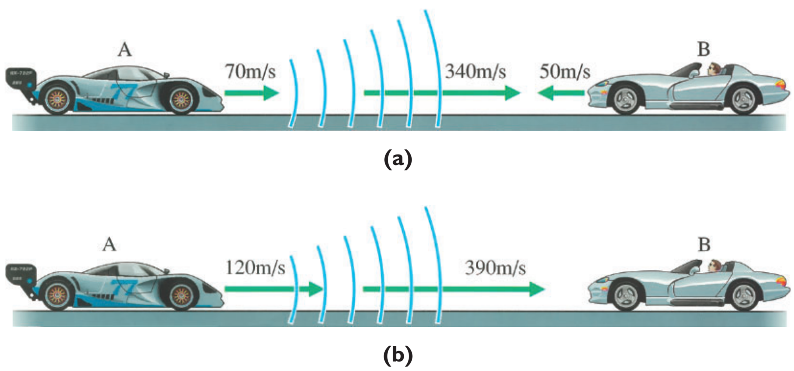


Fig. 27–7 Sound emitted by A, as observed in two different reference frames.

Although car B is an inertial reference frame and therefore the laws of physics are just as good in B's reference frame as in any other, the law of sound propagation must take account of the relative motion of the air—the medium through which the sound propagates. And so the observed speed of the sound wave is different for B from that observed by one who is at rest with respect to the air. For light propagation, no medium is required, and observers in all inertial reference frames observe the same velocity of light.

Einstein's second postulate is actually implied by his first postulate. Remember that the laws of electromagnetism predict the existence of electromagnetic waves that travel at a speed c, which can be calculated in terms of the electric constant ϵ_0 and the magnetic constant μ_0:

$$c = \frac{1}{\sqrt{\epsilon_0 \mu_0}} = 3.00 \times 10^8 \text{ m/s}$$

If the laws of electromagnetism are correct (and they are), it follows from the principle of relativity that the speed of light should be the same in all inertial reference frames.

Experimental Support for Einstein's Postulates

Einstein's postulates are supported by various experiments, some performed before and some after Einstein first published his theory. The Michelson-Morley experiment, described in detail in Problem 4, was the most famous such experiment. Michelson and Morley, along with other nineteenth-century physicists, assumed that light would behave like sound waves, in the sense that there would be a privileged reference frame for the propagation of light. This reference frame would be like a material medium for light waves, but it would be present even in a vacuum, that is, when no matter was present. This strange and elusive medium was called **"the ether"** (not to be confused with ether gas, an anesthetic). Michelson and Morley believed that the earth, at least some time during the year, would move relative to the ether. They were determined to detect this relative motion, using sensitive optical interference methods. (The instrument they used, a Michelson interferometer, was described in Chapter 26, Problem 21).

Many versions of the Michelson-Morley experiment were performed, beginning in 1887 and extending into the 1900s. Some of these experiments used a terrestrial light source; others used sunlight—a moving light source. None of the experiments was able to detect motion relative to the ether. In an effort to keep the ether concept, various explanations for the negative results were proposed. Some physicists believed that the ether somehow clung to the earth, so that no matter how the earth's motion changed throughout the year, it was always in the privileged ether reference frame. In a way this was a return to a geocentric view of the universe. However, all such explanations were shown to be inconsistent with various experimental observations. Eventually physicists became convinced that no one would ever find a way of detecting motion relative to the ether and that indeed there was no ether, that is, no privileged reference frame. The principle of relativity prevailed.

27–2 Time Dilation

In this section we will use Einstein's postulates to show how observers in relative motion measure different values for the duration of any sequence of events. Measurement of a time interval depends on the observer's reference frame. For example, suppose that a football game in Denver lasts 3.00 hours as measured on a clock at the football stadium (or on any other good clock in the earth's reference frame). As we shall see in Example 1, if the game is viewed by observers in a reference frame moving at a speed of 2.70×10^8 m/s relative to the earth, the game lasts 6.88 hours.

We can derive an equation relating time intervals measured in different reference frames by considering the following experiment. Let a laser emit a pulse of light that travels a distance D and is then reflected by a mirror back toward the laser (Fig. 27–8). The light pulse is absorbed by a detector adjacent to the laser. Since the light travels a distance $2D$ at a speed c, the time elapsed between emission and absorption is given by

$$\Delta t_0 = \frac{2D}{c} \tag{27–1}$$

A time interval such as this, **measured on a single stationary clock,** is referred to as a **proper time interval** and is denoted by the zero subscript on the Δt. We shall refer to the arrangement of laser, mirror, and detector in Fig. 27–8 as a "light clock."

The emission and absorption of light by a light clock can also be viewed by an observer in a reference frame relative to which the light clock is moving to the right at velocity **v**. Fig. 27–9 shows the emission, reflection, and absorption of a pulse of light, as seen by such an observer. The observer's reference frame is an inertial frame. Therefore, according to Einstein's postulates, (1) the laws of physics apply (in particular the law of reflection), and (2) light travels at speed c. Relative to this reference frame, the light must travel a longer, diagonal path, and so the time interval between emission and absorption is greater than that in the other reference frame, in which the light travels vertically back and forth. The time elapsed between emission and absorption, during which light travels the distance 2ℓ, is given by

$$\Delta t = \frac{2\ell}{c}$$

Using the figure and applying the Pythagorean theorem, we see that

$$\ell = \sqrt{D^2 + (v\,\Delta t/2)^2}$$

Inserting this expression for ℓ into the preceding equation, we obtain

$$\Delta t = \frac{2\sqrt{D^2 + (v\,\Delta t/2)^2}}{c}$$

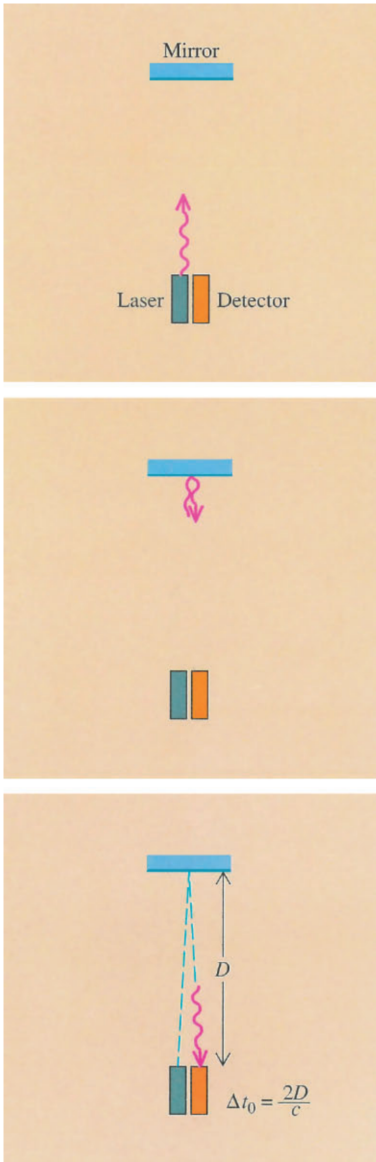


Fig. 27–8 A pulse of light is emitted by a laser, reflected by a mirror a distance D from the laser, and absorbed by a detector next to the laser. The pulse travels from laser to detector in time $2D/c$. We call this arrangement a "light clock."

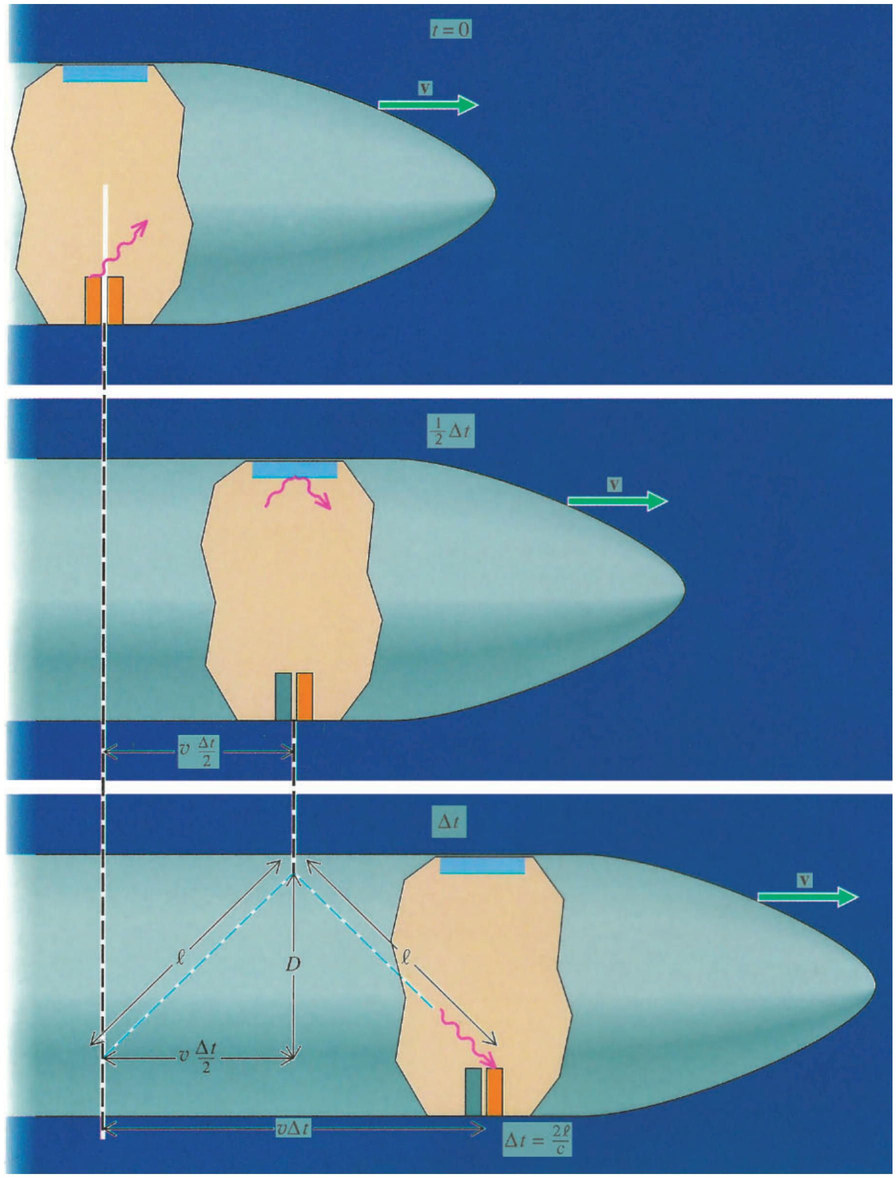


Fig. 27–9 A moving light clock. During the time interval Δt, light travels a distance 2ℓ while the laser, mirror, and detector travel a distance $v\,\Delta t$.

The quantity Δt appears on both sides of this equation. Squaring both sides and solving for Δt, we find

$$\Delta t = \frac{2D/c}{\sqrt{1 - (v/c)^2}}$$

Substituting $2D/c = \Delta t_0$ (Eq. 27–1), we obtain

$$\Delta t = \frac{\Delta t_0}{\sqrt{1 - (v/c)^2}} \qquad (27\text{–}2)$$

The time interval Δt is not a proper time interval; Δt is measured on a system of two synchronized clocks—one at the point where the pulse is emitted and a second at the point where the pulse is absorbed. Eq. 27–2 expresses the relationship between the two different measurements of the elapsed time of any sequence of events, as seen by observers in different reference frames. It is important to remember that Δt_0 represents a proper time interval measured on a single clock and Δt represents the corresponding time interval on a system of clocks.

EXAMPLE 1 Moving Clocks Run Slow

(a) A football game in Denver lasts 3.00 hours. The game is viewed by space travelers in a convoy of spaceships, which happen to be passing the earth as the game is in progress. The spaceships all move at a constant velocity of 2.70×10^8 m/s relative to the earth's surface. How long is the game in the reference frame of the spaceships? (b) A clock on one of the spaceships is compared with clocks in the earth's reference frame. How much time has elapsed in the earth's reference frame while 3.00 hours elapses on the spaceship clock?

SOLUTION **(a)** We apply Eq. 27–2 using $\Delta t_0 = 3.00$ hours, since this is a proper time interval measured on a single clock at the game. This clock and the earth move at a speed $v = 2.70 \times 10^8$ m/s relative to the space travelers, who measure the game's duration to be

$$\Delta t = \frac{\Delta t_0}{\sqrt{1-(v/c)^2}} = \frac{3.00\ \text{h}}{\sqrt{1-\left(\dfrac{2.70\times10^8\ \text{m/s}}{3.00\times10^8\ \text{m/s}}\right)^2}}$$

$$= 6.88\ \text{h}$$

Fig. 27–10 shows how the beginning and end of the game are seen (close up) by different members of the space convoy.

(b) Now the proper time interval $\Delta t_0 = 3.00$ hours is measured on the clock on one of the spaceships while the time interval Δt is measured in the earth's reference frame. The spaceship clock moves at a speed of 2.70×10^8 m/s relative to earth. The calculation is identical to that in part (a), and so we conclude that 6.88 hours elapses in the earth's reference frame. Fig. 27–11 shows the spaceship clock compared with two clocks in the earth's reference frame.

Note the symmetry of the situation. Relative to either inertial reference frame, **a moving clock runs slow!**

EXAMPLE 1 Moving Clocks Run Slow—Continued

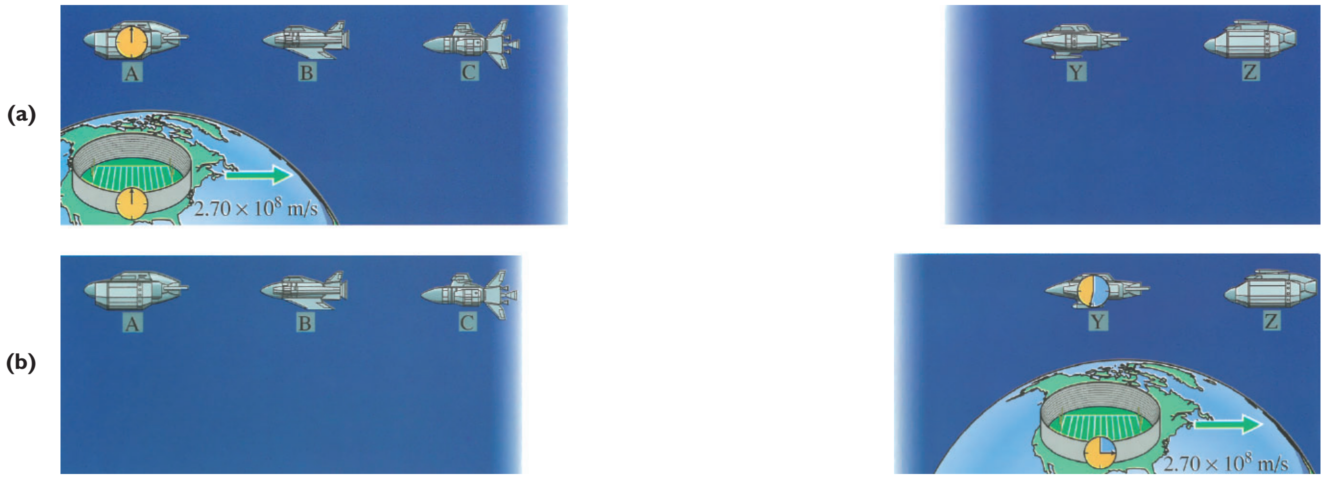


Fig. 27–10 **(a)** The beginning of a football game is witnessed by an observer on board a passing spaceship (A), part of a convoy of spaceships. Relative to the convoy, "spaceship *Earth*" moves at a constant velocity of 2.70×10^8 m/s to the right. **(b)** The end of the football game is witnessed by an observer on board spaceship Y.

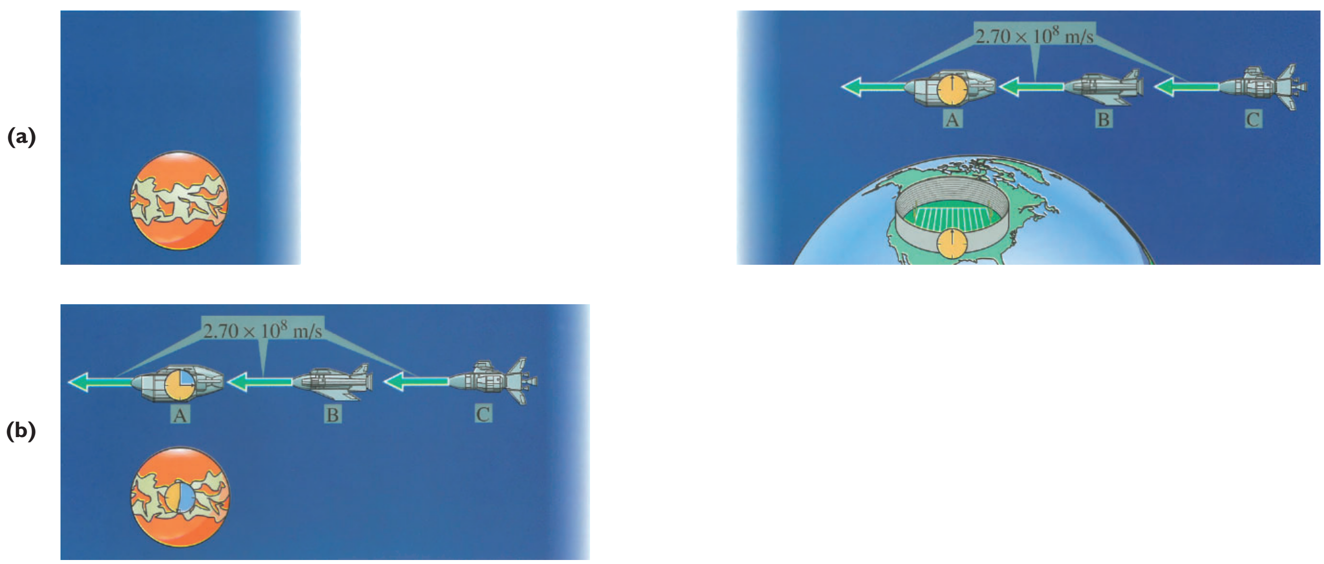


Fig. 27–11 **(a)** Spaceship A compares its clock with an earthbound clock. **(b)** Spaceship A compares its clock with a clock located on a distant planet colonized by earth. The planet is assumed to be at rest with respect to earth, and the planetary clock is synchronized with the earth clock.

The time dilation formula applies to clocks moving at any speed whatsoever. However our experience with the relativistic phenomenon of time dilation is very limited because we never see clocks or any material bodies moving at speeds approaching the speed of light. Suppose a clock is on board a high-speed aircraft moving at 900 m/s (2010 mi/hr). The time dilation factor for this clock has the value

$$\frac{1}{\sqrt{1-(v/c)^2}} = \frac{1}{\sqrt{1-\left(\dfrac{900\text{ m/s}}{3.00\times 10^8\text{ m/s}}\right)^2}} = 1 + 4.50\times 10^{-12}$$

The time dilation factor differs from one by only 4.50×10^{-12}. This means that for all practical purposes you can neglect the relativistic time dilation effect; that is, $\Delta t \approx \Delta t_0$. Measurements of time by the clock on the aircraft and measurement by a system of clocks on earth give the same value. If the pilot compares his watch with an earth-bound clock before and after his flight, he would not be able to observe a difference in the readings.

From the preceding examples you might suppose that meaningful applications of relativity are limited to futuristic or fantasy situations. Such is not the case. Physicists in research labs all over the world routinely use the theory of relativity in describing the motion of electrons or other subatomic particles. Spaceships traveling near the speed of light are only fantasy today. But subatomic particles do move at relativistic speeds, as in the following example.

EXAMPLE 2 Muon Lifetimes

Muons are elementary particles with the same charge as an electron and a mass 207 times the mass of an electron. Muons are unstable, with a mean lifetime of 2.2×10^{-6} s, as measured in their own rest frame. This means that when muons are created in the laboratory by the decay of some other particle, if the muons are either at rest or moving at much less than the speed of light, the muons will decay into other particles, on the average 2.2×10^{-6} s after they are created. Muons created in a high-energy accelerator move at a speed 99.9% of the speed of light, relative to the lab. How long (on the average) after the muons are created do they decay, as measured in the lab?

SOLUTION Applying Eq. 27–2, we find for the mean lifetime, measured in the laboratory:

$$\Delta t = \frac{\Delta t_0}{\sqrt{1-(v/c)^2}} = \frac{2.2\times 10^{-6}\text{ s}}{\sqrt{1-(0.999)^2}}$$

$$= 49 \times 10^{-6}\text{ s}$$

Experimental measurement of high-energy muon lifetimes are in complete agreement with values calculated using the time dilation formula.

Muons are created naturally by cosmic rays in the earth's upper atmosphere. These muons move at very high speed and therefore experience considerable time dilation. Only because the time dilation effect is so large is it possible for muons to live long enough to reach the surface of the earth, where they may be detected.

EXAMPLE 3 The Twin Paradox

Twins part on their twentieth birthday; one remains at home on earth, and the other leaves the earth on a long, high-speed space journey. The spaceship quickly accelerates* to a speed of $0.95c$, maintains this speed for time $\Delta t_0/2$ (ship time), quickly turns around, and travels home at a speed of $0.95c$, arriving at time Δt_0, as measured on the ship and by the astronaut's biological clock. While time Δt_0 has elapsed for the astronaut, the time elapsed for his stationary brother is given by Eq. 27–2:

$$\Delta t = \frac{\Delta t_0}{\sqrt{1-(v/c)^2}} = \frac{\Delta t_0}{\sqrt{1-(0.95)^2}} = 3.2\ \Delta t_0$$

Thus 3.2 years have elapsed on earth for every year on the spaceship. If the astronaut arrives home at age 40, after 20 years of travel, the earthbound twin is 84 years old, having aged $(3.2)(20) = 64$ years during his brother's absence (Fig. 27–12).

A paradox arises if one attempts to describe the space flight from the reference frame of the spaceship. Relative to the spaceship the earthbound twin is traveling first away from the ship at 0.95c and later toward the ship at 0.95c. The astronaut applies Eq. 27–2, computing his elapsed time corresponding to the time elapsed for his moving earthbound brother:

$$\Delta t = \frac{\Delta t_0}{\sqrt{1-(v/c)^2}} = 3.2\ \Delta t_0$$

The astronaut predicts that 3.2 years elapses on the spaceship for every year elapsed on earth. So, if the astronaut returns to earth after a journey of 20 years (ship time), he expects to find that his twin has aged only 20 years/3.2 = 6.3 years; that is, the astronaut predicts that when he is 40, his earthbound twin will be only 26, not 84! These contradictory predictions cannot both be correct. Resolve the paradox.

*To reach relativistic speeds without having the astronaut experience extreme acceleration, the spaceship would have to accelerate over a period of a few years. See Problem 33.

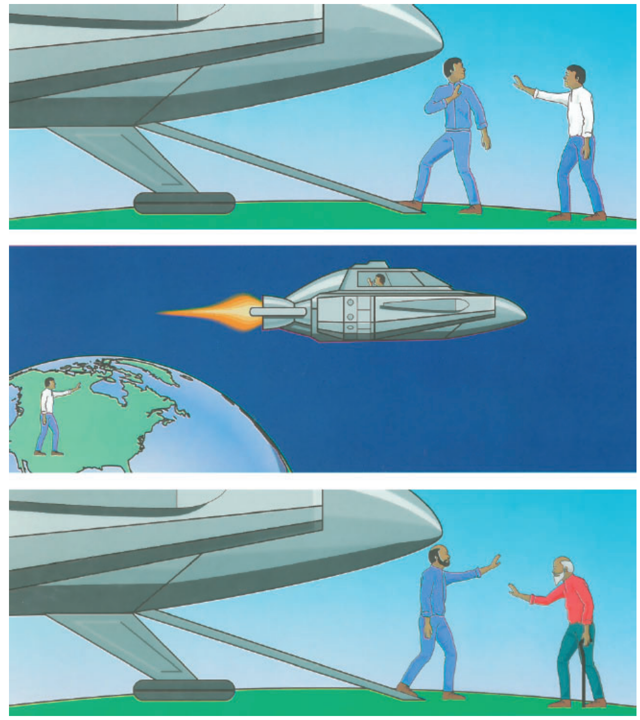


Fig. 27–12 Twins part and years later reunite.

SOLUTION The difficulty lies in the asymmetry between the twins, introduced during the periods of acceleration of the spaceship. It is these accelerations that prevent the spaceship from being inertial. Only the earthbound twin remains in an inertial reference frame continously, and therefore only his calculations are to be trusted. The astronaut does arrive home much younger than his twin brother. The acceleration of the spaceship is somehow responsible for the slower aging of the astronaut.

Although the twin experiment described in this example has never been performed, in 1971 a rather direct experimental verification of the effect was accomplished by Hafele and Keating. Time intervals were measured on two identical cesium atomic clocks. One of the clocks was flown around the world on commercial airlines. The time dilation formula predicted that the traveling clock should run slow by $(184 \pm 23) \times 10^{-9}$ s. When compared to the stationary clock, the traveling clock was found to have lost $(203 \pm 10) \times 10^{-9}$ s, in complete agreement with the prediction of time dilation.

27–3 Length Contraction

In this section we shall show how distances traveled at very high speed appear to the traveler to be shortened or contracted. Such length contraction could theoretically make possible travel to stars hundreds of light years away in a voyage lasting only a few decades. For example, suppose that, in an attempt to reach an extraterrestrial civilization, a space expedition is launched from earth to the star Antares, 424 light-years away. Even if a spaceship were to travel at nearly the speed of light, the trip would take about 424 years, as measured in the earth's reference frame. It might then seem impossible for anyone to live long enough to make such a journey. But remember, moving clocks run slow. So, although approximately 424 years elapses on earth, the duration of the trip could be much shorter, as measured on the spaceship, if it is moving fast enough. Suppose, for example, the average speed is $0.999c$. The trip's duration Δt_0 observed on the spaceship is related to the earth-measured time interval $\Delta t = 424$ years by the time dilation formula (Eq. 27–2):

$$\Delta t = \frac{\Delta t_0}{\sqrt{1-(v/c)^2}}$$

Solving for Δt_0, we find

$$\Delta t_0 = \sqrt{1-(v/c)^2}\,\Delta t = \sqrt{1-(0.999)^2}\,(424 \text{ years})$$
$$= 19.0 \text{ years}$$

From the reference frame of the spaceship, the behavior of clocks on board is entirely normal. An observer on the spaceship sees the earth and Antares* moving relative to the spaceship at nearly the speed of light. And yet the trip takes only 19 years. The observer therefore concludes that the distance from earth to Antares is approximately 19 light-years, not 424 light-years. From the reference frame of the spaceship, the distance from earth to Antares contracted from 424 light-years to 19 light-years after the spaceship left the earth and accelerated to a very high velocity.

The preceding example illustrates that measurement of length, like measurement of time, depends on the reference frame of the observer. We shall now obtain a general formula for length contraction. When the length of a body (or a system of bodies) is measured in the reference frame in which the body is at rest, the measurement can proceed in the usual way—by comparison of the length with a standard, say, a meter stick. We refer to this length, measured in the usual way in the body's rest frame, as a **proper length,** and denote it by ℓ_0.

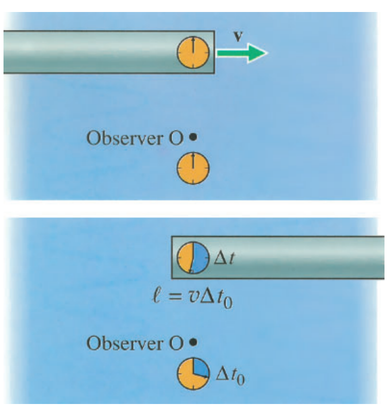


Fig. 27–13 A rod moves to the right at speed v relative to observer O.

Now suppose the body is moving parallel to its length, relative to an observer who attempts to measure its length. To be specific, we can think of the body as a rod moving to the right at speed v, relative to an observer O (Fig. 27–13). A very simple way for the observer to measure the rod's length is to first measure the proper time interval Δt_0 elapsed on the observer's clock as the rod passes. The rod's length ℓ must equal the product of the rod's speed and the elapsed time.

$$\ell = v\,\Delta t_0 \tag{27–3}$$

The corresponding time interval Δt, measured on a system of clocks attached to the moving rod, is related to Δt_0 by Eq. 27–2:

$$\Delta t = \frac{\Delta t_0}{\sqrt{1-(v/c)^2}}$$

or

$$\Delta t_0 = \Delta t\sqrt{1-(v/c)^2}$$

*Although Antares is not at rest with respect to earth, its velocity is much less than the speed of light, only a few thousand meters per second.

Substituting this expression for Δt_0 into Eq. 27–3, we obtain

$$\ell = v\,\Delta t\,\sqrt{1-(v/c)^2}$$

From the reference frame of the rod, the observer travels the length ℓ_0 of the rod at speed v in the time interval Δt (Fig. 27–14). Thus

$$\ell_0 = v\,\Delta t$$

Substituting ℓ_0 for $v\,\Delta t$ in the preceding equation, we obtain the length-contraction formula:

$$\ell = \ell_0\sqrt{1-(v/c)^2} \qquad (27\text{–}4)$$

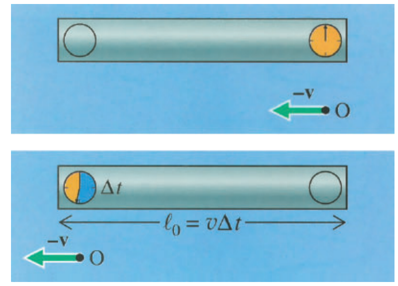


Fig. 27–14 Relative to the rod, observer O moves to the left at speed v.

EXAMPLE 4 Relativistic Contraction of a Meter Stick

Find the length of a meter stick, as measured by an observer, relative to whom the meter stick is moving parallel to its length at a speed of $0.95c$.

SOLUTION Applying Eq. 27–4, we find

$$\ell = \ell_0\sqrt{1-(v/c)^2} = (1\text{ m})\sqrt{1-(0.95)^2} = 0.31\text{ m}$$
$$= 31\text{ cm}$$

The length-contraction formula applies not only to the length of a single rigid body, but also to the distance between two bodies at rest (or nearly at rest) in a single reference frame. Although most stars in our galaxy are moving relative to earth at speeds that are quite large by terrestrial standards (on the order of thousands of meters per second), these speeds are quite small compared to the speed of light. Thus the length-contraction formula can be applied to the distance from earth to these stars, as in the following example.

EXAMPLE 5 Relativistic Contraction of an Astronomical Distance

The proper distance between earth and Antares is 424 light-years. Find the distance between the two as seen by an observer traveling between the two bodies at a speed of either $0.900c$ or $0.999c$.

SOLUTION Applying Eq. 27–4, at a speed $v = 0.900c$, we find

$$\ell = \ell_0\sqrt{1-(v/c)^2} = (424\text{ LY})\sqrt{1-(0.900)^2}$$
$$= 185\text{ LY}$$

At a speed $v = 0.999c$, we find

$$\ell = (424\text{ LY})\sqrt{1-(0.999)^2}$$
$$= 19.0\text{ LY}$$

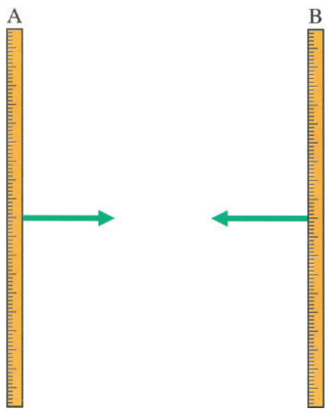


Fig. 27–15 Meter sticks in relative motion.

It is important to note that only lengths parallel to the direction of motion are contracted. Lengths perpendicular to the direction of motion are unaffected by the motion. To see that this must be so, consider two parallel meter sticks, A and B, in relative motion, with a relative velocity directed perpendicular to their lengths (Fig. 27–15). The position of the ends of the meter sticks can be compared as they pass. Observers in the reference frame of either meter stick must agree if the two lengths differ; that is, if A is shorter than B, all would see this contraction of A relative to B. But such contraction would violate the principle of relativity. If relativity predicted that A contracted relative to B, then the same law of contraction, applied in the reference frame of A, would mean that B should be contracted relative to A. Since all observers must agree on which meter stick is shorter, the only possible answer is that neither is shorter. The lengths are the same.

EXAMPLE 6 Observers Moving in Perpendicular Directions

Find the distance from the earth to the moon, as measured by observers O and O′, each of whom are in the spacecraft moving relative to the earth at a speed of $0.80c$, as indicated in Fig. 27–16.

SOLUTION For observer O, the earth-moon system is moving at a velocity of $0.80c$, directed along the line from the earth to the moon, that is, parallel to the length to be measured. We apply Eq. 27–4, and find that observer O measures a length

$$\ell = \ell_0\sqrt{1 - (v/c)^2} = (3.8 \times 10^8\ \text{m})\sqrt{1 - (0.80)^2}$$
$$= 2.3 \times 10^8\ \text{m}$$

For observer O′ the motion of the earth and moon is to the left, perpendicular to the length to be measured. Therefore O′ measures the same length as in the earth's reference frame:

$$\ell = \ell_0 = 3.8 \times 10^8\ \text{m}$$

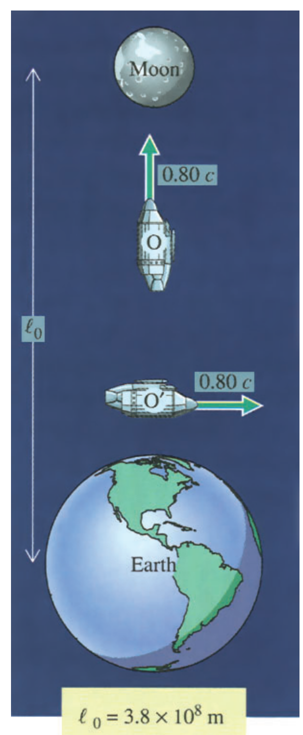


Fig. 27–16

27–4 Relative Velocity

Suppose that an object on board a spaceship moves at a velocity $\mathbf{u}'$ relative to the spaceship, which in turn is moving at velocity $\mathbf{v}$ away from the earth (Fig. 27–17). Relative to the earth, the object in the spaceship is moving away from the earth at a velocity $\mathbf{u}$, which depends on the values of $\mathbf{u}'$ and $\mathbf{v}$. But contrary to what one would intuitively expect, the value of u_x is not equal to $u_x' + v_x$. The rule for determining relative velocities, learned in Chapter 3, is not correct when speeds approach the speed of light. Einstein showed that, in general, u_x is given by

$$u_x = \frac{u_x' + v_x}{1 + \dfrac{u_x' v_x}{c^2}} \qquad (27\text{–}5)$$

Problem 37 outlines a derivation of this equation. We shall see in the following example that if either u' or v is much less than c, this equation reduces to the usual nonrelativistic result:

$$u_x \approx u_x' + v_x \quad (\text{if } u' << c \text{ or } v << c)$$

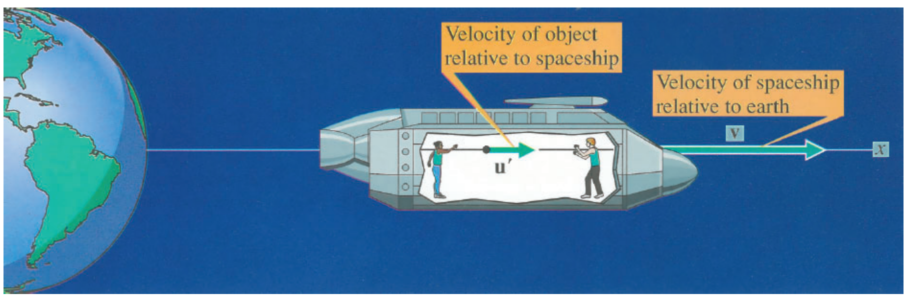


Fig. 27–17 The velocity **u** of the object relative to earth depends on its velocity **u**′ relative to the spaceship and on the velocity **v** of the spaceship relative to earth.

EXAMPLE 7 Addition of Nonrelativistic Velocities

Suppose that a rocket is fired from a spacecraft at a velocity $u_x' = 2.00 \times 10^3$ m/s as the spacecraft moves away from the earth at a velocity $v_x = 3.00 \times 10^3$ m/s. Find the velocity of the rocket, relative to the earth.

SOLUTION Applying Eq. 27–5, we find

$$u_x = \frac{u_x' + v_x}{1 + \dfrac{u_x' v_x}{c^2}} = \frac{2.00 \times 10^3 \text{ m/s} + 3.00 \times 10^3 \text{ m/s}}{1 + \dfrac{(2.00 \times 10^3 \text{ m/s})(3.00 \times 10^3 \text{ m/s})}{(3.00 \times 10^8 \text{ m/s})^2}}$$

$$= 5.00 \times 10^3 \text{ m/s}$$

To an excellent approximation, u_x equals the sum of velocities u_x' and v_x because each of these velocities is much less than the speed of light.

The relative velocity formula (Eq. 27–5) applies to light as well as to material bodies, as illustrated in the following example.

EXAMPLE 8 Light From a Moving Spaceship

As a spaceship moves away from the earth at velocity $\mathbf{v}$, it emits a pulse of laser light in the forward direction. Show that the velocity of the light, relative to earth, equals c, independent of the velocity of the spaceship, in accord with Einstein's second postulate.

SOLUTION Applying Eq. 27–5, we find

$$u_x = \frac{u_x' + v_x}{1 + \dfrac{u_x' v_x}{c^2}} = \frac{c + v_x}{1 + \dfrac{c v_x}{c^2}} = \frac{c + v_x}{\dfrac{c + vx}{c}}$$
$$= c$$

EXAMPLE 9 Relative Motion of Two Spacecraft

Spacecraft A and B both approach a planet at half the speed of light, as shown in Fig. 27–18. Find the velocity of B relative to A.

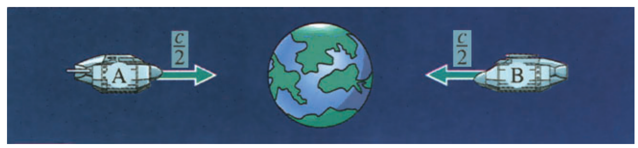


Fig. 27–18

SOLUTION Relative to A, the planet is approaching at half the speed of light (Fig. 27–19). Since the velocity is along the negative x direction, $v_x = -c/2$. To find the velocity of B relative to A, denoted by u_x, we apply Eq. 27–5, using $u_x' = -c/2$ for the velocity of B relative to the planet.

$$u_x = \frac{u_x' + v_x}{1 + \dfrac{u_x' v_x}{c^2}} = \frac{-c/2 - c/2}{1 + \dfrac{(-c/2)^2}{c^2}}$$
$$= \frac{-c}{1 + \frac{1}{4}} = -\tfrac{4}{5}c$$

Fig. 27–19

27–5 Relativistic Mass and Energy

We have found that both time and length are relative, not absolute, quantities. It should therefore not be too surprising to find that mass and energy are also relative quantities—that measured values of mass and energy depend on the reference frame of the observer. Einstein used the theory of relativity to derive formulas for the mass and energy of moving bodies. Einstein showed that, if a body has mass m_0 when it is at rest, then when the body moves at a speed v, its mass m is given by

$$m = \frac{m_0}{\sqrt{1-(v/c)^2}} \qquad (27\text{–}6)$$

Fig. 27–20 shows how the relativistic mass of a body approaches infinity as its speed approaches the speed of light. Since a body's mass is a measure of its resistance to being accelerated, infinite mass means infinite resistance to acceleration. Thus the closer a body comes to the speed of light, the harder it is to accelerate further. The speed of light therefore is a fundamental speed limit, imposed by nature. A body can come very close to the speed of light but can never reach or exceed it.

From Fig. 27–20 we see that only for very high speeds will a body have a mass that differs significantly from its rest mass m_0. Thus in ordinary applications of mechanics we don't have to be concerned about changing mass. For example, the mass of a car does not change measurably, as it is accelerated from 0 to 50 km/h.

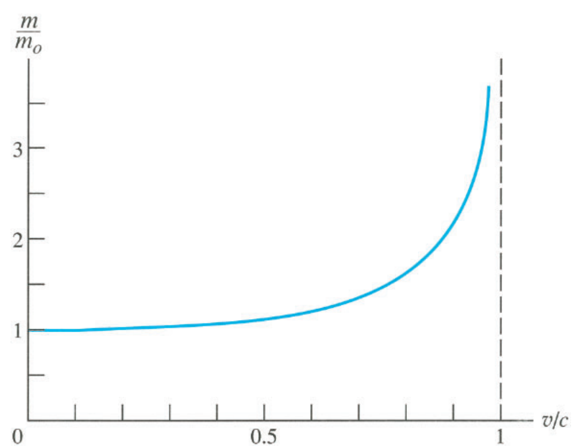


Fig. 27–20 The dependence of the mass of a body on its speed.

EXAMPLE 10 The Mass of a Moving Electron

Find the mass of an electron moving at a speed of $0.999c$.

SOLUTION Applying Eq. 27–6, we find that the electron's mass increases from its rest mass $m_0 = 9.11 \times 10^{-31}$ kg to

$$m = \frac{m_0}{\sqrt{1-(v/c)^2}} = \frac{m_0}{\sqrt{1-(0.999)^2}}$$

$$= 22.4m_0 = 22.4(9.11 \times 10^{-31}\ \text{kg})$$

$$= 2.04 \times 10^{-29}\ \text{kg}$$

One of the most interesting predictions of the theory of relativity is that **mass is a form of energy.** This result is expressed by Einstein's famous equation

$$E = mc^2 \tag{27–7}$$

This equation relates a body's total energy E to its relativistic mass m. The two quantities are proportional. The energy of a body equals its mass times a constant (c^2). So it is fair to say that mass and energy are equivalent, or that mass is a form of energy.

In deriving this equation, Einstein united two fundamental principles. Before Einstein's discovery, conservation of mass and conservation of energy were believed to be two unrelated laws of nature. But Einstein showed that mass and energy are proportional, and so conservation of mass implies conservation of energy.

We can express a body's energy in terms of its rest mass m_0 and velocity v by substituting into the preceding equation for energy the expression for relativistic mass (Eq. 27–6).

$$E = \frac{m_0 c^2}{\sqrt{1 - (v/c)^2}} \tag{27–8}$$

When a body is at rest, $m \rightarrow m_0$ and the energy reduces to $m_0 c^2$, which we refer to as **rest energy** and denote by E_0.

$$E_0 = m_0 c^2 \tag{27–9}$$

This equation predicts that a body of moderate mass has an enormous amount of energy. For example, a 1 kg mass at rest has energy $E_0 = (1\text{ kg})(3 \times 10^8\text{ m/s})^2 = 9 \times 10^{16}$ J—thousands of times greater than the energy released in an atomic bomb. How is it then that we don't notice the tremendous rest energy stored in ordinary objects? As long as nothing changes, there is nothing to notice. Only when a significant amount of rest energy is converted to some other form is the energy observed. For example, when matter and antimatter meet, both the matter and antimatter are annihilated and rest energy is completely converted to radiant energy. However, this has never been observed except on the level of subatomic particles. For example, an electron and its antimatter particle, a positron, can mutually annihilate, producing two photons with about 10^{-13} J of radiant energy.

The most dramatic large-scale conversion of mass into radiant energy occurs in transformations of nuclei in bombs, as described in Chapter 30. In the explosion of an atomic bomb about one thousandth of the rest energy is converted to radiant energy and heat. Even in ordinary combustion processes, such as the combustion of gasoline, the total rest mass of the products of combustion is slightly less than the original rest mass. The difference in rest mass is used to produce heat. However, the heat released is small enough that the reduction in rest mass is not noticeable, as we shall see in the following example.

EXAMPLE 11 Loss of Rest Mass by Burning Gasoline

How much rest mass is lost during combustion of 1 liter of gasoline? Gasoline has a density of 0.74 kg/L and a heat of combustion of 3.4×10^7 J/L.

SOLUTION The reduction in the gasoline's rest energy equals the heat of combustion. Applying Eq. 27–9, we find an extremely small loss of mass.

$$m_0 = \frac{E_0}{c^2}$$

$$\Delta m_0 = \frac{\Delta E_0}{c^2} = \frac{-3.4 \times 10^7\text{ J}}{(3.0 \times 10^8\text{ m/s})^2}$$

$$= -3.8 \times 10^{-10}\text{ kg}$$

The difference between the energy of a moving body and the energy that body would have at rest is defined to be **kinetic energy,** K.

$$K = E - E_0 \tag{27–10}$$

Thus

$$K = mc^2 - m_0c^2$$

or

$$K = m_0c^2\left[\frac{1}{\sqrt{1-(v/c)^2}} - 1\right] \tag{27–11}$$

This expression for kinetic energy reduces to our previous definition of kinetic energy, $K = \frac{1}{2}mv^2$ (Eq. 7–6), when $v << c$. See Problem 30.

$$K \approx \tfrac{1}{2}m_0v^2 \qquad (\text{when } v << c) \quad (27\text{–}12)$$

EXAMPLE 12 A Small Relativistic Correction to Kinetic Energy

Find the kinetic energy of a body having a rest mass of 2.0 kg moving at a speed of $0.10c$.

SOLUTION Applying Eq. 27–11, we find

$$K = m_0c^2\left[\frac{1}{\sqrt{1-(v/c)^2}} - 1\right]$$

$$= (2.0\text{ kg})(3.0 \times 10^8\text{ m/s})^2\left[\frac{1}{\sqrt{1-(0.10)^2}} - 1\right]$$

$$= 9.1 \times 10^{14}\text{ J}$$

If we wish to calculate the kinetic energy by applying the approximate classical expression (Eq. 27–12), we obtain

$$K \approx \tfrac{1}{2}m_0v^2 = \tfrac{1}{2}(2.0\text{ kg})(3.0 \times 10^7\text{ m/s})^2$$

$$= 9.0 \times 10^{14}\text{ J}$$

The error in this approximate calculation is only about 1%. Generally when v is no more than $0.1c$, there is little error in using classical formulas.

EXAMPLE 13 Energy of an Accelerated Electron

An electron is accelerated from rest through a potential difference of 1.00×10^6 V, so that it has a kinetic energy of 1.00×10^6 eV, or 1.00 MeV. Find the electron's rest energy, final total energy, and final speed.

SOLUTION Applying Eq. 27–9, we find the rest energy.

$$E_0 = m_0c^2 = (9.11 \times 10^{-31}\text{ kg})(3.00 \times 10^8\text{ m/s})^2$$

$$= 8.20 \times 10^{-14}\text{ J}$$

We can express this result in units of MeV, using the conversion $1\text{ MeV} = 10^6\text{ eV} = 1.60 \times 10^{-13}$ J.

$$E_0 = (8.20 \times 10^{-14}\text{ J})\left(\frac{1\text{ MeV}}{1.60 \times 10^{-13}\text{ J}}\right)$$

$$= 0.51\text{ MeV}$$

Next we calculate the electron's final total energy, using Eq. 27–10:

$$K = E - E_0$$

or

$$E = K + E_0 = 1.00\text{ MeV} + 0.51\text{ MeV}$$

$$= 1.51\text{ MeV}$$

Finally we relate energy to speed (Eqs. 27–7 to 27–9).

$$E = mc^2 = \frac{m_0c^2}{\sqrt{1-(v/c)^2}} = \frac{E_0}{\sqrt{1-(v/c)^2}}$$

or

$$\sqrt{1-(v/c)^2} = \frac{E_0}{E} = \frac{0.51\text{ MeV}}{1.51\text{ MeV}} = 0.338$$

Solving for v/c, we find

$$v/c = 0.941$$

or

$$v = 0.941c = 0.941(3.00 \times 10^8\text{ m/s})$$

$$= 2.82 \times 10^8\text{ m/s}$$

General Relativity

Soon after Einstein developed his "special theory of relativity," he became convinced that the principle of relativity should extend beyond the special case of inertial reference frames to any reference frame whatsoever. He then set out to develop a more general theory in which the limitation to inertial reference frames could be removed. Roughly 10 years later he succeeded in formulating such a theory—the general theory of relativity.

Einstein was driven by his belief that the laws of physics should apply to all observers in all reference frames. There seemed to be no obvious reason why those reference frames that are inertial should be so. The singling out of special reference frames seemed to endow space itself with an absolute quality that Einstein did not believe it possessed.

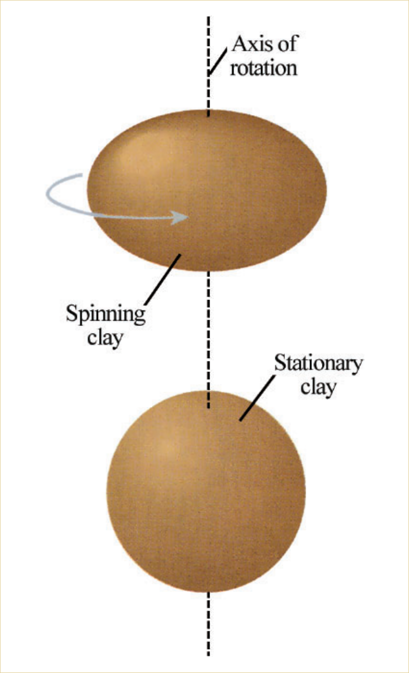


Fig. 27–A Two balls of clay in intergalactic space, viewed from an inertial reference frame. The ball on top spins and bulges outward.

Consider, for example, the following experiment. Two balls of potter's clay are located in intergalactic space, far from all matter, so that nothing exerts force on the balls, which we view from an inertial reference frame. Suppose that one of the balls is spinning about an axis passing through the centers of both balls (Fig. 27–A). The clay in the spinning ball pushes outward, just as it would on a spinning potter's wheel on earth. Thus the spinning ball of clay bulges, while the stationary ball is spherical. (The same effect is seen in spinning planets: the earth bulges slightly at the equator).

Consider the *relative* motion of the two balls. Each is rotating with respect to the other. With this symmetry of motion, why is it that one ball bulges and the other does not? We say that the spherical ball is at rest in an inertial reference frame, while the bulging ball, relative to that inertial reference frame, is spinning and its parts are therefore accelerated. But what is it that makes the reference frame in which the one sphere is at rest an inertial frame? Is it space itself?

Ernst Mach was the first to suggest an answer to this kind of question—an answer that was helpful in guiding Einstein to the general theory. According to Mach, we must look to the distant matter in the universe that we had assumed to have no influence on the balls of clay. Only one of the balls bulges because only one is accelerated with respect to that distant matter. The other ball of clay is at rest (or moving at constant velocity) with respect to the distant stars. Mach's ideas suggested to Einstein that it really is only relative motion that counts after all.

One of Einstein's early insights on the road to discovering the general theory was

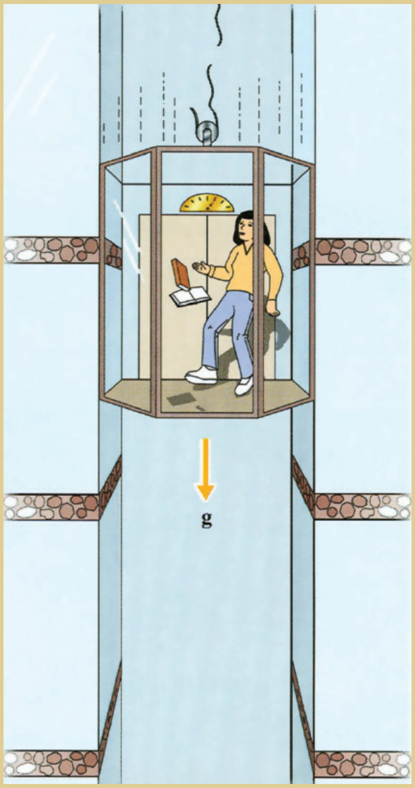


Fig. 27–B To an observer outside a freely falling elevator, a passenger inside is accelerated by the force of gravity. But so long as the elevator continues to fall, it is impossible for the passenger to detect the earth's gravity by any experiment confined to the elevator.

that the observed effects of gravity depend on the reference frame of the observer. For example, suppose you are in a glass-walled elevator and the cable suddenly snaps, so that both you and the elevator are in free fall (Fig. 27–B).

An observer outside the elevator sees you falling freely because there is nothing to support you—no opposing force to balance your weight. But within the elevator (your freely falling reference frame), you see things differently.

Fig. 27–C Astronauts in training experience weightlessness.

You do not see yourself falling relative to the elevator, and you do not "feel" your own weight.* In a freely falling elevator you feel just as weightless as you would in intergalactic space. Astronauts in an earth satellite such as Skylab (Fig. 27–C) experience weightlessness for precisely this reason: they are continuously falling as they orbit the earth. Not only do you feel no weight during free fall, but also it is impossible to detect gravity by *any* experiment confined to a freely falling reference frame. For example, if you drop an object, it falls with you. Relative to the reference frame, it does not move.

*You can experience the feeling of partial weightlessness very briefly even in a functioning elevator, for example, when it is moving up and quickly comes to a stop. The feeling of weightlessness is actually just the absence of the normal feeling of weight we are accustomed to. This feeling of weight is caused by the compression of our bodies' tissue and the pressing of our internal organs against each other. The usual contact and compression are caused by the opposing forces of earth's gravity (your weight) and whatever solid matter such as a chair or a floor that prevents you from falling. In free fall there is no such compression.

Einstein postulated that in any reference frame freely falling in a uniform gravitational field, all the laws of physics would be the same as in an inertial reference frame with no gravitational field present. Einstein claimed that the two reference frames would be completely equivalent. He called this principle the **equivalence principle.**

Einstein claimed further that in an isolated region of space, a reference frame accelerating with respect to an inertial reference frame is completely equivalent to an inertial reference frame with a gravitational field present (Fig. 27–D). In other words, not only can we effectively eliminate a gravitational field by falling in it, we can

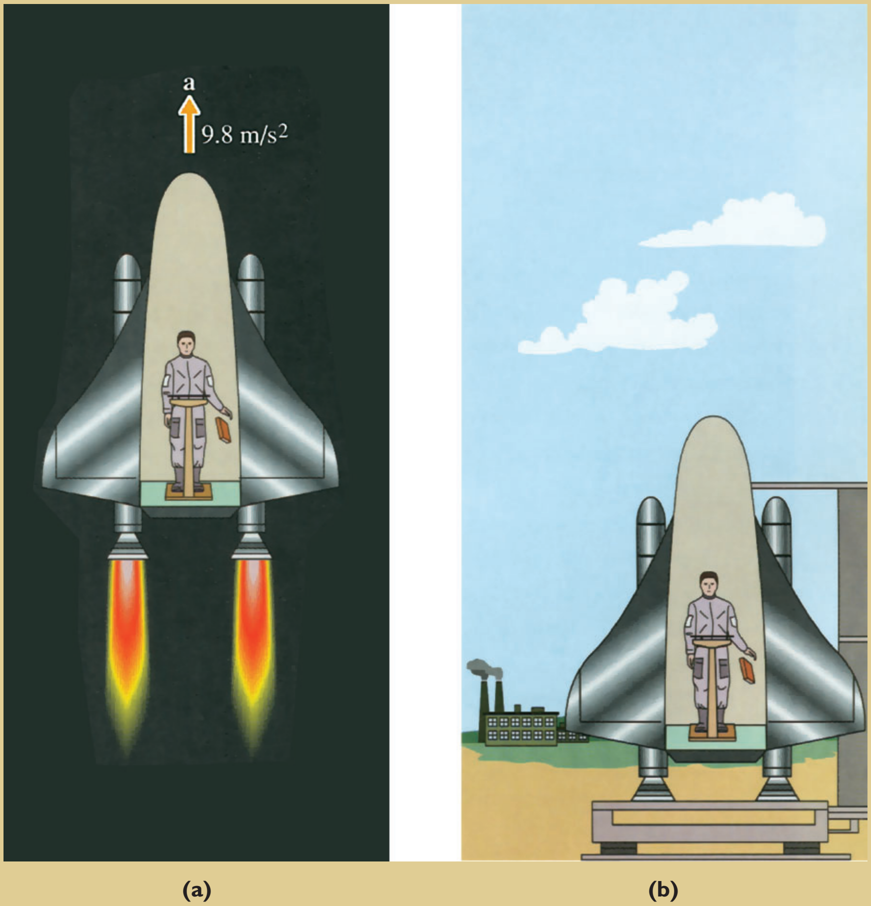


Fig. 27–D Two equivalent reference frames: **(a)** A spaceship accelerating at 9.8 m/s^2; **(b)** A reference frame at rest on earth. Any experiment confined to one or the other of these two reference frames gives exactly the same results, according to the equivalence principle.

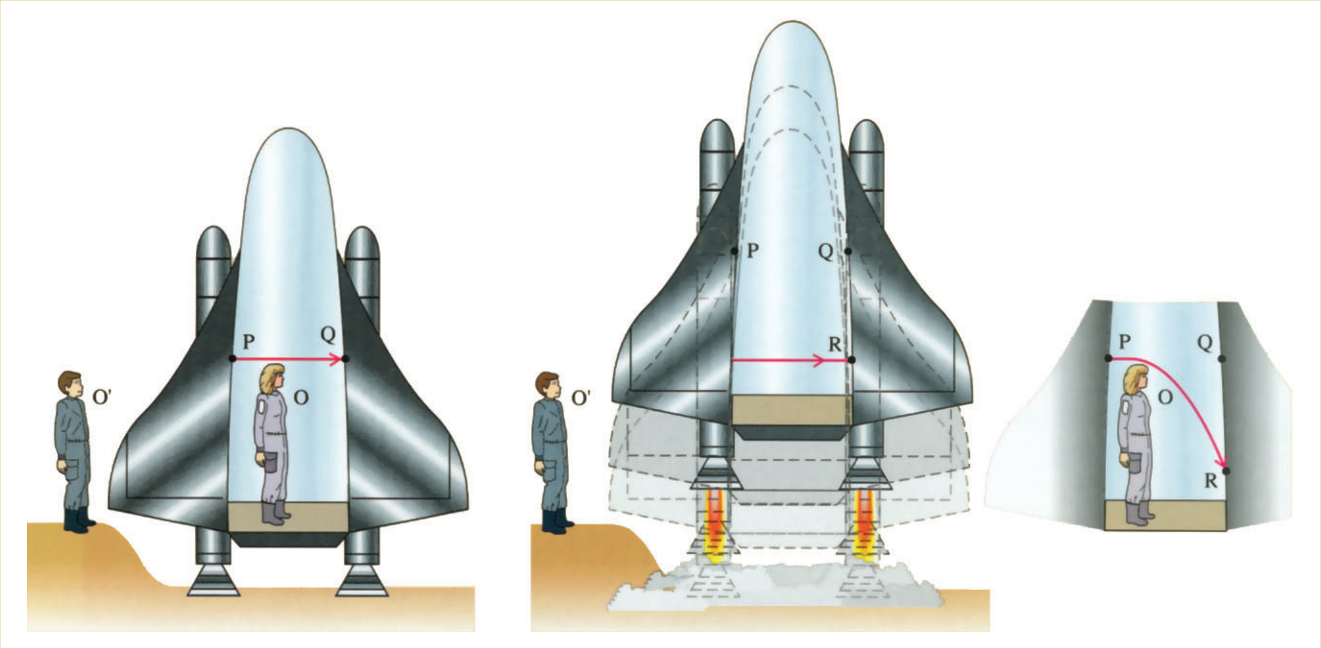


Fig. 27–E **(a)** Observers O and O′ are both at rest in an inertial reference frame. Both observe a pulse of light travel across the stationary spaceship from P to Q. **(b)** The spaceship accelerates as a laser pulse travels across. The pulse travels in a straight line, as seen by O′, and so strikes a point R on the wall lower than P, since the wall moves up as the pulse travels across. **(c)** As seen by O, the path of the second laser pulse bends downward as it travels across the ship.

also effectively create a gravitational field by accelerating in a field-free region of space.

Einstein used his equivalence principle as a first step in developing his general theory of relativity. Unforunately, the theory is too mathematically complex to describe in detail. However, we can use the equivalence principle to understand one of the key experimental predictions of the general theory: the effect of a gravitational field on the path of a light ray. Consider the following experiment. A spaceship is initially at rest in an inertial reference frame in a field-free region of space. An observer O inside the ship directs a laser pulse across the ship from point P to point Q (Fig. 27–Ea). A second observer at rest in the same reference frame, but outside the ship, also observes the experiment through the ship's glass walls. Now suppose the experiment is repeated, but this time the ship accelerates upward (Fig. 27–Eb). The path of the light ray, as seen by O′, who remains at rest in the inertial reference frame, must follow the same straight path as before, and must therefore strike the wall of the upward accelerating ship at a point R lower than P, as indicated in the figure. This means that, as seen by observer O, the light bends downward (Fig. 27–Ec), a conclusion that, according to the equivalence principle, is the same whether O is in an accelerating space ship or is at rest in an inertial frame with a downward-directed gravitational field. So we must conclude that the path of a light ray is bent downward by a gravitational field. The effect, however, is much too small to be seen in the earth's gravitational field. Light travels far too fast for it to drop appreciably even after traveling great distances along the earth's surface.

Einstein predicted that the effect could be seen if you could view a star when the light from it passed very close to the surface of the sun on its way to the earth. The bending of the light toward the sun would cause a change in the apparent position of the star. When the earth is at a point in its orbit around the sun where the earth, sun, and a certain star are approximately aligned so that light from the star passes very close to the sun's surface on its way to the earth, the position of the star relative to other stars appears to change (Fig. 27–F). Of course, under ordinary conditions the sun's light is much too bright for the star's light to be seen then. However, during a total solar eclipse, the sun's light is blocked, permitting the star to be seen. A solar eclipse is a relatively rare and exciting natural phenomenon (Fig. 27–G). Thus great excitement surrounded an expedition of British scientists who set out to observe the solar eclipse on May 29, 1919, to find out if Einstein was right. The deflection predicted by Einstein is small, even though the sun has a gravitational field hundreds of times larger than earth's.

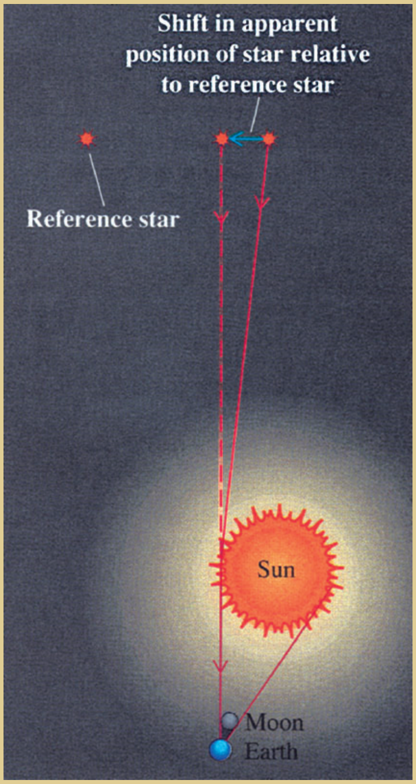


Fig. 27–F Light from a distant star bends in the sun's gravitational field on its way to earth, thereby changing its apparent position. An eclipse of the sun by the moon allows this starlight to be seen.

Fig. 27–G An annular solar eclipse, as seen in Eolia, Missouri on May 10, 1994. The earth is somewhat closer to the sun during an annular eclipse than during a total eclipse, and so the sun's disk is not entirely blocked from view.

Einstein predicted a change in the angular position of the star of only 1.7 seconds of arc, or about 0.0005°. Careful measurement of data and analysis of results were completed months after the expedition. The scientists then announced that light is indeed bent by gravity, as predicted by Einstein, and by precisely the predicted 1.7 seconds. Einstein became an instant celebrity.

Over the years solutions to equations of general relativity have contributed to our fundamental understanding of the universe. For example, based on certain relativistic solutions and some astronomical observations, we now believe that our universe began about 10 billion years ago as a point in space-time, an event referred to as the Big Bang. Another prediction of the general theory is the existence of black holes—stars that collapse under their own gravity and generate fields so intense that nothing can escape, not even light (Fig. 27–H). In May, 1994, improved photographs from the Hubble Space Telescope gave the most convincing evidence yet for the existence of black holes.

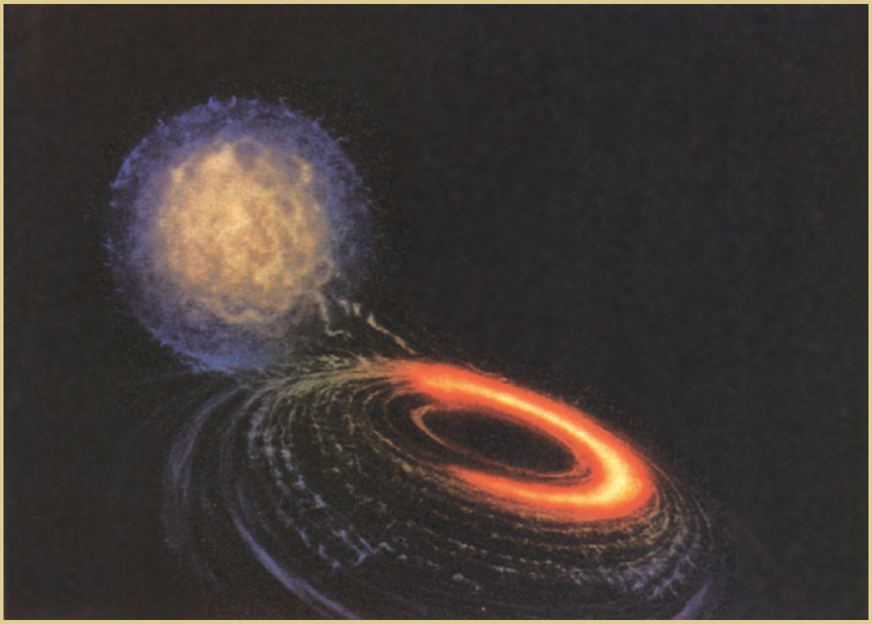


Fig. 27–H Artist's concept of a black hole.

Albert Einstein

The early life of Albert Einstein, the man who was to change forever our concepts of space and time, gave no hint of genius. Einstein was born in the town of Ulm, in southern Germany, on March 14, 1879, to a family of small-businessmen, not known for great learning or revolutionary outlook. As a child, Albert did not seem gifted. Indeed he was very slow in learning to talk. School was a boring and depressing experience for him. He was a daydreamer who did not accept the attitudes his strict, convention-bound teachers attempted to impart.

Surprisingly, it may have been his reluctance to part with his seemingly childish ways of looking at the world that made possible the eventual blossoming of his genius. Later in life, he was to remark that the main requirement for creativity in science is not knowledge but rather a freshness of vision, a childlike openness in seeing the patterns of nature unfettered by the false and narrow traditional assumptions that hinder most thinking. As he wrote in his autobiography, *The World As I See It:* "We have forgotten what features in the world of experience caused us to frame concepts, and we have great difficulty in representing the world of experience to ourselves without the spectacles of the old-established conceptual interpretation."

In his teens, Einstein fantasized about questions that would have seemed foolish to most adults—questions such as: "What would the world look like if I rode on a beam of light?" Thanks to an uncle, who aroused the boy's interest in mathematics, Albert began to give his speculations mathematical form. He later continued his education in Switzerland and enrolled at the Swiss Federal Polytechnic School in Zürich. Once again, however, he found formal schooling deadening, and he turned his attention to the original writings of earlier scientists, especially Maxwell, whom he admired. Academically he managed to do just enough to satisfy his instructors as to his basic competence, and he received his diploma in 1900.

After searching without success for a teaching post, he finally took a rather routine job at a patent office in Berne, the Swiss capital. Fortunately, this position left him enough time to begin to work out some of the profound relationships in nature he had glimpsed early on.

In the year 1905, he wrote and published four scientific articles that were to change the science of physics forever. In one of these articles, he established on a sure footing the atomic theory of matter through his explanation of Brownian motion. In another, he carried the earlier insights of Max Planck to new heights with the first formulation of a photon theory of light. As if these two breakthroughs were not enough, in two other papers he dazzled the scientific world with a wholly original theory of mass, energy, and motion—his special theory of relativity—an attempt, as it were, to tell the world about his imaginary boyhood ride on a light beam.

The catalogue of things changed by his theory is impressive. Suddenly, mass and energy were no longer unalterably different kinds of things, but the same thing in different forms, united by the famous equation $E = mc^2$. Suddenly, the familiar world of Galilean mechanics, with its simple additivity of motions, was overthrown, and with it the possibility of absolute frames of reference. The length and mass of an object now depended on the way in which the object moved, especially as its speed approached that of light, which became an upper limit on all speeds. Not even time could be saved from this new universe of relativity. In short, not a single one of the fundamental concepts of physics would ever again mean what it had meant before. Einstein had changed these concepts forever. Scientists who once would have laughed at his imaginary ride on a light beam now had to take that ride along with him—a ride that would leave the familiar world unreachably far behind.

In the decade that followed, Einstein went on to become a professor at the University of Berlin. There, he succeeded in formulating a general theory of relativity. In that theory, he resolved the long-standing puzzle of the equivalence of inertial and gravitational mass. Einstein had formulated a new theory of gravitation that replaced the old established Newtonian theory. Now gravity could be seen in terms of the curvature of space-time.

Throughout the 1920s, Einstein continued his attempts to unify and simplify the laws of physics and in 1921 received the Nobel Prize in physics. He undertook a valiant search, one that would continue throughout the remainder of his life, for a unified field theory that would bring together the fundamental forces of nature—an effort that others continue. Einstein also offered an ongoing critique of quantum mechanics as a complete description of reality. He objected to the Heisenberg uncertainty principle as creating a fuzzy area of indeterminacy within the atom, saying "God does not play dice with the world." Although it resulted in some philosophical refinement of quantum theory, his critique of quantum theory did not fundamentally change it, and is now generally regarded as a misguided effort.

The rise of the Nazis to power in 1933 led Einstein to resign his position in Berlin and to emigrate to the United States. He soon settled at Princeton, New Jersey, and joined the Institute for Advanced Study there. He later became a citizen of the United States and spent the remainder of his life at Princeton, diligently continuing his research and also working toward the cause of peace and human justice until his death in 1955.

Throughout his life, Einstein had been a modest man, unconcerned with fame. He dressed casually and comfortably, even when giving lectures, often wearing an old sweater, house slippers, and no socks. He was loved as much for his simplicity, kindness, and concern for social justice as he was for his monumental intelligence.

Einstein in his garden.

It can be argued that Einstein's scientific contributions might not have been possible without his very human personal qualities —among them, his sense of the oneness of nature, his boyish wonder, his feeling of awe before the beauty of the universe, and his faith in our ability to grasp its workings. He believed that "the eternal mystery of the world is its comprehensibility."