28 Albert Einstein and the Theory of Relativity

KEY IDEA

All observers, no matter what their frame of reference, see the same laws of nature.

PHYSICS AROUND US . . . The Airport

You walk down the ramp into the plane and get into your seat. It's been a long day—classes and maybe an exam or two. You doze off for a moment and then wake with a start. For a moment, it appears to you that the plane has started to move backward, away from the gate. Then, as you become more alert, you realize that your plane isn't moving at all but another plane is pulling into the gate next to yours.

During that brief moment between sleep and waking, you were seeing the world through eyes unaffected by years of experience. You were realizing that there is always more than one way to view any kind of uniform motion. One way is to say that you are stationary and the other plane is moving with respect to you. But you could also say that the other plane is stationary and you are moving with respect to it.

Which point of view is right?

One of the great scientific discoveries of the early twentieth century, the theory of relativity, grew out of thinking about this sort of question.

FRAMES OF REFERENCE

A **frame of reference** is the physical surroundings from which you observe and measure the world around you. If you read this book at your desk or in an easy chair, you experience the world from the frame of reference of your room, which seems firmly rooted to solid Earth. If you read on a train or in a plane, your frame of reference is the vehicle, which moves with respect to Earth's surface. If you could imagine yourself in an accelerating spaceship in deep space, your frame of reference would be different still. In each of these reference frames you are what scientists call an "observer." An observer looks at the world from a particular frame of reference, with anything from casual interest to a full-fledged laboratory investigation of phenomena that leads to a determination of natural laws.

For human beings who grow up on Earth's surface, it is natural to think of the ground as a fixed, immovable frame of reference and to refer all motion to it. After all, train or plane passengers don't think of themselves as stationary while the countryside zooms by. However, as we have seen in the opening Physics Around Us section, there are indeed times when we lose this prejudice and see that the question of who is moving and who is standing still is largely one of definition.

From the point of view of an observer in a spaceship above the solar system, there is nothing solid about the ground you're standing on. Earth is rotating on its axis and moving in an orbit around the Sun, while the Sun itself is performing a stately rotation around the galaxy. Thus, even though a reference frame fixed in Earth may seem "right" to us, there is nothing special about it.

Descriptions in Different Reference Frames

Different observers in different reference frames may provide very different accounts of the same event. To convince yourself of this idea, think about a simple experiment. While riding on a train, take a coin out of your pocket and flip it. You know what will happen—the coin goes up in the air and falls straight back into your hand, just as it would if you flipped it while sitting in a chair in your

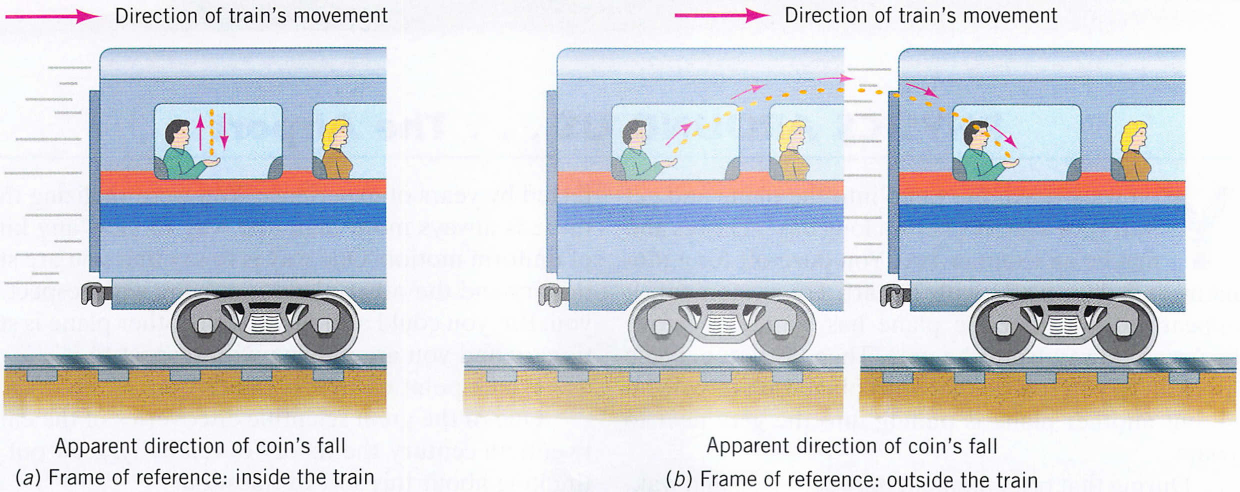


FIGURE 28-1. The path of a coin flipped in the air depends on the observer's frame of reference. (*a*) A rider in the car sees the coin go up and fall straight down. (*b*) An observer on the street sees the coin follow an arching path.

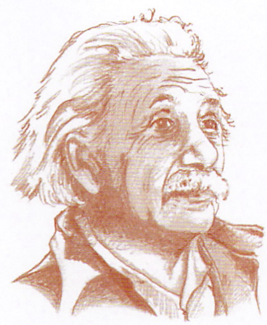
room (Figure 28-1*a*). But now ask yourself this question: how would a friend standing near the tracks, watching your train go by, describe the flip of the coin? To your friend, it appears that the coin goes up into the air, but by the time it comes down the car has traveled some distance down the tracks. As far as your friend on the ground is concerned, the coin has traveled in an arc (Figure 28-1*b*).

So you, sitting in the train, say the coin has gone straight up and down, while someone on the ground says it has traveled in an arc. You and the ground-based observer would describe the path of the coin quite differently, and you would both be correct in your respective frames of reference. The universe we live in possesses this general feature—different observers describe the same event in different terms, depending on their frames of reference.

Does this mean that we are doomed to live in a world where nothing is fixed, where everything depends on the frame of reference of the observer? Not necessarily. The possibility exists that even though different observers give different descriptions of the same event, they agree on the underlying laws that govern it. Even though the observers disagree on the path followed by the flipped coin, they may very well agree that motion in their frame is governed by Newton's laws of motion and the law of universal gravitation.

THE PRINCIPLE OF RELATIVITY

Albert Einstein came to his theories of relativity by thinking about a fundamental contradiction between Newton's laws and Maxwell's equations. You can see the problem by thinking about a simple example. Imagine you're on a moving railroad car and you throw a baseball. What speed does the baseball have according to an observer on the ground?



Albert Einstein (1879–1955).

If you throw the ball forward at 40 kilometers per hour while on a train traveling 100 kilometers per hour, the ball appears to a ground-based observer to travel 140 km/h—that is, 40 km/h from the ball plus 100 km/h from the train. On the other hand, if you throw the ball backward, the ground-based observer sees the ball moving at only 60 km/h—the train's 100 km/h minus the ball's 40 km/h. In our everyday world, we just add the two speeds to get the answer, and this notion is reflected in Newton's laws.

Now suppose that instead of throwing a ball you turn on a flashlight and measure the speed of the light coming from it. In Chapter 19 we noted that the speed of light is built into Maxwell's equations. If every observer is to see the same laws of nature, they all have to see the same speed of light. In other words, the ground observer would have to see light from the flashlight moving at 300,000 km/s and not 300,000 km/s plus 100 km/h. In this case, velocities wouldn't add, as our intuition tells us they must.

Albert Einstein thought long and hard about this paradox, and he realized that it could be resolved in only three possible ways:

1. The laws of nature are not the same in all frames of reference (an idea Einstein was reluctant to accept on philosophical grounds).
2. Maxwell's equations are wrong and the speed of light depends on the speed of the source emitting the light (in spite of abundant experimental support for the equations).
3. Our intuitions about the addition of velocities are wrong, in which case the universe might be a very strange place indeed.

Einstein focused on the third of these possibilities.

The idea that the laws of nature are the same in all frames of reference is called the *principle of relativity,* and it can be stated as follows:

Every observer must experience the same natural laws.

This statement is the central assumption of Einstein's **theory of relativity.** Hidden beneath this seemingly simple statement lies a view of the universe that is both strange and wonderful. The extraordinary effort required to understand the consequences of this one simple assumption occupied Einstein during much of the first decades of the twentieth century.

We can begin to understand Einstein's work by recalling what Isaac Newton had demonstrated three centuries earlier—that all motions fall into one of two categories, uniform motion or accelerated motion (Chapter 3). Einstein therefore divided his theory of relativity into two parts—one for each of these kinds of motion. The first part, published by Einstein in 1905, is called **special relativity** and deals with all frames of reference in uniform motion relative to one another—reference frames that do not accelerate. It took Einstein another decade to complete his treatment of **general relativity,** mathematically a much more complex theory, which applies to any reference frame, whether or not it is accelerating relative to another.

At first glance, the underlying principle of relativity seems obvious, perhaps almost too simple. Of course the laws of nature are the same everywhere—that's the only way that scientists can explain how the universe behaves in an ordered way. But once you accept that central assumption of relativity, be prepared for some surprises. Relativity forces us to accept the fact that nature doesn't always behave as our intuition says it must. You may find it disturbing that nature sometimes violates our sense of the way things should be. But you'll have little problem with relativity if you just accept the idea that the universe is what it is and not necessarily what we think it should be.

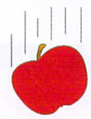
Another way of saying this is to note that our intuitions about how the world works are built up from experience with things that are moving at modest speeds—a few hundred, or at most a few thousand, miles per hour. None of us has any experience with things moving near the speed of light, so when we start examining phenomena in that range, our intuitions won't necessarily apply. As with our examination of the concepts of quantum mechanics at the scale of atoms and molecules, we shouldn't be surprised by anything we find.

Relativity and the Speed of Light

As the example of the train and the flashlight shows, one of the most disturbing aspects of the principle of relativity has to do with our everyday notions of speed. According to the principle, any observer, no matter what his or her reference frame, should be able to confirm Maxwell's description of electricity and magnetism. Because the speed of light is built into these equations, it follows that

The speed of light, c, is the same in all reference frames.

Strictly speaking, this statement is only one of many consequences of the principle of relativity. However, so many of the surprising results of relativity follow from this statement that it is often accorded special status and given special attention in discussions of relativity.



Physics in the Making

Einstein and the Streetcar

Newton and his apple have entered modern folklore as a paradigm of unexpected discovery. A less well known incident led Albert Einstein, then an obscure patent clerk in Berne, Switzerland, to relativity.

One day, while riding home in a streetcar, he happened to glance up at a clock on a church steeple (Figure 28-2). In his mind he imagined the streetcar speeding up, moving faster and faster, until it was going at almost the speed of light. Einstein realized that if the streetcar were traveling at the speed of light, it would appear to someone on the streetcar that the clock had stopped. A passenger looking at the clock would always see the same thing—for him or her, the clock would be "frozen." On the other hand, a clock moving with Einstein—his pocket watch, for example—would still tick away the seconds in its usual way. Perhaps, Einstein thought, time as measured on a clock, just like motion, is relative to one's frame of reference.

In later years, Einstein liked to talk to other physicists about his ideas as he continued to develop the theory of relativity. Eve Curie, in her biography of her mother Marie Curie, tells of Einstein walking with Madame Curie and her two young daughters during a visit. Einstein delighted the children because he talked about wanting to know what it would be like to ride on a beam of light. But Einstein was quite serious about these ideas and they led him to revolutionize our basic ideas of time and space. ●

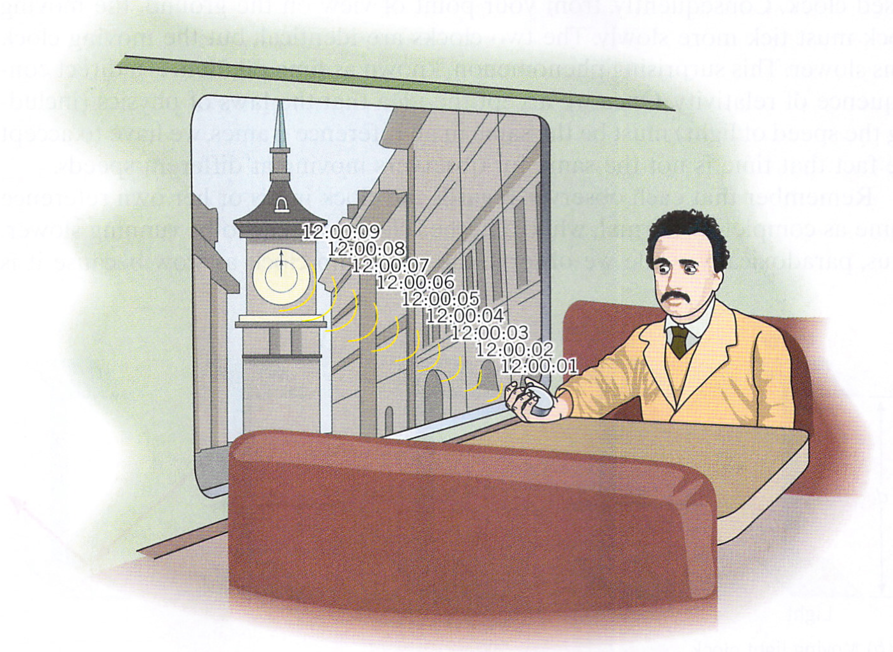


FIGURE 28-2. Albert Einstein, moving away from a clock tower, imagined how different observers might view the passage of time. If Einstein were traveling at the speed of light, for example, the clock would appear to him to have stopped, even though his own pocket watch would still be ticking.

SPECIAL RELATIVITY

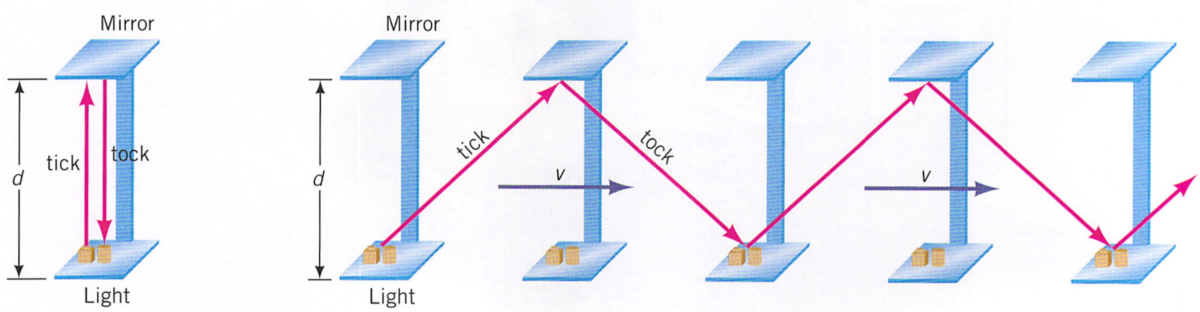
Time Dilation

Think about how you measure time. The passage of time can be measured by any kind of regularly repeating phenomenon—a swinging pendulum, a beating heart, or an alternating electric current. To get at the theory of relativity, however, it's easiest to think of a rather unusual kind of clock. Suppose, as in Figure 28-3, we have a flashbulb, a mirror, and a photon detector. A "tick–tock" of this clock would consist of the flashbulb going off, the light traveling to the mirror, bouncing back down to the detector, and then triggering the next flash. By adjusting the distance, *d*, between the light source and mirror, these pulses could correspond to any desired time interval. This unusual light clock, therefore, serves the same function as any other clock—in fact, you could adjust it to be synchronized with the ticking of anything from a grandfather's clock to a wristwatch.

Now imagine two identical light clocks: one next to you on the ground (Figure 28-3*a*) and the other whizzing by in a spaceship (Figure 28-3*b*). Imagine, further, that the mirrors are adjusted so that both clocks would be ticking at the same rate if they were standing next to one another. How would the moving clock look to you?

Standing on the ground, you would see the ground-based clock ticking along as the light pulses bounce back and forth between the mirror and detector. When you looked at the moving clock, however, you would see the light following a longer, zigzag path. If the speed of light is indeed the same in both frames of reference, it should appear to you that the light in the moving frame takes longer to travel the zigzag path from flashbulb to detector than the light on the ground-based clock. Consequently, from your point of view on the ground, the moving clock must tick more slowly. The two clocks are identical, but the moving clock runs slower. This surprising phenomenon, known as **time dilation,** is a direct consequence of relativity. Once we accept the idea that the laws of physics (including the speed of light) must be the same in all reference frames, we have to accept the fact that time is not the same for observers moving at different speeds.

Remember that each observer regards the clock in his or her own reference frame as completely normal, while all other clocks appear to be running slower. Thus, paradoxically, while we observe the spaceship clock as slow because it is



(*a*) Stationary light clock (*b*) Moving light clock

FIGURE 28-3. A light clock incorporates a flashing light and a mirror. A light pulse from a flashbulb bounces off the mirror and returns to trigger the next pulse. Two light clocks, one stationary (*a*) and one moving (*b*), illustrate the phenomenon of time dilation. Light from the moving clock must travel farther, and so the moving clock appears to the stationary observer to tick more slowly.

moving, observers in the speeding spaceship see the Earth-based clock moving and believe that the Earth-based clock is running more slowly than theirs.

Relativity's prediction of time dilation can be tested in a number of ways. Physicists have actually documented relativistic time dilation by comparing two extremely accurate atomic clocks, one on the ground and one strapped into a jet aircraft. Even though jets travel at a paltry hundred-thousandth of the speed of light, the difference in the time recorded by the two clocks can be measured and has verified the predictions of relativity.

Time dilation can also be observed with high-energy particle accelerators that routinely produce unstable subatomic particles (see Chapter 27). The normal half-life of these particles is well known. However, when accelerated to near the speed of light, these particles last much longer because of the relativistic slowdown in their decay rates.

Thus, although the notion that moving clocks run slower than stationary ones violates our intuition, it seems to be well documented by experiment. Why, then, aren't we aware of this effect in everyday life? To answer that question, we have to ask how big an effect time dilation is. How much do moving clocks slow down?

LOOKING DEEPER

The Size of Time Dilation

We have tried, in general, to talk about science in everyday terms and stay away from formulas in this book. But we have now run into a rather fundamental question that requires some simple mathematics to answer. In this section, you'll be able to follow the kind of thought process used by Einstein when he first formulated his revolutionary theory.

Consider the two identical light clocks in Figure 28-3, one moving at a velocity v relative to the ground and one stationary on the ground. Each clock has a flashbulb-to-mirror separation distance of d. (The various symbols we are using are summarized in Table 28-1.) Note that we use the terms "moving" and "stationary" for convenience; this same derivation holds for any two clocks moving relative to one another.

The notation for the time it takes for light to travel the distance d from the flashbulb to its opposite mirror—that is, one tick of the stationary clock—is a little trickier because we have to keep track of which clock we're looking at and from which reference frame we're looking. We will use two subscripts—the first subscript to tell us whether the clock is on the ground (G) or moving (M), and the second subscript to indicate whether the observer is on the ground or moving. Thus, t_{GG} is the time for one tick of the ground-based clock as measured by an observer on the ground. On the other hand, t_{MG} is the time for one tick of the moving clock from the point of view of this ground-based observer. According to the principle of relativity, all observers see clocks in their own reference frames as normal. Or, in equation form,

$$t_{GG} = t_{MM}$$

As ground-based observers, we are interested in determining the relative values of t_{GG} and t_{MG}—what

TABLE 28-1 Symbols for Deriving Time Dilation

Symbol	Description
v	Velocity of the moving light clock relative to the ground
d	Distance between the clock's flashbulb and mirror
t_{GG}	Time for one tick (ground clock, ground observer)
t_{MG}	Time for one tick (moving clock, ground observer)
t_{GM}	Time for one tick (ground clock, moving observer)
t_{MM}	Time for one tick (moving clock, moving observer)
c	Speed of light, a constant

we see as ticks of the stationary versus the moving clocks. In the stationary ground-based frame of reference, one tick is simply the time it takes light to travel the distance *d*:

$$\text{Time} = \frac{\text{Distance}}{\text{Speed}}$$

Substituting values for the light clock into this equation,

$$\text{Time for one tick} = \frac{\text{Flashbulb-to-mirror distance}}{\text{Speed of light}}$$

or

$$t_{GG} = \frac{d}{c}$$

where *c* is the standard symbol for the speed of light.

We have argued that to the observer on the ground it appears that the light beam in the moving clock travels on a zigzag path, as shown in Figure 28-3*b*, and that this makes the moving clock appear to run more slowly. In what follows, we show how to take an intuitive statement such as this and convert it into a precise mathematical equation. We begin by labeling the dimensions of our two clocks.

The moving clock travels a horizontal distance of $v \times t_{MG}$ during each of its ticks. In order to determine the value of t_{MG}, we must first determine how far light must travel in the moving clock as seen by the observer on the ground. As illustrated in Figure 28-4, we know the lengths of the two shortest sides of a right triangle. One side has length *d*, representing the vertical distance between flashbulb and mirror (a distance, remember, that is the same in both frames of reference). The other side is $v \times t_{MG}$, which corresponds to the distance traveled by the moving clock as observed in the stationary frame of reference. The distance traveled by the moving light beam in one tick is represented by the hypotenuse of this right triangle and is given by the Pythagorean theorem.

1. In words:

   The square of the length of a right triangle's long side equals the sum of the squares of the lengths of the other two sides.

2. In an equation with words (applied to our light clock):

   The square of the distance light travels during one tick equals the sum of the squares of the flashbulb-to-mirror distance and the horizontal distance the clock moves during one tick.

3. In an equation with symbols:

$$(\text{Distance light travels})^2 = d^2 + (v \times t_{MG})^2$$

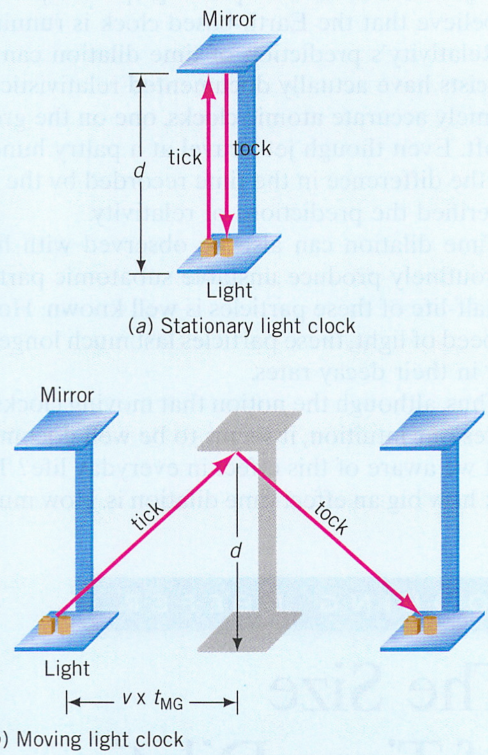


FIGURE 28-4. Light clocks with dimensions labeled. Both the stationary clock (*a*) and the moving clock (*b*) have flashbulb-to-mirror distance *d*. During one tick the moving clock must travel a horizontal distance $v \times t_{MG}$.

We can begin to simplify this equation by taking the square roots of both sides:

$$\text{Distance light travels} = \sqrt{d^2 + (v \times t_{MG})^2}$$

Remember, time equals distance divided by velocity. So the time it takes light to travel this distance t_{MG}, is given by the distance $\sqrt{d^2 + (v \times t_{MG})^2}$ divided by the velocity of light *c*:

$$t_{MG} = \frac{\sqrt{d^2 + (v \times t_{MG})^2}}{c}$$

We now must engage in a bit of algebraic manipulation. First, square both sides of this equation.

$$t_{MG}{}^2 = \frac{d^2}{c^2} + \frac{v^2 t_{MG}{}^2}{c^2}$$

But we saw previously that $t_{GG} = d/c$, so, substituting gives us

$$t_{MG}{}^2 = t_{GG}{}^2 + \frac{v^2 t_{MG}{}^2}{c^2}$$

Dividing both sides by t_{MG}^2 gives

$$\frac{t_{MG}^2}{t_{MG}^2} = \frac{t_{GG}^2}{t_{MG}^2} + \frac{v^2 t_{MG}^2/c^2}{t_{MG}^2}$$

or

$$1 = \left(\frac{t_{GG}}{t_{MG}}\right)^2 + \left(\frac{v}{c}\right)^2$$

Finally, regrouping yields

$$t_{MG} = \frac{t_{GG}}{\sqrt{1 - \left(\frac{v}{c}\right)^2}}$$

This equation expresses in mathematical form what we said earlier in words—that moving clocks appear to run slower. It tells us that t_{MG}, the time it takes for one tick of the moving clock as seen by an observer on the ground, is equal to the time it takes for one tick of an identical clock on the ground divided by a number less than 1. Thus, the time required for a tick of the moving clock is always greater than that for a stationary clock.

The expression $\sqrt{1 - (v/c)^2}$ is called the *Lorentz factor* and this number appears over and over again in relativistic calculations. In the case of time dilation, the Lorentz factor arises from an application of the Pythagorean theorem.

An important point to notice is that if the velocity of the moving clock is very small compared to the speed of light, the quantity $(v/c)^2$ becomes very small and the Lorentz factor is almost equal to 1. In this case, the time on the moving clock is almost equal to the time on the stationary one, as our intuition demands that it should be. Only when speeds get very high do the effects of relativity become important; close to the speed of light, the clock appears to stop ticking altogether.

LOOKING DEEPER

How Important Is Relativity?

To understand why we aren't aware of relativity in everyday life, let's calculate the size of the time dilation for a clock in a car moving relative to the ground at 70 km/h (about 50 miles per hour).

The first problem is to convert the familiar speed in kilometers per hour to a speed in meters per second so we can compare it to the speed of light. There are 60 minutes/hour × 60 seconds/minute = 3600 seconds in an hour, so a car traveling 70 km/h is moving at a speed of

$$70 \text{ km/h} = \frac{70{,}000 \text{ m}}{3600 \text{ s}}$$
$$= 19.4 \text{ m/s}$$

For this speed, the Lorentz factor is

$$\sqrt{1 - \left(\frac{19.4}{300{,}000{,}000}\right)^2} = 0.9999999999999999$$

Thus the passage of time for a stationary car and a speeding car differs by only one part in the sixteenth decimal place.

To get an idea of how small the difference is between the ground clock and the moving one in this case, we can note that if you watched the moving car for a time equal to the age of the universe, you would observe it running 10 seconds slow compared to your ground clock.

However, for an object traveling at 99% of the speed of light, the Lorentz factor is

$$\sqrt{1 - \left(\frac{v}{c}\right)^2} = \sqrt{1 - (0.99)^2}$$
$$= \sqrt{0.0199}$$
$$= 0.1411$$

In this case, you would observe the stationary clock to be ticking about seven times as fast as the moving one—that is, the ground clock would tick about seven times while the moving clock ticked just once.

This numerical example illustrates a very important point about relativity. Our intuition and experience tell us that the exterior clock on our local bank doesn't suddenly slow down when we view it from a moving car. Consequently, we find the prediction of time dilation to be strange and paradoxical. But all of our intuition is built up from experiences at very low velocities—none of us has ever moved at an appreciable fraction of the speed of light. For the everyday world, the predictions of relativity coincide precisely with our experience. It is only when we get into regions near the speed of light, where that experience isn't relevant, that the "paradoxes" arise.

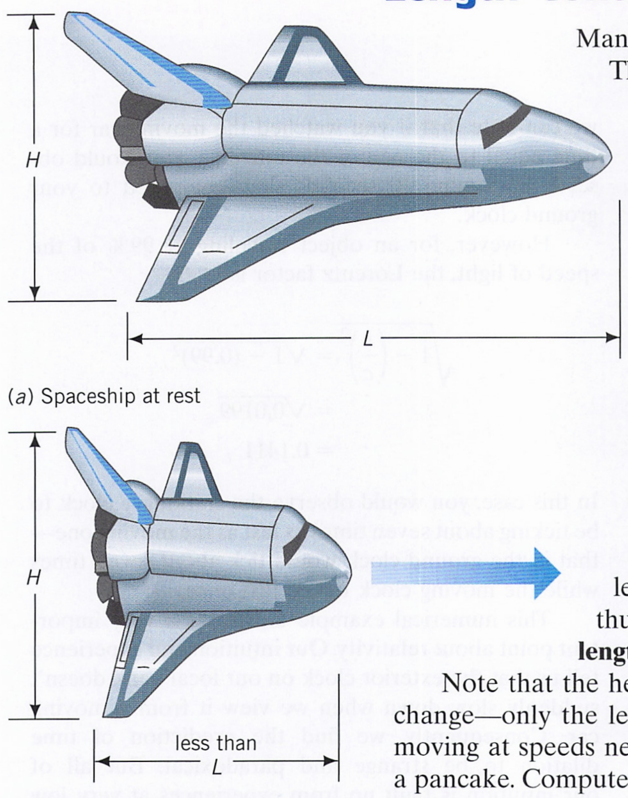
Connection
Space Travel and Aging

While humans presently do not experience the direct effects of time dilation in their day-to-day lives, at some future time they might. If we ever develop interstellar space travel at near-light speed, then time dilation may wreak havoc with family lives (and genealogists' records).

Imagine a spaceship that accelerates to 99% of the speed of light and goes on a long journey. While 15 years seem to pass for the crew of the ship, more than a century goes by on Earth. The space explorers return almost 15 years older than when they left, but biologically younger than their great-grandchildren! Friends and family would all be long-since dead.

If we ever enter an era of extensive high-speed interstellar travel, people may drift in and out of other people's lives in ways we can't easily imagine. Parents and children could repeatedly leapfrog one another in age, and the notion of relatedness could take on complex twists in a society with widespread relativistic travel. ●

Length Contraction



(*a*) Spaceship at rest

(*b*) Spaceship at high speed

FIGURE 28-5. A spaceship in motion appears to contract in length, L, along the direction of motion. However, the height, H, and width of the ship do not appear to change.

Many results from relativity run counter to our intuition. They can be derived by procedures similar to (but more complicated than) the one we just gave for working out time dilation. In fact, using arguments like those we have presented, Einstein showed that moving objects must appear to be shorter than stationary ones (see Figure 28-5).

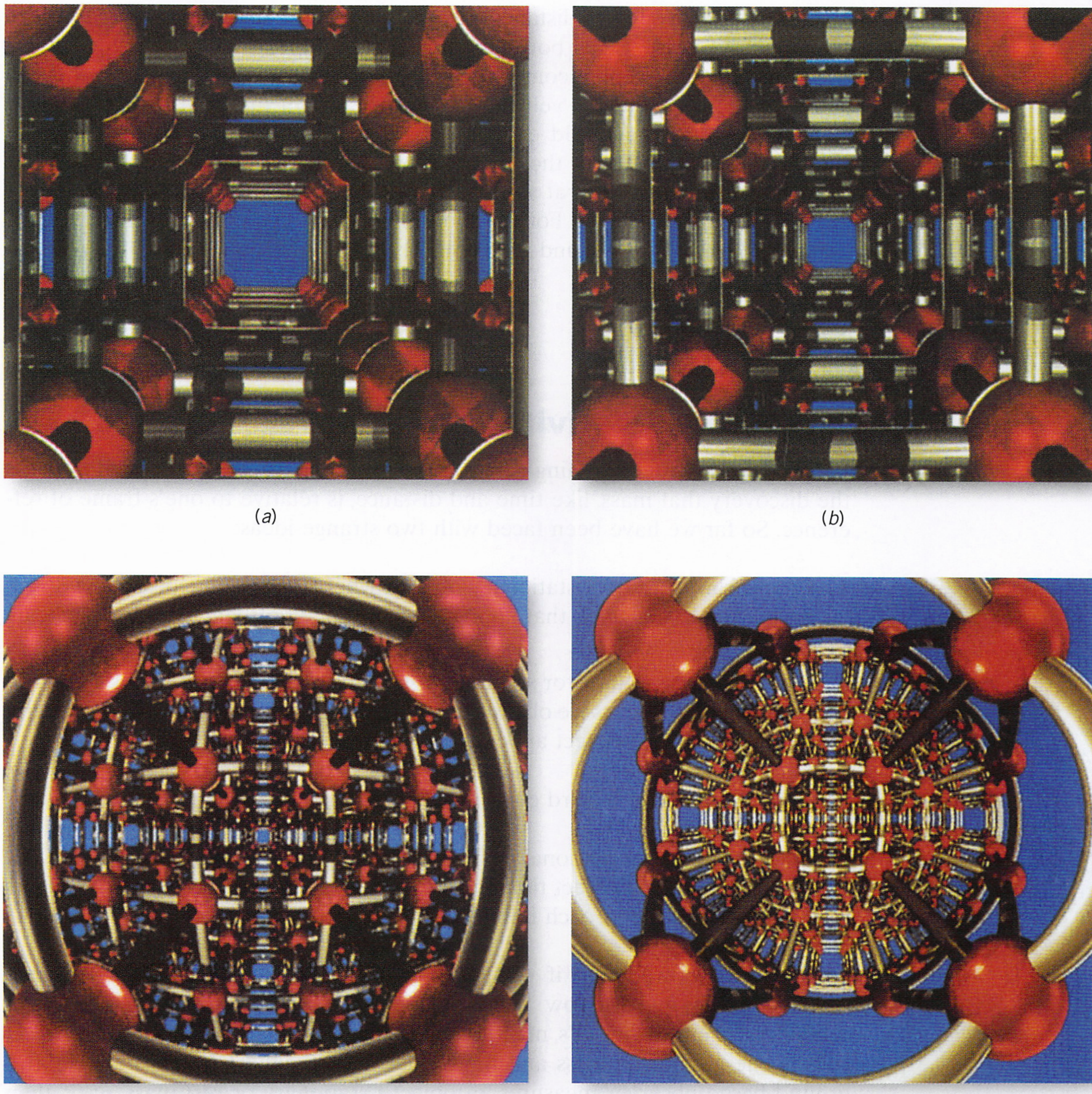
The equation that relates the ground-based observer's measurement of a stationary object's length, L_{GG}, to that observer's measurement of the length of an identical moving object, L_{MG}, is

$$L_{MG} = L_{GG} \times \sqrt{1 - (v/c)^2}$$

The term on the right side of this equation is the familiar Lorentz factor that we derived from our study of light clocks. The equation tells us that the length of the moving ruler can be obtained by multiplying the length of the stationary ruler by a number less than 1, and thus must appear shorter. This phenomenon is known as **length contraction.**

Note that the height and width of the moving object do not appear to change—only the length along the direction of motion. Thus, a basketball moving at speeds near the speed of light would take on the appearance of a pancake. Computer simulations have shown that because length contracts in the direction of motion, but not in other directions, the appearance of objects seen by an observer moving at speeds near the speed of light can become warped in unexpected ways.

Length contraction is not just an optical illusion. While relativistic shortening doesn't affect most of our daily lives, the effect is real. Physicists who work at particle accelerators inject bunches of particles into their machines. As these particles approach light speed, the bunches are observed to contract according to the Lorentz factor, an effect that must be compensated for.



(a) (b) (c) (d)

A series of four computer-generated images shows the changing appearance of a network of balls and rods as it moves toward you at different speeds. (*a*) At rest, the normal view. (*b*) At 50% of light speed, the array appears to contract. (*c*) At 95% of light speed, the lattice has curved rods. (*d*) At 99% of light speed, the network is severely distorted.

So What About the Train and the Flashlight?

Now that we understand a little about how relativity works, we can go back and unravel the paradox we discussed earlier in this chapter—the problem of how both an observer on the ground and an observer on the train could see light from a flashlight moving at the same speed.

Velocity is defined as distance traveled divided by the time required for the travel to take place. Since both length and time appear to be different for different observers, it should come as no surprise that the rule that tells us how to add velocities (such as the velocity of the light and of the train) might be more complicated than we would expect. The simple intuition that tells us that we should add the velocity of the train to the velocity of the ball, like our notions of time and space, is valid at small velocities but breaks down for objects moving near the speed of light. For those objects, a more complex addition has to be done, and, when it is, we find that both observers see the light moving at a velocity of c.

RELATIVISTIC DYNAMICS

Mass and Relativity

Perhaps the most far-reaching consequence of Einstein's theory of relativity was the discovery that mass, like time and distance, is relative to one's frame of reference. So far we have been faced with two strange ideas:

1. Clocks run fastest for stationary objects, whereas moving clocks slow down. As we observe a clock that approaches the speed of light, the clock appears to slow down and stop.
2. Distances are greatest for stationary objects; moving objects shrink in the direction of motion. As we observe an object that approaches the speed of light, the length of that object appears to shrink and approach zero.

Einstein showed that a third consequence followed from his principle:

3. Mass is lowest for stationary objects; moving objects become more massive. As we observe an object that approaches the speed of light, its mass appears to increase and approach infinity.

Einstein showed that if the speed of light is a constant in all reference frames—which must follow from the central assumption of the theory of relativity—then an object's mass depends on its velocity. The faster an object travels, the greater its mass and the harder it is to deflect from its course. If a ground-based observer measures an object's stationary or rest mass, m_{GG}, then the apparent mass, m_{MG}, of that object moving at velocity v is

$$m_{MG} = \frac{m_{GG}}{\sqrt{1 - \left(\frac{v}{c}\right)^2}}$$

Once again the Lorentz factor comes into play. As we observe an object approach the speed of light, its mass appears to us to approach infinity.

Mass and Energy

Time, distance, and mass—all quantities that we can easily measure in our homes or laboratories—actually depend on our frame of reference. But not everything in nature is so variable. The central tenet of relativity is that natural laws must apply in every frame of reference. Light speed is constant in all reference frames in accord with Maxwell's equations. Similarly, the first law of thermodynamics—the idea that the total amount of energy in any closed system is constant—must hold, no matter what the frame of reference. Yet here, Einstein's description of the universe seems to run into a problem. He claims that the observed mass depends on your frame of reference. But, in that case, kinetic energy—defined as mass times velocity squared—could not follow the conservation of energy law. In Einstein's treatment, faster frames of reference seem to possess more energy than slower ones. Where does the extra energy come from?

Conservation of energy appears to be violated because we have missed one key form of energy in our equations: mass itself. In fact, Einstein was able to show that the amount of energy contained in any mass turns out to be the mass times a constant.

1. In words:

All objects contain a rest energy (in addition to any kinetic or potential energy), which is equal to the object's rest mass times the speed of light squared.

2. In an equation with words:

$$\text{Rest energy} = \text{Rest mass} \times (\text{Speed of light})^2$$

3. In an equation with symbols

$$E = mc^2$$

This familiar equation has become an icon of our modern age because it defines a new form of energy. It says that mass can be converted to energy, and vice versa. Furthermore, the amounts of energy involved are prodigious (because the constant, the speed of light squared, is so large). A handful of nuclear fuel can power a city; a fist-sized chunk of nuclear explosive can destroy it.

Until Einstein traced the implications of special relativity, the nature of mass and its vast potential for producing energy was hidden from us. Now more than 10% of all electric power in the United States is produced in nuclear reactors that confirm the predictions of Einstein's theory every day of our lives (see Chapter 26).

GENERAL RELATIVITY

Special relativity is a fascinating and fairly accessible intellectual exercise, requiring little more than an open mind and a lot of basic algebra. General relativity, which deals with all reference frames, including accelerating ones, is much more challenging in its full rigor. While the details are tricky, you can get a pretty good feeling for Einstein's general theory by thinking about the nature of forces.

The Nature of Forces

Begin by imagining yourself in a completely sealed spaceship far from the reaches of gravity that is accelerating at exactly 1 g—Earth's gravitational acceleration. Could you devise any experiment that would reveal one way or the other if you were on Earth or accelerating in deep space?

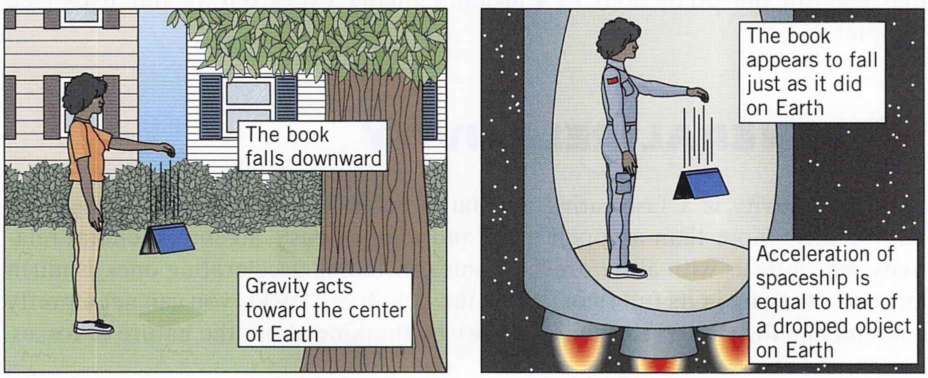
If you dropped this book on Earth, the force of gravity would cause it to fall to your feet (Figure 28-6*a*). However, if you dropped the book in the accelerating spaceship, then Newton's first law tells us that it will keep moving with whatever speed it had when it was released. The floor of the ship, still accelerating, will therefore come up to meet it (Figure 28-6*b*). To you, standing in the ship, it appears that the book falls, just as it does if you are standing on Earth.

From an external frame of reference these two situations would involve very different descriptions. In the first case, the book falls due to the force of gravity; in the second, the spaceship accelerates up to meet the free-floating book. But no experiment you could devise in your reference frame could distinguish between acceleration in deep space and the force of Earth's gravitational field.

In some deep and profound way, therefore, gravitational forces and acceleration are equivalent. Einstein went a step further by recognizing that calling something "gravity" versus calling it "acceleration" is a purely arbitrary decision, based on our choice of reference frame. Whether we think of ourselves as stationary on a planet with gravity or accelerating on spaceship Earth makes no difference in the passage of events. This idea is often called the "principle of equivalence:" observations made in a gravitational field can be duplicated exactly in an appropriately accelerated reference frame, far from the reaches of gravity.

Although this connection between gravity and acceleration may seem a bit abstract, you already have had experiences that should tell you it is true. Have you ever been in an elevator and felt momentarily heavier when it starts up or momentarily lighter when it starts down? If so, you know that the feeling we call "weight" can indeed be affected by acceleration.

The actual working out of the consequences of the equivalence of acceleration and gravity is complicated, but a simple analogy can help you visualize the difference between Einstein's and Newton's views of the universe. In the Newtonian universe, forces and motions can be described by a ball rolling on a perfectly flat surface with neatly inscribed grid lines. The ball rolls on and on, following a line exactly, unless an external force is applied. If, for example, a large



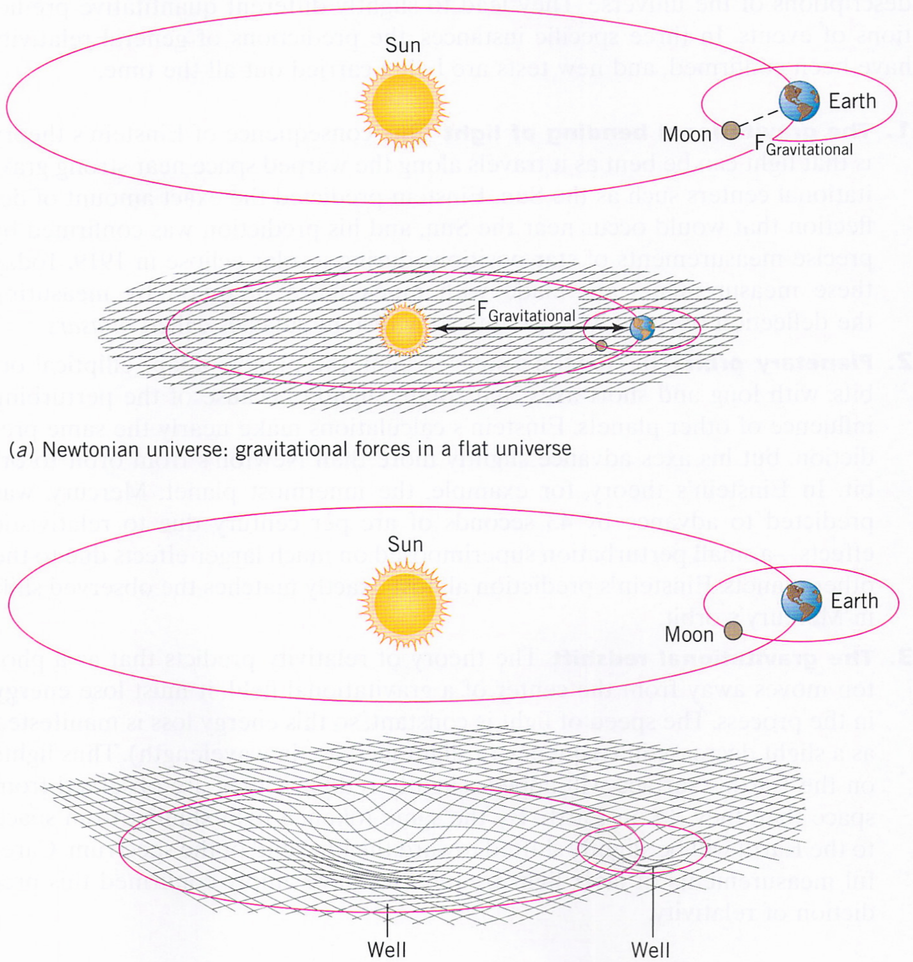
(*a*) On Earth (*b*) In an accelerating spaceship

FIGURE 28-6. (*a*) If you drop a book at Earth's surface, the force of gravity causes it to fall. (*b*) However, if you drop the same book in an accelerating spaceship, it will keep moving with whatever speed it had when it was released, as the floor of the accelerating ship comes up to meet it. Standing in the ship, it appears that the book falls, just as it does on Earth.

mass rests on the surface, the rolling ball changes its direction and speed—it accelerates in response to the force of gravity. Thus, for Newton, motion occurs along curving paths in a flat universe. This is shown by the example of Earth revolving around the Sun in Figure 28-7*a*.

The description of that same event in general relativity is very different. In this case, we say that the heavy object distorts the surface. Peaks and depressions on the surface influence the ball's path, deflecting it as it rolls across the surface. For Einstein, the ball moves in a straight line across a curved universe. This is shown by the example of the Earth–Sun system in Figure 28-7*b*.

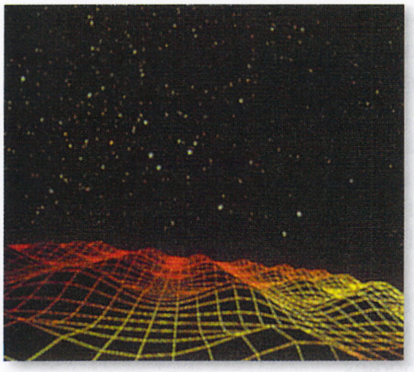
Given these differing views, Newton and Einstein would give very different descriptions of physical events. For example, Newton would say that the Moon orbits Earth because of an attractive gravitational force between the two bodies (Figure 28-7*a*). Einstein, on the other hand, would say that space has been warped



(*a*) Newtonian universe: gravitational forces in a flat universe

(*b*) Einstein's universe: motion in a curved universe.

FIGURE 28-7. Newtonian and Einsteinian universes treat the motion of planets in orbit in different ways. In the Newtonian scheme (*a*), a planet travels in uniform motion along curved paths in a flat universe. In the Einsteinian universe (*b*), a planet's mass distorts the universe; it moves in a straight line across a curved surface.



A computer-generated image of a gravity field. A mass distorts an otherwise flat grid to form depressions or "gravity wells."

in the vicinity of the Earth–Moon system and this warping of space governs the Moon's motion (Figure 28-7*b*). In the relativistic view, space deforms around the Sun, and planets follow the curvature of space like marbles rolling around in the bottom of a curved bowl.

We now have two very different ways of thinking about the universe. In the Newtonian universe, forces cause objects to accelerate. Space and time are separate dimensions that are experienced in very different ways. This view more closely matches our everyday experience of how the world seems to be. In Einstein's universe, objects move according to distortions in space, and the distinction between space and time depends on your frame of reference.

Predictions of General Relativity

The mathematical models of Newton and Einstein are not just two equivalent descriptions of the universe. They lead to slightly different quantitative predictions of events. In three specific instances, the predictions of general relativity have been confirmed, and new tests are being carried out all the time.

1. **The gravitational bending of light** One consequence of Einstein's theory is that light can be bent as it travels along the warped space near strong gravitational centers such as the Sun. Einstein predicted the exact amount of deflection that would occur near the Sun, and his prediction was confirmed by precise measurements of star positions during a solar eclipse in 1919. Today these measurements are made with much more precision by measuring the deflection of radio waves emitted by distant galaxies called *quasars*.
2. **Planetary orbits** In Newton's solar system, the planets adopt elliptical orbits, with long and short axes that rotate slightly because of the perturbing influence of other planets. Einstein's calculations make nearly the same prediction, but his axes advance slightly more than Newton's from orbit to orbit. In Einstein's theory, for example, the innermost planet, Mercury, was predicted to advance by 43 seconds of arc per century due to relativistic effects—a small perturbation superimposed on much larger effects due to the other planets. Einstein's prediction almost exactly matches the observed shift in Mercury's orbit.
3. **The gravitational redshift** The theory of relativity predicts that as a photon moves away from the center of a gravitational field, it must lose energy in the process. The speed of light is constant, so this energy loss is manifested as a slight decrease in frequency (a slight increase in wavelength). Thus lights on the Earth's surface will appear slightly redder if they are observed from space than they do on Earth. By the same token, a light shining from space to the Earth will be slightly shifted toward the blue end of the spectrum. Careful measurements of laser light frequencies have amply confirmed this prediction of relativity.

Connection

Black Holes

According to general relativity, light can be bent toward a large mass by its gravitational attraction. Suppose light approaches an extremely large mass, with a very powerful gravitational field. Would it be possible for the light to be trapped within the gravitational field so it can't escape? What would such an object look like?

One of the most surprising predictions of general relativity is that objects of extremely strong gravitational attraction can, in fact, occur. Astronomers call such objects "black holes" because they are so dense, so concentrated, that nothing, not even light, can escape from them.

Theorists have talked about three different kinds of black holes—galactic, stellar, and quantum. Observations of the motion of stars and gases near the centers of galaxies have confirmed that most galaxies (including our own Milky Way) have huge black holes at their centers—objects with masses a million times or more the mass of the sun. These are galactic black holes. Recent observations have supplied strong circumstantial evidence for such an object (Figure 28-8).

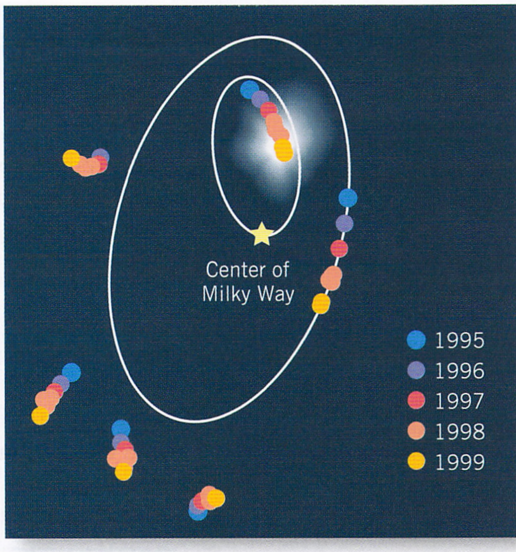


FIGURE 28-8. Stars near the center of our galaxy are observed to orbit rapidly around an exceptionally massive, yet unseen, object. Astronomers suspect that this object is a black hole 3 million times the mass of the Sun.

According to present-day theories of astronomy, a large star—some 30 times as massive as the Sun—can collapse into a black hole after all its nuclear fuel has been used up. These are stellar black holes. The problem with confirming this theory is that since light can't escape from a black hole, you can't see it. The only way to detect a black hole is to find one that is attracting a large amount of material into itself. This process would release such a tremendous amount of energy that it would be visible in the X-ray and gamma-ray parts of the electromagnetic spectrum. There are several candidates for stellar black holes whose X-ray emissions seem to match those predicted.

Some of the unified field theories discussed in Chapter 27 predict the existence of black holes whose dimensions are much smaller than those of an elementary particle. At the moment, these quantum black holes remain in the realm of theoretical speculation. ●

Recent advances in highly sensitive electronics are now providing more opportunities for researchers to measure the predictions of general relativity. One of the most intriguing tests will be conducted as part of a satellite mission in the near future. Meticulously machined quartz spheres will be set into rotation and carefully measured. According to general relativity, these spheres should develop a small wobble as they rotate in Earth's gravitational field. Sensitive electronics will detect any perturbations of this sort.

As scientists get better and better at making precision measurements, more and more tests of the extremely small differences between Newtonian and relativistic predictions of physical events can be made. A few years ago, for example, a group of scientists at institutions in the Washington, D.C. area proposed an experiment in which light from a laser would be sent out over the city from the University of Maryland, reflected from a mirror on top of the National Cathedral, and received by detectors at the Naval Research Laboratory. Because of the rotation of Earth, there should be a tiny difference in travel time between light traveling east and light traveling west. The theory of relativity predicts an additional, tinier difference as well. With good enough clocks and short enough laser pulses, these sorts of differences can be measured, and they provide just as good a check on general relativity as instruments in a satellite. This experiment, and many others like it, all deliver the same verdict: whenever our experimental techniques are good enough to test the predictions of general relativity, the theory is confirmed.

Develop Your Intuition: The Global Positioning System

We briefly described the Global Positioning System (GPS) in Chapter 5. The system consists of 24 satellites in orbit around Earth at distances of about 27,000 km from Earth's center, whizzing along at speeds of about 3.9 km/s. The system is designed to provide locations on Earth that are accurate to within 2 meters. Is the theory of relativity significant for the GPS?

The GPS works by sending radio signals from two or more satellites to the receiver on Earth. The accuracy we're looking for in distance requires an accuracy in time of about 6 nanoseconds (ns). This makes the time corrections due to relativity very important. We won't work out the details here, but it turns out that the correction factor due to time dilation is about 0.08 ns and the correction factor due to the gravitational redshift is about 0.16 ns. If corrections such as these were not taken into account by the system, the accumulated errors would exceed the required accuracy in less than 1 minute.

Physics in the Making

Who Can Understand Relativity?

Einstein's theory of relativity is extraordinary. When first introduced, the theory was difficult to grasp, in part because it relied on some complex mathematics that were unfamiliar to many physicists at the time. Furthermore, while the theory made specific predictions about the physical world, most of those predictions were exceedingly difficult to test. Soon after the theory's publication, it became conventional wisdom that only a handful of geniuses in the world could understand it.

One of those who did understand both the theory and its significance was Arthur Eddington, one of the leading physicists and astronomers of the time. The story is told that after a meeting of the Royal Society, Eddington was approached by a member, who said, "Well! Professor Eddington, you must be one of the three people in the world who understand relativity." Eddington looked puzzled and said, "Oh, I don't know . . ." The member continued, "Come, Professor Eddington, don't be modest." And Eddington replied, "On the contrary! I am wondering who the third person might be."

Einstein did make one very specific prediction, however, that could be tested. His proposal that the strong gravitational field of the Sun would bend the light coming from a distant star was different from other theories. The total eclipse of the Sun in 1919, just after the end of the First World War, gave scientists the chance to test Einstein's prediction. Eddington himself led a British expedition to observe the eclipse and, sure enough, the apparent position of stars near the Sun's disk was shifted by exactly the predicted amount.

Around the world, front-page newspaper headlines trumpeted Einstein's success. He became an instant international celebrity and his theory of relativity became a part of scientific folklore. Attempts to explain the revolutionary theory to a wide audience began almost immediately.

Few scientists may have grasped the main ideas of general relativity in 1915, when the full theory was first unveiled, but that certainly is not true today. The basics of special relativity are taught to tens of thousands of college freshmen every year, while hundreds of students in astronomy and physics explore general relativity in its full mathematical splendor.

If this subject intrigues you, you might want to read some more, watch TV specials or videos about relativity, or even sign up for one of those courses! ●

THINKING MORE ABOUT

Relativity: Was Newton Wrong?

The theory of relativity describes a universe about which Isaac Newton never dreamed. Time dilation, contraction of moving objects, and mass as energy play no role in his laws of motion. Curved space-time is alien to the Newtonian view. Does that mean that Newton was wrong? Not at all.

In fact, all of Einstein's equations reduce exactly to Newton's laws of motion, at speeds significantly less than the speed of light. This feature was shown specifically for time dilation in Looking Deeper: The Size of Time Dilation on page 609. Newton's laws, which have worked so well in describing our everyday world, fail only when dealing with extremely high velocities or extremely large masses. Astronomers must work with relativity theory routinely to explain their observations of stars and galaxies, which have large mass and move at extremely high speed. Such conditions do not apply to most activities on Earth. Thus Newton's laws represent an extremely important special case of Einstein's more general theory.

Science often progresses in this way, with one theory encompassing previous valid ideas. For example, Newton merged Galileo's discoveries about Earth-based motions and Kepler's laws of planetary motion into his unified theory of gravity. Someday, Einstein's theory of relativity may be incorporated into an even grander view of the universe.

Some modern philosophers have argued that because scientific ideas change over time, they are nothing more than social conventions with no grounding in any external reality. In an extreme version of this view, what we have called *laws of nature* have little more meaning than the agreement that a red traffic light means "stop." How would you answer this argument? (*Hint:* You might want to compare the change in science that occurred when the Copernican system replaced its predecessors to the relation between Einstein and Newton.)

Summary

Every observer sees the world from a different **frame of reference.** Descriptions of actual physical events are different for different observers, but the **theory of relativity** states that all observers must see the universe operating according to the same laws. Because the speed of light is built into Maxwell's equations, this principle requires that all observers must measure the same speed of light in their frames of reference.

Special relativity deals with observers who are not accelerating with respect to one another, while **general relativity** deals with observers in any frame of reference whatsoever. In special relativity, simple arguments lead to the conclusion that moving clocks appear to tick more slowly than stationary ones—a phenomenon known as **time dilation.** Furthermore, moving objects appear to get shorter in the direction of motion—the phenomenon of **length contraction.** Finally, moving objects become more massive than stationary ones, and an equivalence exists between mass and energy, as expressed by the famous equation $E = mc^2$.

General relativity begins with the observation that the force of gravity is equivalent to acceleration and describes a universe in which heavy masses warp the fabric of space–time and affect the motion of other objects. There are three classic tests of general relativity—the bending of light rays passing near the Sun, the changing orientation of the orbit of Mercury, and the redshift of light passing through a gravitational field.

Key Terms

frame of reference A set of physical surroundings from which events are observed and measured. (p. 604)

general relativity The part of relativity theory that deals with accelerated reference frames and gravity. (p. 606)

length contraction The observed shortening of an object that is moving with respect to the observer. (p. 612)

principle of relativity The principle that states that the laws of physics are the same in all frames of reference. (p. 605)

special relativity The part of relativity theory that deals with events in reference frames moving uniformly. (p. 606)

theory of relativity The physical laws that govern the measurement of time and space as observed in differing reference frames. (p. 606)

time dilation The slowing of time relative to an observer in a different reference frame. (p. 608)

Key Equations

Time dilation: $t_{MG} = \dfrac{t_{GG}}{\sqrt{1 - \left(\dfrac{v}{c}\right)^2}}$

Length contraction: $L_{MG} = L_{GG} \times \sqrt{1 - \left(\dfrac{v}{c}\right)^2}$

Mass effect: $m_{MG} = \dfrac{m_{GG}}{\sqrt{1 - \left(\dfrac{v}{c}\right)^2}}$

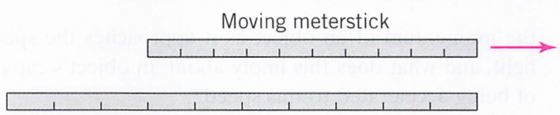
Rest mass: $E = mc^2$

Review

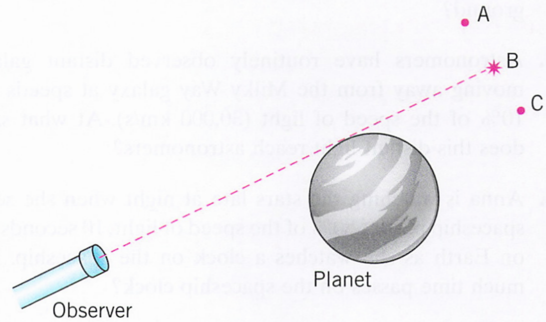
1. What is a frame of reference? What are some of the frames of reference that you have been in today?
2. What is the central idea of Einstein's theory of relativity?
3. Imagine arriving by spaceship at the solar system for the first time. Identify three different frames of reference that you might choose to describe Earth.
4. What is the difference between special and general relativity?
5. Does the speed of light depend at all on your frame of reference or on how fast the source of light is moving when it is emitted? Explain.
6. What is time dilation?
7. What are two examples of time dilation in the real world?
8. How might it be possible for a child to be older than its parent?
9. How fast does something have to be moving for time dilation to be appreciable? Why don't we normally notice this effect?
10. What is the Lorentz factor? When is it most commonly used?
11. According to an observer on the ground, how does the length of a moving object along the line of motion appear compared to the length of an identical object on the ground? How about the height and width of the same object?
12. Is the length of contraction simply an optical illusion? How do we know this?
13. An observer on the ground sees a fast-moving object above him. How does the mass of this object compare to the mass of an identical object at rest on the ground?
14. Does relativity allow anything to travel faster than the speed of light? Explain.
15. What is the relation between the mass of an object and its energy?
16. Which has greater mass, a flexed bow pulled back as if ready to shoot an arrow, or the same bow unflexed with the same string loosely attached?
17. How can we say that gravitational forces and acceleration are equivalent?
18. How is the warping of space around a massive object an equivalent but different description of the gravitational force generated by that object?
19. What is the difference between a curved and a flat universe?
20. Did Einstein disprove Newton's laws of motion? Explain.
21. What are the three specific predictions of general relativity that have been confirmed? In each case, what would Newton have predicted that differs from the general relativity prediction?

Questions

1. For each of the following situations, specify whether you are in a uniformly moving reference frame or an accelerated reference frame.
   a. You are standing still on the surface of Earth.
   b. You are floating deep in space, far from the effects of gravity.
   c. You are in your car, slowing down to make a stop.
2. Imagine taking a ride on a perfectly quiet train that rides on perfectly smooth and straight tracks. If the train is moving at a constant speed and you throw a ball straight up, will it appear to you that it falls straight back down? What if the train is accelerating forward?
3. You are riding on a flatbed truck moving at 50 kilometers per hour. You have two identical guns, one aimed forward and one aimed backward, and you fire them at the same time. According to an observer on the ground, which bullet is moving faster? According to an observer on the truck, which bullet is moving faster?
4. You are riding on a flatbed truck moving at 100 kilometers per hour. You have two identical lasers, one aimed forward and one aimed backward. According to an observer on the ground, which laser light moves faster? According to an observer on the truck, which laser light moves faster?
5. A meterstick moves by at a very high rate of speed. As it flies by, you measure it with an identical meterstick and find that its length is only 70 cm, as shown in the figure. According to you, are the masses of the metersticks the same or different? If different, which one is more massive?



6. You and a friend buy two identical watches. Some days later you see your friend traveling relative to you at 25% of the speed of light. Is your friend's watch running faster or slower than your watch? Does your friend agree with you? Explain.
7. You take your pulse while sitting in your room and you measure 60 beats per second. All else being equal, what would your pulse measure if you took it while on a fast-moving train? Explain.
8. Does relativity theoretically allow you to go backward in time into the past?
9. In your own words, explain why no object traveling at less than the speed of light can be accelerated all the way to, or faster than, the speed of light.
10. As you ride in an elevator, when is the apparent acceleration greater than the acceleration due to gravity outside the elevator, on the surface of Earth? When is the apparent acceleration smaller? What does this experience tell you about acceleration and gravity?
11. If you are in a spaceship far from the reaches of gravity, under what conditions will it feel to you as if the spaceship were sitting stationary on Earth's surface?
12. As you look up into the sky, you see a planet and a star. The star appears to be at location B in the figure. Assume that the planet creates very strong gravity. Where is the star actually located: toward A, at B, or toward C?



13. Due to length contraction, you notice that a train passing by appears to be shorter than when it is stationary. What do the people on the train observe about you?
14. Why is it that we don't ordinarily notice the bending of light?
15. To an outside observer, would you appear to age faster on top of a mountain or at sea level? Explain.
16. You've decided to let your sister, a NASA astronaut, cook the Thanksgiving turkey this year. Normally the turkey takes 6 hours to cook, but your sister decides to cook it on her spaceship while traveling at close to the speed of light. According to your watch, she was gone for 6 hours. Is the turkey overcooked, undercooked, or just right? Explain.
17. Because of relative motion, you notice a friend's clock running slowly. How does your friend view your clock?
18. Someone shines a light while moving toward you at 1000 m/s. With what speed will the light strike you? (The speed of light is 300,000,000 m/s.)
19. If you can do 20 pushups on the surface of Earth, how many can you do in a spaceship, far from gravity, accelerating at g?
20. You are jealous of your younger brother, who looks very young for his age. You are interested in reducing the rate at which you age relative to him. Having heard of general relativity and the effect of gravity on time, you decide that you need to spend more time at an altitude that makes you age more slowly relative to your brother. Given the choice, would you work as a park ranger high in the mountains, or as a taxi cab driver at sea level? (Take into account the effects of gravity only.) Explain your reasoning.

Problems

1. While running at 10 mph directly toward Patrick, Lisa passes a basketball to him. Patrick is stationary when he receives the ball, which is moving at a speed of 35 mph. How fast did Lisa throw the ball?

2. Giselle is traveling on her bicycle at a speed of 10 mph when a car passes her. From her frame of reference, she estimates that the car is going 45 mph toward her and 45 mph away from her. What is the speed of the car from the frame of reference of someone standing on the ground?

3. Astronomers have routinely observed distant galaxies moving away from the Milky Way galaxy at speeds over 10% of the speed of light (30,000 km/s). At what speed does this distant light reach astronomers?

4. Anna is watching the stars late at night when she sees a spaceship pass at 80% of the speed of light; 10 seconds pass on Earth as she watches a clock on the spaceship. How much time passes on the spaceship clock?

5. Elliott is traveling by a building at 150,000 km/s, moving along the width of the building. Elliott measures the building to be 50 m wide and 100 m tall. What is the height and width of the building as measured by a person standing at rest next to the building?

6. An interplanetary spaceship has windows that are 3 meters wide. How fast must it pass by a planet so that an observer on that planet measures the width of the windows to be 1.5 meters?

7. You are traveling 80 km/h and you throw a ball 40 km/h with respect to yourself. What is the ball's apparent speed to a person standing by the road when the ball is thrown in each of the following ways?
   a. Straight ahead
   b. Sideways
   c. Backward

8. Calculate the Lorentz factor for objects traveling at 1%, 50%, and 99.9% of the speed of light.

9. What is the apparent mass of a 1-kg object that has been accelerated to 99% of light speed?

10. If a moving clock appears to be ticking one-half as fast as normal, at what percentage of light speed is it traveling?

11. Draw a picture illustrating how a spaceship passing Earth might look at 1%, 90%, and 99.9% of light speed.

12. If you were able to extract 100% of the energy available in 1 kilogram of hydrogen, how much energy would you have? How much energy would be available from 1 kilogram of uranium if the same 100% efficiency were attained in this extraction?

Investigations

1. Read a biography of Albert Einstein. What were his major scientific contributions? For what work did he receive the Nobel Prize?

2. Take a bathroom scale into an elevator in a tall building, stand on it, and record your weight under acceleration and deceleration. Why does the scale reading change?

3. In Chapter 6 we discussed the concept of momentum, where $p = mv$. How did Einstein redefine momentum with yet another application of the Lorentz factor? What happens to the momentum of an object as it approaches the speed of light, and what does this imply about an object's capability of being accelerated to this speed?

4. Read the novel *Einstein's Dreams* by Alan Lightman. Each of the chapters explores different time–space relationships. Which chapters teach you something about Einstein's theory of relativity?

5. Investigate the influence of Einstein's theory of relativity on twentieth-century art and philosophy.

WWW Resources

See the *Physics Matters* home page at **www.wiley.com/college/trefil** for valuable web links.

1. **http://www.aip.org/history/einstein/** The online exhibit *Albert Einstein: Image and Impact* by the American Institute of Physics.

2. **http://www.learner.org/vod/index.html?sid=42&pid=611&po=42** *The Lorentz Transformations,* a thirty-minute streamed video program from the CPB-Annenberg series *The Mechanical Universe.* Cable modem or faster connection and free registration required.

3. **http://www.learner.org/vod/index.html?sid=42&pid=613&po=43** *Velocity and Time,* a thirty-minute streamed video program from the CPB-Annenberg series *The Mechanical Universe.* Cable modem or faster connection and free registration required.
4. **http://www.walter-fendt.de/ph11e/timedilation.htm** A time dilation Java applet simulation by Walter Fendt.
5. **http://www.mira.org/fts0/s_system/161/text/txt001z.htm** A site on gravitational lenses from the Monterey Institute of research in Astronomy.
6. **http://www.curtin.edu.au/curtin/dept/phys-sci/gravity/index2.htm** The Exploring Gravity tutorial site from Australia's Curtin University of Technology.