CHAPTER 1

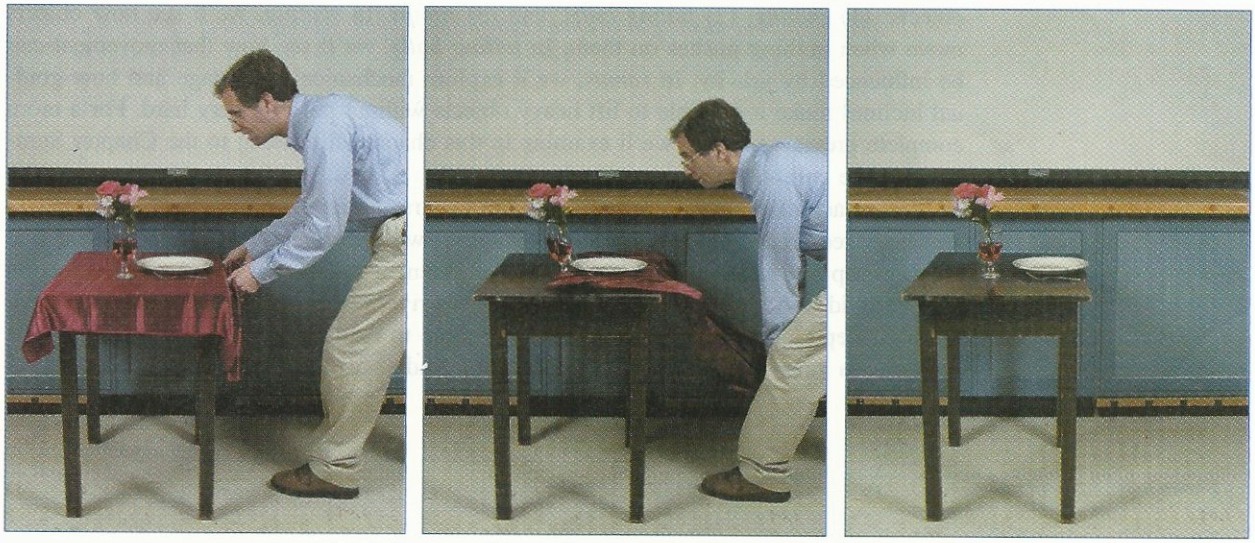
The Laws of Motion Part 1

The purpose of this book is to broaden your perspectives on familiar objects and situations by helping you understand the physical processes that make them work. Although science is part of our daily existence—not some special activity we do only occasionally, if at all—most of us ignore it or take it for granted. In this book we'll counter that tendency by seeking out science in the world around us, in the objects we encounter every day. We'll see that seemingly "magical" objects and effects are really very straightforward once we know a few of the physical concepts that make them possible. In short, we'll learn about *physics*—the study of the material world and the rules that govern its behavior.

To help us get started, this first pair of chapters will do two main things: introduce the language of physics, which we'll be using throughout the book, and present the basic laws of motion on which everything else will rest. In later chapters, we'll explore objects that are interesting and important, both in their own right and because of the scientific issues they raise. Most of these objects, as we'll see, involve many different aspects of physics and thus bring variety to each section and chapter. These first two chapters are special, though, because they must provide an orderly introduction to the discipline of physics itself.

EXPERIMENT: Removing a Tablecloth from a Table

One famous "magical" effect is the feat of removing a tablecloth from a set table without breaking the dishes on top. The person performing this stunt pulls the tablecloth out from under the place settings in one lightning-swift motion. With a little luck—not



Courtesy Lou Bloomfield

to mention a smooth, slippery tablecloth—the covering slides off the table suddenly, leaving the dishes behind and virtually unaffected.

With a little practice, you too can do this stunt. Choose a slick, unhemmed tablecloth, one with no flaws that might catch on the dishes. A soft, flexible material such as silk helps because you can then pull the cloth downward and over the edge of the table. When you finally get up the nerve to try this stunt—with unbreakable dishes, of course—make sure you pull as abruptly as possible, keeping the time you spend moving the cloth out from under the dishes to an absolute minimum. It helps to hold the cloth with your palms downward and to let the cloth hang loosely between each hand and the table so that you can get your hands moving before the cloth snaps taut and begins to slide off the table. Don't make the mistake of starting slowly or you'll be picking up pieces.

What will happen when you pull the cloth? How far will the dishes move—or will they not move at all? How important is the speed with which you pull the cloth? How does the weight of each dish affect its movement or lack of movement? Is the surface texture of each dish important? How would rubbing each dish with wax paper alter the results?

Give the tablecloth a pull and watch what happens. Hopefully, the table will remain set. If it doesn't, try again, but this time increase the tablecloth's speed or change the types of dishes or the way you pull the cloth.

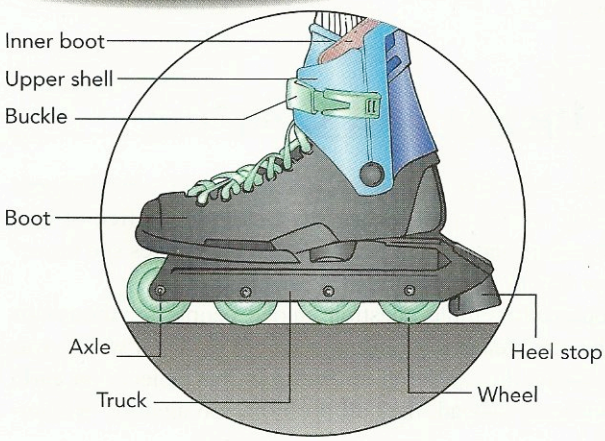
If you don't have a suitable tablecloth, or any dishes you care to risk, there are many similar experiments you can try. Put several coins on a sheet of paper and whisk that sheet out from under them. Or stack several books on a table and use a stiff ruler to knock out the bottom one. Most impressive of all is to balance a short eraserless pencil on top of a wooden needlepoint ring that is itself balanced on the open mouth of a glass bottle. If you yank the ring away quickly enough, the pencil will be left behind and will drop right into the bottle.

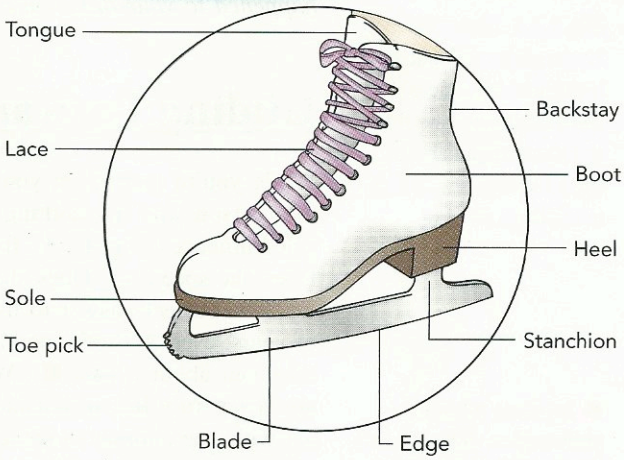
We'll return to the tablecloth stunt at the end of this chapter. In the meantime, we'll explore some of the physics concepts that help explain why your stunt worked—or, if it didn't, why the floor is now covered with dishes.

Chapter Itinerary

To examine these concepts, we'll look carefully at three kinds of everyday activities and objects: (1) *skating*, (2) *falling balls*, and (3) *ramps*. In *skating*, we'll see how objects move when nothing pushes on them. In *falling balls*, we'll see how that movement can be influenced by gravity. In *ramps*, we'll explore mechanical advantage and how gradual inclines make it possible to lift heavy objects without pushing very hard. For a more complete preview of what we'll examine in this chapter, flip ahead to the Chapter Summary at the end of the chapter.

These activities may seem mundane, but understanding them in terms of basic physical laws requires considerable thought. These two introductory chapters will be like climbing up the edge of a high plateau: the ascent won't be easy, and our destination will be hidden from view. However, once we arrive at the top, with the language and basic concepts of physics in place, we'll be able to explain a broad variety of objects with only a small amount of additional effort. And so we begin the ascent.

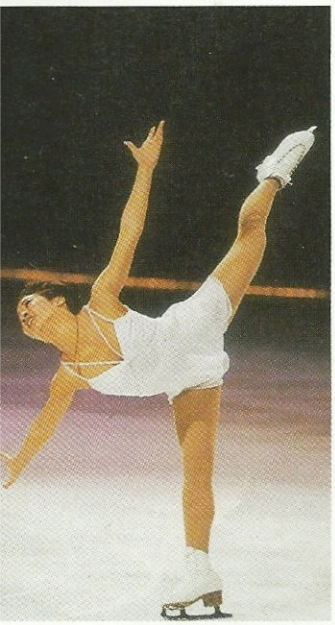




SECTION 1.1 Skating

Like many sports, skating is trickier than it appears. If you're a first-time skater, you'll likely find yourself getting up repeatedly from the ground or ice, and it will take some practice before you can glide smoothly forward or come gracefully to a stop. Whether you're wearing ice skates or Rollerblades, though, the physics of your motion is surprisingly simple. When you're on a level surface with your skates pointing forward, you coast!

Coasting is one of the most basic concepts in physics, and it is our starting point in this book. Joining it in this section will be starting, stopping, and turning, which together will help us understand the first few laws of motion. We'll leave sloping surfaces for the section on ramps and won't have time to teach you how to do spins or win a race. Nonetheless, our exploration of skating will get us well on the way to an understanding



Chris Trotman/Duomo Photography, Inc

Fig. 1.1.1 Skater Michelle Kwan glides without any horizontal influences. If she's stationary, she'll tend to remain stationary; if she's moving, she'll tend to continue moving.

of the fundamental principles that govern all movement and thereby prepare us for many of the objects we'll examine in the rest of this book.

Questions to Think About: *What do we mean by "movement"? What makes skaters move and, once they're moving, what keeps them in motion? What does it take to stop a moving skater or turn that skater in another direction?*

Experiments to Do: *An hour or two on the ice or roller rink would be ideal, but if you don't have skates then try a skateboard or a chair with wheels. Get yourself moving forward on a level surface and then let yourself coast. What's propelling you forward? Are you being pushed forward by anything? Does your direction ever reverse as you coast? How would you describe where you are at a given moment? How would you measure your speed?*

Before you run into a wall or tree, slow yourself to a stop. What was it that slowed you down? Were you still coasting as you stopped? Did anything push on you as you slowed yourself?

Get yourself moving again. What caused you to speed up? How quickly can you pick up speed, and what do you do differently to speed up quickly? Now turn to one side or the other. Did anything push on you as you turned? What happened to your speed? What happened to your direction of travel?

Gliding Forward: Inertia and Coasting

While you're putting on your skates, let's take a moment to think about what happens to a person who has nothing pushing on her at all. When she's completely free of outside influences (Fig. 1.1.1), free of pushes and pulls, does she stand still? Does she move? Does she speed up? Does she slow down? In short, what does she do?

The correct answer to that apparently simple question eluded people for thousands of years; even Aristotle, perhaps the most learned philosopher of the classical world, was mistaken about it (see ■). What makes this question so tricky is that objects on earth are never truly free of outside influences; instead, they all push on, rub against, or interact with one another in some way.

■ Aristotle (Greek philosopher, 384–322 BC) theorized that objects' velocities were proportional to the forces exerted on them. While this theory correctly predicted the behavior of a sliding object, it incorrectly predicted that heavier objects should fall faster than lighter objects. Nonetheless, Aristotle's theory was respected for a long time, in part because finding the simpler and more complete theory was hard and in part because the scientific method of relating theory and observation took time to develop.

As a result, it took the remarkable Italian astronomer, mathematician, and physicist Galileo Galilei many years of careful observation and logical analysis to answer that question ■. The solution he came up with, like the question itself, is simple: if the person is stationary, she will remain stationary; if she is moving in some particular direction, she will continue moving in that direction at a steady pace, following a straight-line path. This property of steady motion in the absence of any outside influence is called **inertia**.

> **Inertia**
> A body in motion tends to remain in motion; a body at rest tends to remain at rest.

The main reason why Aristotle failed to discover inertia, and why we often overlook inertia ourselves, is friction. When you slide across the floor in your shoes, friction

quickly slows you to a stop and masks your inertia. To make inertia more obvious, we must get rid of friction. That's why you're wearing skates.

Skates almost completely eliminate friction, at least in one direction, so that you can glide effortlessly across the ice or roller rink and experience your own inertia. For simplicity, imagine that your skates are perfect and experience no friction at all as you glide. Also, for this and the next couple of sections, let's forget not only about friction but also about air resistance. Since the air is calm and you're not moving too fast, air resistance isn't all that important to skating anyway.

Now that you're ready to skate, we'll begin to examine five important physical quantities relating to motion and look at their relationships to one another. These quantities are position, velocity, mass, acceleration, and force.

Let's start by describing where you are. At any particular moment, you're located at a **position**—that is, at a specific point in space. Whenever we report your position, it's always as a **distance** and **direction** from some reference point: how many meters north of the refreshment stand or how many kilometers west of Cleveland.

Position is an example of a vector quantity. A **vector quantity** consists of both a magnitude and a direction; the **magnitude** tells you how much of the quantity there is, while the direction tells you which way the quantity is pointing. Vector quantities are common in nature. When you encounter one, pay attention to the direction part; if you're looking for buried treasure 30 paces from the old tree but forget that it's due east of that tree, you'll have a lot of digging ahead of you.

You're on your feet and beginning to skate. If you're moving, then your position is changing. In other words, you have a velocity. **Velocity** measures how quickly your position changes; it's our second vector quantity and consists of the speed at which you're moving and the direction in which you're heading. Your **speed** is the distance you travel in a certain amount of time,

$$\text{speed} = \frac{\text{distance}}{\text{time}},$$

and the direction you're heading might be east, north, or down—if you're taking a spill.

When you're gliding freely, however, with nothing pushing you horizontally, your velocity is particularly easy to describe. Since you travel at a steady pace along a straight-line path, your velocity never changes—it is constant. For example, if you're heading west at a speed of 10 meters-per-second (33 feet-per-second), you will have that same velocity indefinitely. A speed of 10 meters-per-second means that, if you travel for 1 second at your present speed, you'll cover a distance of 10 meters. Since your velocity is constant, you'll travel 100 meters in 10 seconds, 1000 meters in 100 seconds, and so on. Furthermore, the path you'll take is a straight line. In a word, you coast.

Thanks to your skates, we can now restate the previous description of inertia in terms of velocity: an object that is not subject to any outside influences moves at a constant velocity, covering equal distances in equal times along a straight-line path. This statement is frequently identified as **Newton's first law of motion**, after its discoverer, the English mathematician and physicist Sir Isaac Newton ■. The outside influences referred to in this law are called **forces**, a technical term for pushes and pulls.

Newton's First Law of Motion

An object that is not subject to any outside forces moves at a constant velocity, covering equal distances in equal times along a straight-line path.

■ While a professor in Pisa, Galileo Galilei (Italian scientist, 1564–1642) was obliged to teach the natural philosophy of Aristotle. Troubled with the conflict between Aristotle's theory and observations of the world around him, Galileo devised experiments that measured the speeds at which objects fall and determined that all falling objects fall at the same rate.

■ In 1664, while Sir Isaac Newton (English scientist and mathematician, 1642–1727) was a student at Cambridge University, the university was forced to close for 18 months because of the plague. Newton retreated to the country, where he discovered the laws of motion and gravitation and invented the mathematical basis of calculus. These discoveries, along with his observation that celestial objects such as the moon obey the same simple physical laws as terrestrial objects such as an apple (a new idea for the time), are recorded in his *Philosophiæ Naturalis Principia Mathematica*, first published in 1687. This book is perhaps the most important and influential scientific and mathematical work of all time.

Intuition Alert: Coasting

Intuition says that when nothing pushes on an object, that object slows to a stop; you must push it to keep it going.

Physics says that when nothing pushes on an object, that object coasts at constant velocity.

Resolution: Objects usually experience hidden forces, such as friction or air resistance, that tend to slow them down. Eliminating those hidden forces is difficult, so that you rarely see the full coasting behavior of force-free objects.

Check Your Understanding #1: A Puck on Ice

Why does a moving hockey puck continue to slide across an ice rink even though no one is pushing on it?

Answer: The puck coasts across the ice because it has inertia.

Why: A hockey puck resting on the surface of wet ice is almost completely free of horizontal influences. If someone pushes on the puck, so that it begins to travel with a horizontal velocity across the ice, inertia will ensure that the puck continues to slide at constant velocity.

The Alternative to Coasting: Acceleration

As you glide forward with nothing pushing you horizontally, what prevents your speed and direction from changing? The answer is your mass. **Mass** is the measure of your inertia, your resistance to changes in velocity. Almost everything in the universe has mass. Because you have mass, your velocity will change only if something pushes on you—that is, only if you experience a force. You'll keep moving steadily in a straight path until something exerts a force on you to stop you or send you in another direction. Force is our third vector quantity, having both a magnitude and a direction. After all, a push to the right is different from a push to the left.

When something pushes on you, your velocity changes; in other words, you accelerate. **Acceleration**, our fourth vector quantity, measures how quickly your velocity changes. *Any* change in your velocity is acceleration, whether you're speeding up, slowing down, or even turning. If either your speed or direction of travel is changing, you're accelerating!

Like any vector quantity, acceleration has a magnitude and a direction. To see how these two parts of acceleration work, imagine that you're at the starting line of a speed-skating race, waiting for it to begin. The starting buzzer sounds and you're off! You dig your skates into the surface beneath you and begin to accelerate—your speed increases and you cover ground more and more quickly. The magnitude of your acceleration depends on how hard the skating surface pushes you forward. If it's a long race and you're not in a hurry, you take your time getting up to full speed. The surface pushes you forward gently and the magnitude of your acceleration is small. Your velocity changes slowly. However, if the race is a sprint and you need to reach top speed as quickly as possible, you spring forward hard and the surface exerts an enormous forward force on you. The magnitude of your acceleration is large and your velocity changes rapidly. In this case, you can actually feel your inertia opposing your efforts to pick up speed.

Acceleration has more than just a *magnitude,* though. When you start the race, you also select a *direction* for your acceleration—the direction toward which your velocity is shifting with time. This acceleration is in the same direction as the force causing it. If you obtain a forward force from the surface, you'll accelerate forward—your velocity will shift more and more forward. If you obtain a sideways force from the surface, the other racers will have to jump out of your way as you careen into the wall. They'll laugh all the way to the finish line at your failure to recognize the importance of direction in the definitions of force and acceleration.

Once you're going fast enough, you can stop fighting inertia and begin to glide. You coast forward at a constant velocity. Now inertia is helping you; it keeps you moving steadily along even though nothing is pushing you forward. (Recall that we're neglecting friction and air resistance. In reality, those effects push you backward and gradually slow you down as you glide. However, since we're ignoring them in this section, your motion is smooth and steady.)

Even when you're not trying to speed up or slow down, you can still accelerate. As you steer your skates or go over a bump, you experience sideways or up–down forces that change your *direction of travel* and thus cause you to accelerate.

Finally, the race is over and you skid to a stop. You're accelerating again. This time you're accelerating backward, in the direction opposite your forward velocity. Although we often call this process *deceleration*, it's just a special type of acceleration. Your forward velocity gradually diminishes until you come to rest.

To help you recognize acceleration, here are some accelerating objects:

1. A runner who's leaping forward at the start of a race—the runner's velocity is changing from zero to forward so the runner is accelerating *forward.*
2. A bicycle that's stopping at a crosswalk—its velocity is changing from forward to zero so it's accelerating *backward* (that is, it's decelerating).
3. An elevator that's just starting upward from the first floor to the fifth floor—its velocity is changing from zero to upward so it's accelerating *upward.*
4. An elevator that's stopping at the fifth floor after coming from the first floor—its velocity is changing from upward to zero so it's accelerating *downward.*
5. A car that's beginning to shift left to pass another car—its velocity is changing from forward to left-forward so it's accelerating mostly *leftward.*
6. An airplane that's just beginning its descent—its velocity is changing from level-forward to descending-forward so it's accelerating almost directly *downward.*
7. Children riding a carousel around in a circle—while their speeds are constant, their directions of travel are always changing. We'll discuss the directions in which they're accelerating in Section 3.3.

Here are some objects that are *not* accelerating:

1. A parked car—its velocity is always zero.
2. A car traveling straight forward on a level road at a steady speed—there is no change in its speed or direction of travel.
3. A bicycle that's climbing up a smooth, straight hill at a steady speed—there is no change in its speed or direction of travel.
4. An elevator that's moving straight upward at a steady pace, halfway between the first floor and the fifth floor—there is no change in its speed or direction of travel.

Seeing acceleration isn't as easy as seeing velocity. You must watch skaters closely for some time to see whether or not they're accelerating. If their paths aren't straight or if their speeds aren't steady, then they're accelerating.

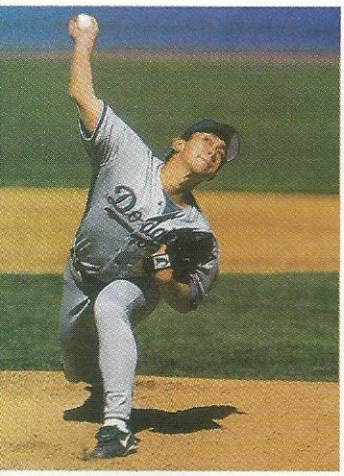
Check Your Understanding #2: Changing Trains

Trains spend much of their time coasting along at constant velocity. When does a train accelerate forward? Backward? Leftward? Downward?

Answer: The train accelerates forward when starting out from a station, backward when it arrives at the next station, to the left when it turns left, and downward when it begins its descent out of the mountains.

Why: Whenever the train changes its speed or its direction of travel, it is accelerating. When it speeds up on leaving a station, it is accelerating forward (more forward-directed speed). When it slows down at the next station, it is accelerating backward (more backward-directed speed or, equivalently, less forward-directed speed). When it turns left, it is accelerating to the left (more leftward-directed speed). When it begins to descend, it is accelerating downward (more downward-directed speed).

How Forces Affect Skaters



Jeff Christensen/Liaison Agency, Inc./Getty Images

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Fig. 1.1.2 A baseball accelerates easily because of its small mass. A bowling ball has a large mass and is harder to accelerate.

Your friends skate over to congratulate you after the race, patting you on the back and giving you high-fives. They're exerting forces on you, so you accelerate—but how much do you accelerate and in which direction?

First, although each of your friends is exerting a separate force on you, you can't accelerate in response to each force individually. After all, you only have one acceleration. Instead, you accelerate in response to the **net force** you experience—the sum of all the individual forces being exerted on you. Drawing this distinction between individual forces and net force is important whenever an object is experiencing several forces at once, and we'll return to it later in this section. For simplicity now, however, let's wait until you have only one friend left on the ice. When that friend finally pats you on the back, you experience only that one force, so it is the net force on you and it causes you to accelerate.

Your acceleration depends on the strength of that net force: the stronger the net force, the more you accelerate. However, your acceleration also depends on your mass: the more massive you are, the less you accelerate. For example, it's easier to change your velocity before you eat Thanksgiving dinner than afterward.

There is a simple relationship between the net force exerted on you, your mass, and your acceleration. Your acceleration is equal to the net force exerted on you divided by your mass or, as a word equation,

$$\text{acceleration} = \frac{\text{net force}}{\text{mass}}. \tag{1.1.1}$$

Your acceleration, as we've seen, is in the same direction as the net force on you.

This relationship was deduced by Newton from his observations of motion and is referred to as **Newton's second law of motion**. Structuring the relationship this way sensibly distinguishes the causes (net force and mass) from their effect (acceleration). However, it has become customary to rearrange this equation to eliminate the division. The relationship then takes its traditional form, which can be written in a word equation:

$$\text{net force} = \text{mass} \cdot \text{acceleration} \tag{1.1.2}$$

in symbols:

$$\mathbf{F}_{\text{net}} = m \cdot \mathbf{a},$$

and in everyday language:

Throwing a baseball is much easier than throwing a bowling ball (Fig. 1.1.2).

Remember that in Eq. 1.1.2 the direction of the acceleration is the same as the direction of the net force.

Newton's Second Law of Motion
The net force exerted on an object is equal to the product of that object's mass times its acceleration. The acceleration is in the same direction as the net force..

Because it's an equation, the two sides of Eq. 1.1.1 are equal. Your acceleration equals the net force on you divided by your mass. Since your mass is constant unless you visit the snack bar, Eq. 1.1.1 indicates that an increase in the net force on you is accompanied by a similar increase in your acceleration. That way, as the right side of the equation increases, the left side increases to keep the two sides equal. Thus the harder your friend pushes on you, the more rapidly your velocity changes in the direction of that push.

We can also compare the effects of equal forces on two different masses, for example, you and the former sumo wrestler to your left. I'll assume, for the sake of argument, that you're the less massive of the two. Equation 1.1.1 indicates that an increase in mass must be accompanied by a corresponding decrease in acceleration. Sure enough, your velocity changes more rapidly than the velocity of the sumo wrestler when the two of you are subjected to identical forces (Fig. 1.1.3).

So far we've explored five principles:

1. Your position indicates exactly where you're located.
2. Your velocity measures how quickly your position changes.
3. Your acceleration measures how quickly your velocity changes.
4. In order for you to accelerate, you must experience a net force.
5. The greater your mass, the less acceleration you experience for a given net force.

We've also encountered five important physical quantities—mass, force, acceleration, velocity, and position—as well as some of the rules that relate them to one another. Much of the groundwork of physics rests on these five quantities and on their interrelationships.

Skating certainly depends on these quantities. We can now see that, in the absence of any horizontal forces, you either remain stationary or coast along at a constant velocity. To start, stop, or turn, something must push you horizontally and that something is the ice or pavement. We haven't talked about how you obtain horizontal forces from the ice or pavement, and we'll leave that problem for later sections. As you skate, however, you should be aware of these forces and notice how they change your speed, direction of travel, or both. Learn to watch yourself accelerate.

Courtesy Lou Bloomfield

Fig. 1.1.3 If you give these two skaters identical pushes, the boy will accelerate more quickly than the girl. That's because the girl has more mass than the boy.

Check Your Understanding #3: Hard to Stop

It's much easier to stop a bicycle traveling toward you at 5 kilometers-per-hour (3 miles-per-hour) than an automobile traveling toward you at the same velocity. What accounts for this difference?

Answer: An automobile has a much greater mass than a bicycle.

Why: To stop a moving vehicle, you must exert a force on it in the direction opposite its velocity. The vehicle will then accelerate backward so that it eventually comes to rest. If the vehicle is heading toward you, you must push it away from you. The more mass the vehicle has, the less it will accelerate in response to a certain force and the longer you will have to push on it to stop it completely. Although it's easy to stop a bicycle by hand, stopping even a slowly moving automobile by hand requires a large force exerted for a substantial amount of time.

Check Your Figures #1: At the Bowling Alley

Bowling balls come in various masses. Suppose that you try bowling two different balls, one with twice the mass of the other. If you push on them with equal forces, which one will accelerate faster and how much faster?

Answer: The less massive ball will accelerate twice as rapidly.

Why: Equation 1.1.1 shows that an object's acceleration is inversely proportional to its mass:

$$\text{acceleration} = \frac{\text{force}}{\text{mass}}.$$

If you push on both bowling balls with equal forces, then their accelerations will depend only on their masses. Doubling the mass on the right side of this equation halves the acceleration on the left side. That means that the more massive ball will accelerate only half as quickly as the other ball.

Several Skaters: Frames of Reference

While skating alone is peaceful, it's usually more fun with other skaters around. That way, you have people to talk to and an audience for your athleticism and artistry.

However, with several skaters coasting on the ice at once, there's a question of perspective. As you glide steadily past a friend, the two of you see the world somewhat differently. From your perspective, you are motionless and your friend is moving. From your friend's perspective, though, your friend is motionless and you are moving. Who is right?

It turns out that you're both right and that physics has a way of accommodating this apparent paradox. Each of you is observing the world from a different **inertial frame of reference**, the viewpoint of an **inertial** object—an object that is not accelerating and that moves according to Newton's first law. One of the remarkable discoveries of Galileo and Newton is that the laws of physics work perfectly in any inertial frame of reference. From an inertial frame, everything you see in the world around you obeys the laws of motion that we're in the process of exploring. Though you may find it odd to think of scenery as moving, your inertial frame of reference is as good as any and in your frame you are at rest amidst the moving landscape.

Since both you and your friend are coasting, each of you views the world from an inertial frame of reference and sees the surrounding objects moving in perfect accordance with the laws of motion. Some objects travel at constant velocity while others accelerate in response to forces. However, because the two of you are observing those objects from different inertial frames, you will disagree on the particular values of some of the physical quantities you might measure.

In the present case, you see yourself as motionless because you view the world from your own inertial frame. In that frame, your friend is coasting westward at

2 meters-per-second (2 m/s, which is roughly 6.6 feet-per-second or 6.6 ft/s). However, your friend sees things differently. In your friend's inertial frame, your friend is motionless and you yourself are coasting eastward at 2 m/s. As long as the two of you don't try to compare the positions or velocities of objects you observe, or certain physical quantities derived from those values, there will be no disagreements and no inconsistencies. However, if you forget to watch where you're going and crash into a wall, don't expect your friend to sympathize when you claim that you were motionless and that the moving wall ran into you. That's not how your friend saw it.

Each time we examine an object in this book, we'll pick a specific inertial frame of reference from which to view that object. We'll normally select an inertial frame that makes the object and its motions appear as simple as possible and then stick with that frame consistently. The best choice of inertial frame will usually be so obvious that we'll adopt it without even a moment's thought. On occasion, however, we'll have to pick the frame carefully and deliberately. Finally, although there are formal methods for working with two or more inertial frames at once, I'll leave that for another book.

Check Your Understanding #4: Two Views

You are standing on the sidewalk, watching a train coast eastward at constant velocity. Your friend is riding in that train. In her inertial frame of reference, the sweater in her lap is motionless. Describe the sweater's motion in your inertial frame of reference.

Answer: The sweater is coasting eastward at constant velocity.

Why: Although both of you agree that the sweater is not accelerating and that it is moving according to Newton's first law, you disagree on its specific velocity. She sees the sweater at rest while you see it coasting eastward at constant velocity. Your viewpoints are equally valid.

Measure for Measure: The Importance of Units

If you went to the grocery store and asked for "6 of sugar," the clerk wouldn't know how much sugar to give you. The number *6* wouldn't be enough information; you need to specify which units—cups, pounds, cubes, or tons—you have in mind. This need to specify units applies to almost all physical quantities—velocity, force, mass, and so on—and has led our society to develop units that everyone agrees on, also known as **standard units**.

For example, when you say that a skater's speed is 20 miles-per-hour, you have chosen "miles-per-hour" as the standard unit of speed and you're asserting that the skater is moving 20 times that fast. You can report the skater's speed as a multiple of any standard unit of speed—feet-per-second, yards-per-day, or inches-per-century, to name only a few—and you can always find a simple relationship to convert from one unit of speed to another. For example, to convert the skater's speed from miles-per-hour to kilometers-per-hour, you multiply it by 1.609 kilometers/mile:

$$20\,\frac{\text{mi}}{\text{h}} \cdot \frac{1.609\ \text{km}}{1\ \text{mi}} = 32.2\,\frac{\text{km}}{\text{h}}.$$

Many of the common units in the United States come from the old **English system of units**, which most of the world has abandoned in favor of **SI units** (Systéme

Internationale d'Unités). The continued use of English units in the United States often makes life difficult. If you have to triple a cake recipe that calls for ¾ cup of milk, you must work hard to calculate that you need 2¼ cups. Then you go to buy 2¼ cups of milk, which is slightly more than half a quart, but end up buying two pints instead. You now have 14 ounces of milk more than you need—but is that 14 fluid ounces or 14 ounces of weight? And so it goes.

The SI system has two important characteristics that distinguish it from the English system and make it easier to use. In the SI system:

1. Different units for the same physical quantity are related by factors of 10.
2. Most of the units are constructed out of a few basic units: the meter, the kilogram, and the second.

Let's start with the first characteristic: different units for the same physical quantity are related by factors of 10. When measuring volume, 1000 milliliters is exactly 1 liter, and 1000 liters is exactly 1 cubic meter (1 meter^3). When measuring mass, 1000 grams is exactly 1 kilogram, and 1000 kilograms is exactly 1 metric ton. Because of this consistent relationship, enlarging a recipe that's based on the SI system is as simple as multiplying a few numbers. You never have to think about converting pints into quarts, teaspoons into tablespoons, or ounces into pounds. Instead, if you want to triple a recipe that calls for 500 milliliters of sugar, you just multiply the recipe by 3 to obtain 1500 milliliters of sugar. Since 1000 milliliters is 1 liter, you'll need 1.5 liters of sugar. Converting milliliters to liters is as simple as multiplying by 0.001 liter/milliliter. (See Appendix B for more conversion factors.)

SI units remain somewhat mysterious to many U.S. residents, even though some of the basic units are slowly appearing on our grocery shelves and highways. As a result, although the SI system really is more sensible than the old English system, developing a feel for some SI units is still difficult. How many of us know our heights in meters (the SI unit of length) or our masses in kilograms (the SI unit of mass)? If your car is traveling 200 kilometers-per-hour and you pass a police car, are you in trouble? Yes, because 200 kilometers-per-hour is about 125 miles-per-hour. Actually, the hour is not an SI unit—the SI unit of time is the second—but the hour remains customary for describing long periods of time. Thus the kilometer-per-hour is a unit that is half SI (the kilometer part) and half customary (the hour part).

The second characteristic of the SI system is its relatively small number of basic units. So far, we've noted the SI units of mass (the **kilogram**, abbreviated kg), length (the **meter**, abbreviated m), and time (the **second**, abbreviated s). One kilogram is about the mass of a liter of water; one meter is about the length of a long stride; one second is about the time it takes to say "one banana." From these three basic units, we can create several others, such as the SI units of velocity (the **meter-per-second**, abbreviated m/s) and acceleration (the **meter-per-second^2**, abbreviated m/s^2). One meter-per-second is a healthy walking speed; one meter-per-second^2 is about the acceleration of an elevator after the door closes and it begins to head upward. This conviction that many units are best constructed out of other, more basic units dramatically simplifies the SI system; the English system doesn't usually suffer from such sensibility.

The SI unit of force is also constructed out of the basic units of mass, length, and time. If we choose a 1-kilogram object and ask just how much force is needed to make that object accelerate at 1 meter-per-second^2, we define a specific amount of force. Since 1 kilogram is the SI unit of mass and 1 meter-per-second^2 is the SI unit of acceleration, it's only reasonable to let the force that causes this acceleration be the SI unit of force: the **kilogram-meter-per-second^2**. Since this composite unit sounds unwieldy but is very

important, it has been given its own name: the **newton** (abbreviated N)—after, of course, Sir Isaac, whose second law defines the relationship among mass, length, and time that the unit expresses. One newton is about the weight of 18 U.S. quarter dollars; if you hold 18 quarters steady in your hand, you'll feel a downward force of about 1 newton.

Because a complete transition to the SI system will take generations, this book uses both unit systems whenever possible. Although we will emphasize the SI system, English and customary units may give you a better intuitive feel for a particular physical quantity. A bullet train traveling "67 meters-per-second" doesn't mean much to most of us, whereas one moving "150 miles-per-hour" (150 mph) or "240 kilometers-per-hour" (240 km/h) should elicit our well-deserved respect.

Quantity	*SI Unit*	*English Unit*	*SI → English*	*English → SI*
Position	meter (m)	foot (ft)	1 m = 3.2808 ft	1 ft = 0.30480 m
Velocity	meter-per-second (m/s)	foot-per-second (ft/s)	1 m/s = 3.2808 ft/s	1 ft/s = 0.30480 m/s
Acceleration	meter-per-second^2 (m/s^2)	foot-per-second^2 (ft/s^2)	1 m/s^2 = 3.2808 ft/s^2	1 ft/s^2 = 0.30480 m/s^2
Force	newton (N)	pound-force (lbf)†	1 N = 0.22481 lbf	1 lbf = 4.4482 N
Mass	kilogram (kg)	pound-mass (lbm)†	1 kg = 2.2046 lbm	1 lbm = 0.45359 kg

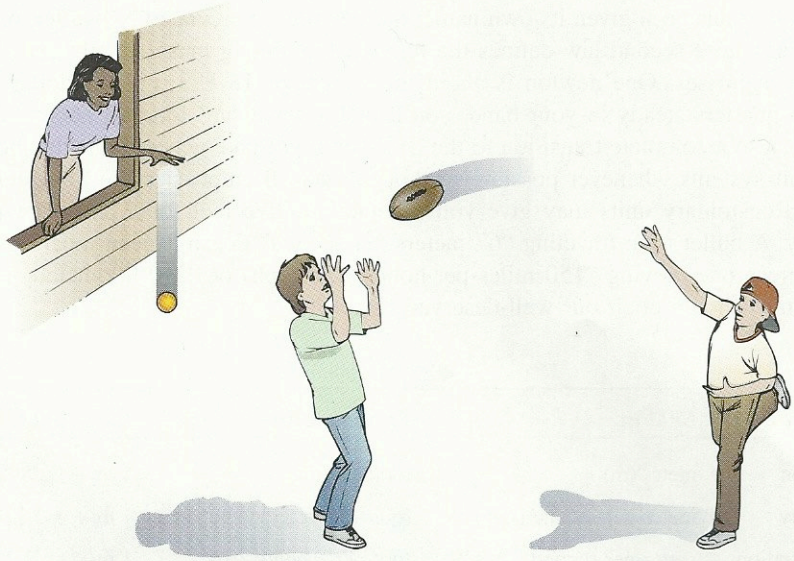
†The English units of force and mass are both called the pound. To distinguish these two units, it has become standard practice to identify them explicitly as pound-force and pound-mass.

Check Your Understanding #5: **Going for a Walk**

If you're walking at a pace of 1 meter-per-second, how many miles will you travel in an hour?

Answer: You would travel about 2.24 miles.

Why: There are many different units in this example, so we must do some converting. First, an hour is 3600 seconds, so that in an hour of walking at 1 meter-per-second, you will have walked 3600 meters. Second, a mile is about 1609 meters, so that each time you travel 1609 meters, you have traveled a mile. By walking 3600 meters, you have completed 2 miles and are about one-quarter of the way into your third mile.



SECTION 1.2 Falling Balls

We've all dropped balls from our hands or seen them arc gracefully through the air after being thrown. These motions are simplicity itself and, not surprisingly, they're governed by only a few universal rules. We encountered several of those rules in the previous section, but we're about to examine our first important type of force: gravity. Like Newton, who reportedly began his investigations after seeing an apple fall from a tree, we'll start simply by exploring gravity and its effects on motion in the context of falling objects.

Questions to Think About: *What do we mean by "falling," and why do balls fall? Which falls faster: a heavy ball or a light ball? Can a ball that's heading upward still be falling? How does gravity affect a ball that's thrown sideways?*

Experiments to Do: *A few seconds with a baseball will help you see some of the behaviors that we'll be exploring. Toss the ball into the air to various heights, catching it in your hand as it returns. Have a friend time the flight of the ball. As you toss the ball higher, how much more time does it spend in the air? How does it feel coming back to your hands? Is there any difference in the impact it makes? Which takes the ball longer: rising from your hand to its peak height or returning from its peak height back to your hand?*

Now drop two different balls—a baseball, say, and a golf ball. If you drop them simultaneously, without pushing either one up or down, does one ball strike the ground first, or do they arrive together? Now throw one ball horizontally while dropping the second. If they both leave your hands at the same time and the first one's initial motion is truly horizontal, which one reaches the ground first?

Weight and Gravity

Like everything else around us, a ball has a weight. For example, a golf ball weighs about 0.45 N (0.10 lbf)—but what is weight? Evidently it's a force, since both the newton (N) and the pound-force (lbf) are units of force. To understand what weight is, however—and, in particular, where it comes from—we need to look at gravity.

Gravity is a physical phenomenon that produces attractive forces between every pair of objects in the universe. In our daily lives, however, the only object massive enough and near enough to have obvious gravitational effects on us is our planet, the earth. Gravity weakens with distance and the moon and sun are so far away that we notice their gravities only through such subtle effects as the ocean tides.

The earth's gravity exerts a downward force on any object near its surface. That object is attracted directly toward the center of the earth with a force we call the object's **weight** (Fig. 1.2.1). Remarkably enough, this weight is exactly proportional to the object's mass—if one ball has twice the mass of another ball, it also has twice the weight. Such a relationship between weight and mass is astonishing because weight and mass are very different attributes: weight is how hard gravity pulls on a ball, and mass is how difficult that ball is to accelerate. Because of this proportionality, a ball that's heavy is also hard to shake!

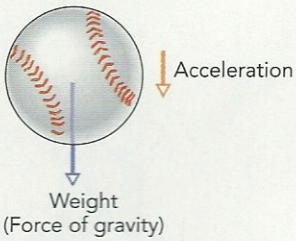


Fig. 1.2.1 A ball experiencing the force of gravity. It accelerates downward.

An object's weight is also proportional to the local strength of gravity, which is measured by a downward vector called the **acceleration due to gravity**—an odd name that I'll explain shortly. At the surface of the earth the acceleration due to gravity is about 9.8 N/kg (1.0 lbf/lbm). That value means that a mass of 1 kilogram has a weight of 9.8 newtons, and that a mass of 1 pound-mass has a weight of 1 pound-force.

More generally, an object's weight is equal to the product of its mass times the acceleration due to gravity, which can be written as a word equation:

$$\text{weight} = \text{mass} \cdot \text{acceleration due to gravity}, \tag{1.2.1}$$

in symbols:

$$\mathbf{w} = m \cdot \mathbf{g},$$

and in everyday language:

You can lose weight either by reducing your mass or by going someplace, like a small planet, where the gravity is weaker.

But why *acceleration* due to gravity? What acceleration do we mean? To answer that question, let's consider what happens to a ball when you drop it.

If the only force on the ball is its weight, the ball accelerates downward; in other words, it falls. Although a ball moving through the earth's atmosphere encounters additional forces due to air resistance, let's ignore those forces for the time being. Doing so costs us only a little in terms of accuracy—the effects of air resistance are negligible as long as the ball is dense and its speed relatively small—and allows us to focus exclusively on the effects of gravity.

How much does the falling ball accelerate? According to Eq. 1.1.1, the ball's acceleration is equal to the net force exerted on it divided by its mass. Because the ball is falling, however, the only force on it is its own weight. That weight, according to Eq. 1.2.1, is equal to the ball's mass times the acceleration due to gravity. Using

a little algebra, we get

$$\text{falling ball's acceleration} = \frac{\text{ball's weight}}{\text{ball's mass}}$$
$$= \frac{\text{ball's mass} \cdot \text{acceleration due to gravity}}{\text{ball's mass}}$$
$$= \text{acceleration due to gravity.}$$

As you can see, the falling ball's acceleration is equal to the acceleration due to gravity. Thus acceleration due to gravity really is an acceleration after all: it's the acceleration of a freely falling object. Moreover, the units of acceleration due to gravity can be transformed easily from those relating weight to mass, 9.8 N/kg (1.0 lbf/lbm), into those describing the acceleration of free fall, 9.8 m/s^2 (32 ft/s^2).

Thus a ball falling near the earth's surface experiences a downward acceleration of 9.8 m/s^2 (32 ft/s^2), regardless of its mass. This downward acceleration is substantially more than that of an elevator starting its descent. When you drop a ball, it picks up speed very quickly in the downward direction.

Because all falling objects at the earth's surface accelerate downward at exactly the same rate, a billiard ball and a bowling ball dropped simultaneously from the same height will reach the ground together. (Remember that we're not considering air resistance yet.) Although the bowling ball weighs more than the billiard ball, it also has more mass, so while the bowling ball experiences a larger downward force, its larger mass ensures that its downward acceleration is equal to that of the lighter and less massive billiard ball.

Check Your Understanding #1: **Weight and Mass**

Out in deep space, far from any celestial object that exerts significant gravity, would an astronaut weigh anything? Would that astronaut have a mass?

Answer: The astronaut would have zero weight but would still have a normal mass.

Why: Weight is a measure of the force exerted on the astronaut by gravity. Far from the earth or any other large object, the astronaut would experience virtually no gravitational force and would have zero weight. But mass is a measure of inertia and doesn't depend at all on gravity. Even in deep space, it would be much harder to accelerate a school bus than to accelerate a baseball because the school bus has more mass than the baseball.

Check Your Figures #1: **Weighing in on the Moon**

You're in your spacecraft on the surface of the moon. Before getting into your suit, you weigh yourself and find that your moon weight is almost exactly one-sixth your earth weight. What is the moon's acceleration due to gravity?

Answer: It is about 1.6 m/s^2 (5.3 ft/s^2).

Why: You can rearrange Eq. 1.2.1 to show that the acceleration due to gravity is proportional to an object's weight:

$$\text{acceleration due to gravity} = \frac{\text{weight}}{\text{mass}}.$$

Your mass doesn't change in going to the moon, so any change in your weight must be due to a change in the acceleration due to gravity. Since your moon weight is one-sixth of your earth weight, the moon's acceleration due to gravity must be one-sixth that of the earth or about 1.6 m/s^2.

The Velocity of a Falling Ball

We're now ready to examine the motion of a falling ball near the earth's surface. A falling ball is one that has only the force of gravity acting on it and gravity, as we've seen, causes any falling object to accelerate downward at a constant rate. However, we're usually less interested in the falling object's acceleration than we are in its position and velocity. Where will the object be in 3 seconds, and what will its velocity be then? When you're trying to summon up the courage to jump off the high dive, you want to know how long it'll take you to reach the water and how fast you'll be going when you hit.

The first step in answering these questions is to look at how a ball's velocity is related to the time you've been watching it fall. To do that, you'll need to know the ball's *initial velocity*—that is, its speed and direction at the moment you start watching it. If you drop the ball from rest, its initial velocity is zero.

You can then describe the ball's present velocity in terms of its initial velocity, its acceleration, and the time that has passed since you started watching it. Because a constant acceleration causes the ball's velocity to change by the same amount each second, the ball's present velocity differs from its initial velocity by the product of the acceleration times the time over which you've been watching it. We can relate these quantities as a word equation:

$$\text{present velocity} = \text{initial velocity} + \text{acceleration} \cdot \text{time}, \qquad (1.2.2)$$

in symbols:

$$\mathbf{v}_f = \mathbf{v}_i + \mathbf{a} \cdot t,$$

and in everyday language:

A stone dropped from rest descends faster with each passing second, but you can give it a boost by throwing it downward instead of just letting go.

For a ball falling from rest, the initial velocity is zero, the acceleration is downward at 9.8 m/s^2 (32 ft/s^2), and the time you've been watching it is simply the time since it started to drop (Fig. 1.2.2). After one second, the ball has a downward velocity of 9.8 m/s (32 ft/s). After two seconds, the ball has a downward velocity of 19.6 m/s (64 ft/s).

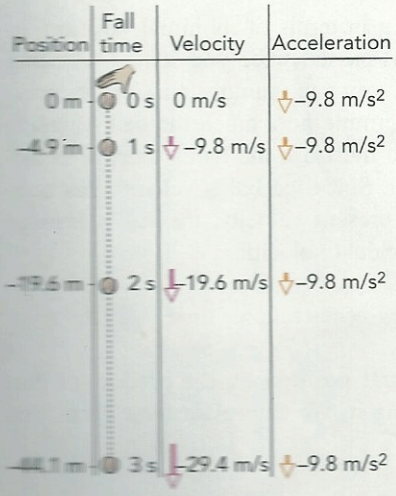


Fig. 1.2.2 The moment you let go of a ball that was resting in your hand, it begins to fall. Its weight causes it to accelerate downward. After 1 second, it has fallen 4.9 m and has a velocity of 9.8 m/s downward. After 2 seconds, it has fallen 19.6 m and has a velocity of 19.6 m/s downward, and so on. As the ball continues to accelerate downward, its velocity continues to increase downward. Negative values for the position and velocity are meant to indicate downward movement, caused by a negative or downward acceleration.

After three seconds, its downward velocity is 29.4 m/s (96 ft/s), and so on. Since the ball's motion is strictly vertical, we often put a negative sign in front of the acceleration to indicate the direction. By convention, we say that a negative sign means "down."

Check Your Understanding #2: Half a Fall

You drop a marble from rest and after 1 s, its velocity is 9.8 m/s (32 ft/s) in the downward direction. What was its velocity after only 0.5 s of falling?

Answer: Its velocity was 4.9 m/s (16 ft/s) in the downward direction.

Why: A freely falling object accelerates downward at a steady rate. Its velocity changes by 9.8 m/s (16 ft/s) in the downward direction each and every second. In half a second, the marble's velocity changes by only half that amount or 4.9 m/s (16 ft/s).

Check Your Figures #2: The High Dive

If it takes you about 1.4 s to reach the water from the 10-meter (32-foot) diving platform, how fast are you going just before you enter the water?

Answer: You are going about 14 m/s (45 ft/s, 50 km/h, or 31 mph).

Why: The downward acceleration due to gravity is 9.8 m/s^2 (32 ft/s^2). You fall for 1.4 s, during which time your velocity increases steadily in the downward direction. Since you start with zero velocity, Eq. 1.2.2 gives a final velocity of

$$\text{final velocity} = 9.8\ \text{m/s}^2 \cdot 1.4\ \text{s} = 13.72\ \text{m/s}.$$

Since the time of the fall is only given to two digits of accuracy (1.4 s could really be 1.403 s or 1.385 s), we shouldn't claim that our calculated final velocity is accurate to four digits. We should round the value to 14 m/s (45 ft/s).

The Position of a Falling Ball

The ball's velocity continues to increase as it falls, but where exactly is the ball located? To answer that question, you need to know the ball's *initial position*—that is, where it was when you started to watch it fall. If you dropped the ball from rest, the initial position was your hand and you can define that spot as 0.

You can then describe the ball's present position in terms of its initial position, its initial velocity, its acceleration, and the time that has passed since you started watching it. However, because the ball's velocity is changing, you can't simply multiply its present velocity by the time that it's been falling to determine how much the ball's present position differs from its initial position. Instead, you must use the ball's average velocity during the whole period you've been watching it. Since the ball's velocity has been changing uniformly from its initial velocity to its present velocity, the ball's average velocity is exactly halfway in between the two individual velocities:

$$\text{average velocity} = \text{initial velocity} + \tfrac{1}{2} \cdot \text{acceleration} \cdot \text{time}.$$

The ball's present position differs from its initial position by the product of this average velocity times the time you've been watching it. We can relate these quantities as a word equation:

present position = initial position + initial velocity · time + $\frac{1}{2}$ · acceleration · time^2, (1.2.3)

in symbols:

$$\mathbf{x_f} = \mathbf{x_i} + \mathbf{v_i} \cdot t + \tfrac{1}{2} \cdot \mathbf{a} \cdot t^2,$$

and in everyday language:

The longer a stone has been falling, the more its height diminishes with each passing second. However, it won't overtake a stone that was dropped next to it at an earlier time or dropped from beneath it at the same time.

For a ball falling from rest, the initial velocity is zero, the acceleration is downward at 9.8 m/s^2 (32 ft/s^2), and the time you've been watching it is simply the time since it started to drop (Fig. 1.2.2). After one second, the ball has fallen 4.9 m (16 ft). After two seconds, the ball has fallen downward a total of 19.6 m (64 ft). After three seconds, the ball has fallen a total of 44.1 m (145 ft), and so on.

Equations 1.2.2 and 1.2.3 depend on the definition of acceleration as the measure of how quickly *velocity* changes and the definition of velocity as the measure of how quickly *position* changes. Because the acceleration of a falling ball doesn't change with time, the two equations can be derived using algebra. In more complicated situations, however, where an object's acceleration changes with time, predicting position and velocity usually requires the use of calculus. *Calculus* is the mathematics of change, invented by Newton to address just these sorts of problems.

We've been discussing what happens to a falling ball, but we could have chosen another object instead. Everything falls the same way; heavy or light, large or small, all objects take the same amount of time to fall some distance near the earth's surface, as long as they're dense enough to overcome air resistance. If there were no air, this statement would be exactly true for any object; a feather and a lead brick would plummet downward together if you dropped them simultaneously.

Now that we've explored acceleration due to gravity, we can see why a ball dropped from a tall ladder is more dangerous than the same ball dropped from a short stool. The farther the ball has to fall, the longer it takes to reach the ground and the more time it has to accelerate. During its long fall from the tall ladder, the ball acquires a large downward velocity and becomes very hard to stop. If you try to catch it, you'll have to exert a very large upward force on it to accelerate it upward and bring it to rest quickly. Exerting that large upward force may hurt your hand.

The same notion holds if you're the falling object. If you leap off a tall ladder, a substantial amount of time will pass before you reach the ground. By the time you arrive, you'll have acquired considerable downward velocity. The ground will then accelerate you upward and bring you to rest with a very large and unpleasant upward force. (For an interesting and less painful application of long falls, see ■.)

■ In 1782, William Watts, a plumber from Bristol, England, patented a technique for forming perfectly spherical, seamless lead shot for use in guns. His idea was to pour molten lead through a sieve suspended high above a pool of water. The lead droplets cool in the air as they fall, solidifying into perfect spheres before reaching the water. Shot towers based on this idea soon appeared throughout Europe and eventually in the United States. Nowadays, iron shot has all but replaced environmentally dangerous lead shot. Iron shot is cast, rather than dropped, because the longer cooling time needed to solidify molten iron would require impractically tall shot towers.

Check Your Understanding #3: Half a Fall Again

You drop a marble from rest and after 1 s, it has fallen downward a distance of 4.9 m (16 ft). How far had it fallen after only 0.5 s?

Answer: It had fallen about 1.2 m (4 ft).

Why: While a freely falling object's velocity changes steadily in the downward direction, its height is more complicated. When you drop the marble from rest, it starts its

descent slowly but picks up speed and covers the downward distance faster and faster. In the first 0.5 s, it travels only a quarter of the distance it travels in the first 1 s, or about 1.2 m (4 ft).

Check Your Figures #3: Extreme Physics

You're planning to construct a bungee-jumping amusement at the local shopping center. If you want your customers to have a 5-second free-fall experience, how tall will you need to build the tower from which they'll jump? (Don't worry about the extra height needed to stop people after the bungee pulls taut.)

Answer: The tower should be about 122 meters (402 feet or a 40-story building).

Why: As they fall, the jumpers will travel downward at ever increasing speeds. Since the jumpers start from rest and fall downward for 5 seconds, we can use Eq. 1.2.3 to determine how far they will fall:

$$\begin{aligned}\text{final height} &= \text{initial height} - \tfrac{1}{2} \cdot 9.8\ \text{m/s}^2 \cdot (5\ \text{s})^2 \\ &= \text{initial height} - 122.5\ \text{m}.\end{aligned}$$

The downward acceleration is indicated here by the negative change in height. At the end of 5 seconds, the jumpers will have fallen more than 122 m (402 ft) and will be traveling downward at about 50 m/s (160 ft/s). The tower will need additional height to slow the jumpers down and begin bouncing them back upward. Clearly, a 5-second free fall is pretty unrealistic. Try for a 2- or 3-second free fall instead.

How a Thrown Ball Moves: Projectile Motion

If the only force acting on an object is its weight, then the object is falling. So far, we've explored this principle only as it pertains to balls dropped from rest. However, a thrown ball is falling, too; once it leaves your hand, it's subject only to the downward force of gravity and it falls. It may seem odd but even though it's initially traveling upward, a ball tossed upward is accelerating downward at 9.8 m/s^2 (32 ft/s^2). As a result, the tossed ball's upward velocity diminishes, it stops rising, its velocity becomes downward, and it eventually returns to the ground.

Equation 1.2.2 still describes how the ball's velocity depends on the fall time, but now the initial velocity isn't zero; it points in the upward direction! If you toss a ball straight up in the air, it leaves your hand with a large upward velocity (Fig. 1.2.3). As soon as you let go of the ball, it begins to accelerate downward. If the ball's initial upward velocity is 29.4 m/s (96 ft/s), then after one second its upward velocity is 19.6 m/s (64 ft/s). After another second, its upward velocity is only 9.8 m/s (32 ft/s). After a third second, the ball momentarily comes to a complete stop with a velocity of zero. It then descends from this peak height, falling just as it did when you dropped it from rest.

The ball's flight before and after its peak is symmetrical. It travels upward quickly at first, since it has a large upward velocity. As its upward velocity diminishes, it travels more and more slowly until it comes to a stop. It then begins to descend, slowly at first and then faster and faster as it continues its constant downward acceleration. The time the ball takes to rise from its initial position in your hand to its peak height is exactly equal to the time it takes to descend back down from that peak to your hand.

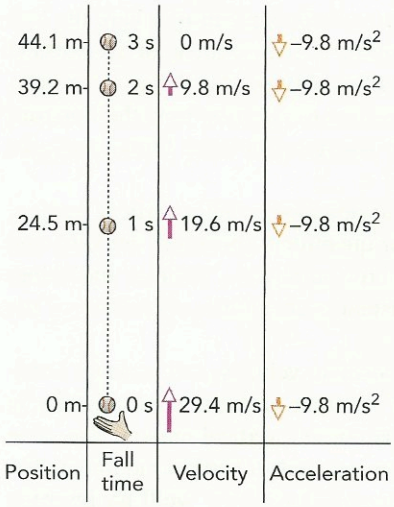


Fig. 1.2.3 The moment you let go of a ball thrown straight upward, it begins to accelerate downward at 9.8 m/s^2. The ball rises but its upward velocity diminishes steadily until it momentarily comes to a stop. It then descends with its downward velocity increasing steadily. In this example, the ball rises for 3 seconds and comes to rest. It then descends for 3 seconds before returning to your hand in a very symmetrical flight.

Equation 1.2.3 indicates how the position of the ball depends on the fall time, with the initial velocity being the upward velocity of the ball as it leaves your hand.

The larger the initial upward velocity of the ball, the longer it rises and the higher it goes before its velocity is reduced to zero. It then descends for the same amount of time it spent rising. The higher the ball goes before it begins to descend, the longer it takes to return to the ground and the faster it's traveling when it arrives. That's why catching a high fly ball with your bare hands stings so much: the ball is traveling very, very fast when it hits your hands, and a large force is required to bring the ball to rest quickly.

What happens if you don't toss the ball exactly straight up? Suppose that you throw the ball upward at some angle. The ball still rises to a peak height and then begins to descend; but as it rises and descends, it also travels away from you horizontally so that it strikes the ground at some distance from your feet. How much does this horizontal travel complicate the motion of a falling ball?

The answer is not very much. One of the beautiful simplifications of physics is that we can often treat an object's vertical motion independently of its horizontal motion. This technique involves separating the vector quantities—acceleration, velocity, and position—into **components**, those portions of the quantities that lie along specific directions (Fig. 1.2.4). For example, the vertical component of an object's position is that object's altitude.

If you know a ball's altitude, you know only part of its position; you still need to know where it is to your left or right and to your front or back. In fact, you can specify its position (or any other vector quantity) in terms of three components along three directions that are perpendicular (or at right angles) to one another. This means that you can completely specify the ball's position by its vertical altitude, its horizontal distance to your left or right, and its horizontal distance in front or in back of you. For example, the ball might be 10 m above you, 3 m to your left, and 2 m behind you. These three distances indicate just where the ball is located.

Up until now, we've actually been examining only the vertical components of position, velocity, and acceleration. Now, however, we're going to let the ball move horizontally so that we also have to consider what happens to the two horizontal components of each vector quantity. Keeping track of all three components of each quantity is difficult. Since we're interested in the motion of a tossed ball, we can eliminate the left–right component by throwing the ball forward; that way, the ball will move only in a vertical plane that extends directly in front of us. We can then specify the ball's position as its altitude and its horizontal distance in front of us.

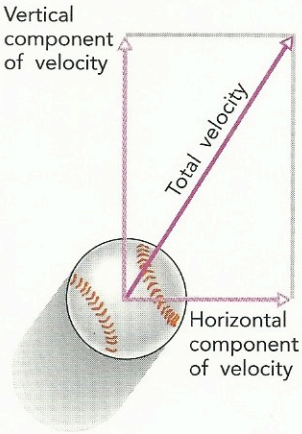


Fig. 1.2.4 Even if the ball has a velocity that is neither purely vertical nor purely horizontal, its velocity may nonetheless be viewed as having a vertical component and a horizontal component. Part of its total velocity acts to move this ball upward, and part of its total velocity acts to move this ball in a horizontal direction.

Courtesy Lou Bloomfield

Fig. 1.2.5 This golf ball drifts steadily to the right after being thrown because gravity affects only the ball's vertical component of velocity.

Because the falling ball's acceleration is constant and independent of where the ball is near the earth's surface, the ball's horizontal motion is independent of its vertical motion. We already know about the falling ball's vertical motion, but what is its horizontal motion? It appears we need some new relationships to describe how the horizontal components of position, velocity, and acceleration change with time. Fortunately, we can reuse Eqs. 1.2.2 and 1.2.3.

Although Eqs. 1.2.2 and 1.2.3 were introduced to describe a ball's vertical motion, they're actually more general. They relate three vector quantities—position, velocity, and constant acceleration—to one another. They describe how an object's position and velocity change with time when the object undergoes constant acceleration, regardless of the direction of that constant acceleration.

These equations also apply to the components of position, velocity, and constant acceleration. If you add the words "vertical component of" in front of each vector quantity in Eqs. 1.2.2 and 1.2.3, the equations correctly describe the object's vertical motion. The same can be done with the object's horizontal motion. Our previous look at vertical motion implicitly inserted the words "vertical component of" into the equations. Now we'll try inserting the words "horizontal component of" to understand the tossed ball's horizontal motion.

As soon as the ball leaves your hand, its motion can be broken into two parts: a vertical motion and a horizontal motion (Fig. 1.2.4). Part of the ball's initial velocity is in the upward direction, and that vertical velocity component determines the object's ascent and descent. Part of the ball's initial velocity is in the horizontal or downfield direction, and that horizontal velocity component determines the ball's drift downfield.

Because gravity is the only force on the ball and it acts only in the downward vertical direction, there is no horizontal component of acceleration. The horizontal velocity component therefore remains constant, and the ball travels downfield at a steady rate throughout its flight (Fig. 1.2.5). Overall, the upward vertical component of the ball's initial velocity determines how high the ball goes and how long it stays aloft before striking the ground, while the horizontal component of the initial velocity determines how quickly the ball travels downfield during its time aloft (Fig. 1.2.6).

Just before the ball hits the ground it still has its original horizontal velocity component, but its vertical velocity component is now in the downward direction. The total velocity of the ball is composed of these two components. The ball starts with its velocity up and forward and ends with its velocity down and forward.

If you want a ball or shot put to hit the ground as far from your feet as possible, you should keep it aloft for a long time *and* give it a sizable horizontal component of velocity; in other words, you must achieve a good balance between the vertical and

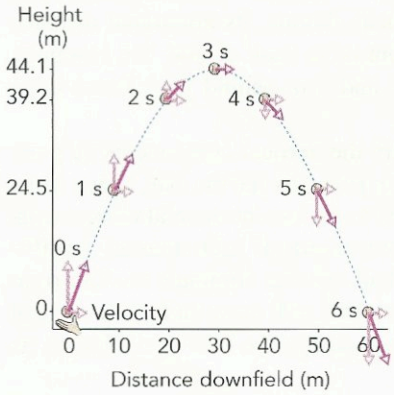
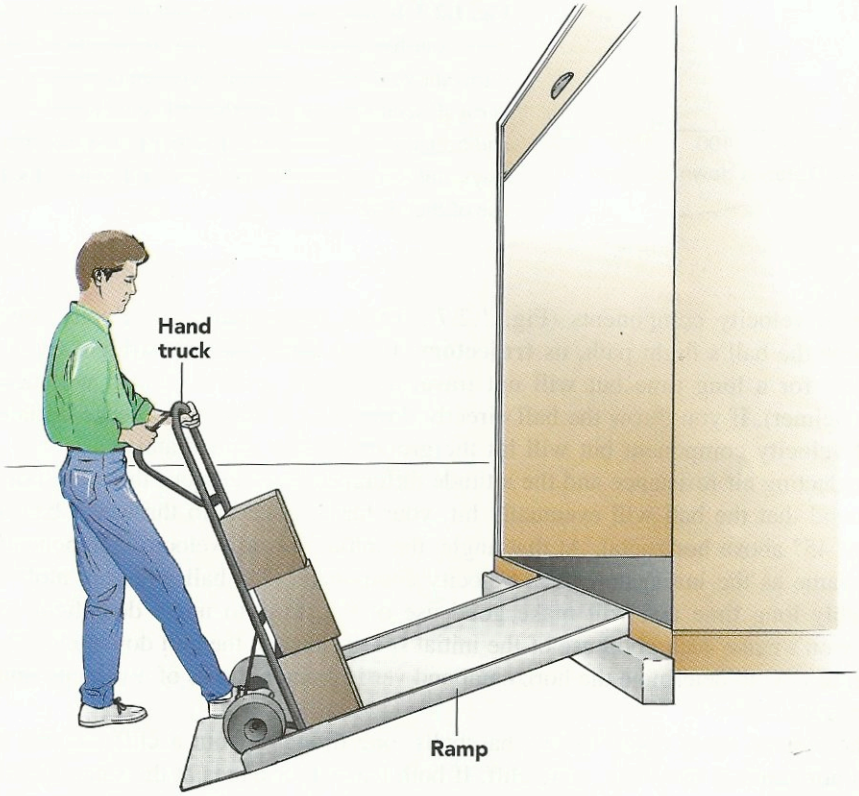


Fig. 1.2.6 If you throw a ball upward, at an angle, part of the initial velocity will be in the vertical direction and part will be in the horizontal direction. The vertical and horizontal motions will take place independently of one another. The ball will rise and fall just as it did in Figs. 1.2.2 and 1.2.3; at the same time, however, it will move downfield. Because there is no horizontal acceleration (gravity acts only in the vertical direction), the horizontal velocity remains constant, as indicated by the velocity arrows. In this example, the ball travels 10 m downfield each second and strikes the ground 60 m from your feet after a 6-s flight through the air.



SECTION 1.3 Ramps

In the previous section, we looked at what happens to an object experiencing only a single force: the downward force of gravity. But what happens to objects that experience two or more forces at the same time? Imagine, for example, an object resting on the floor. That object experiences both the downward force of gravity and an upward force from the floor. If the floor is level, the object doesn't accelerate; but if the floor is tilted, so that it forms a ramp, the object accelerates downhill. In this section, we'll examine the motion of objects traveling along ramps. In addition to making sports such as skateboarding and skiing more fun, ramps are common tools that help us lift and move heavy objects.

Questions to Think About: *How does a ramp make it possible for one person to lift a very heavy object? Why is lowering a heavy object so much easier than raising it? What changes about that object as you raise it? Why is a steep hill so much scarier to ski or sled down than a more gradual slope? Why is the steeper hill so much harder to bicycle up?*

Experiments to Do: *Place a book on a slippery but level table or board. Hold the book steady for a second and then let go of it without pushing on it. Why does the book remain motionless?*

Now, equip yourself with a pencil. Have a friend tilt the surface of the table or board slightly so that the book begins to slide downhill. Can you stop the book by pushing on

it with the pencil? Place the book back on the table and have your friend tilt the table more sharply. Does the tilt of the table affect your ability to stop the book from sliding? Now try to push the book uphill with the pencil (a) when the table is slightly tilted and (b) when it is more sharply tilted. Which task requires more force? Why?

Evidently a gentle push is all that may be needed to raise a relatively heavy object if you use a ramp to help you. To understand why this feat is possible, we need to explore a handful of physical concepts and a few basic laws of motion.

A Piano on the Sidewalk

Imagine that you have a friend who's a talented but undiscovered pianist. She's renting a new apartment, and because she can't afford professional movers (Fig. 1.3.1), she's asked you to help her move her baby grand. Fortunately, her new apartment is only on the second floor. The two of you still face a difficult challenge, however: how do you get that heavy piano up there? More important, how do you keep it from falling on you during the move?

The problem is that you can't push upward hard enough to lift the entire piano at once. One solution to this problem, of course, would be to break the piano into pieces and carry them up one by one. This method has obvious drawbacks—your friend isn't expecting a firewood delivery. A better solution would be to find something else to help you push upward, and one of your best choices would be the simple machine known as a ramp.

Throughout the ages, **ramps**, also known as inclined planes, have made tasks like piano-moving possible. Because ramps can exert the enormous upward forces needed to lift stone and steel, they've been essential building equipment since the days of the pyramids. To see how ramps provide these lifting forces, we'll continue to explore the example of the piano, looking first at the force that the piano experiences when it touches a surface. For the time being, we'll continue to ignore friction and air resistance; they would needlessly complicate our discussion. Besides, as long as the piano is on wheels, friction is negligible.

Courtesy Jerry Ohlinger's Movie Material Store

Fig. 1.3.1 A ramp would make this move much easier.

Check Your Understanding #1: Brick Work

Which requires larger forces: lifting a pile of bricks one at a time or lifting them all together?

Answer: Lifting the bricks all together requires larger forces.

Why: To lift a brick upward steadily, you must support it with an upward force equal in amount to its downward weight. If you lift several bricks at once, you will have to support all of them together and that will involve a larger upward force.

The Sidewalk Pushes Back: Newton's Third Law

With the piano resting on the sidewalk outside the apartment you make a startling discovery: the piano is *not* falling. Has gravity disappeared? The answer to that question would be painfully obvious if your foot were underneath one of the piano's wheels. No, the piano's weight is still all there, but something is happening at the surface of the sidewalk to keep the piano from falling. Let's take a careful look at the situation.

To begin with, the piano is clearly pushing down hard on the sidewalk. That's why you're keeping your toes out of the way. But the presence of a new downward force *on the sidewalk* doesn't explain why *the piano* isn't falling. Instead, we must look at the sidewalk's

response to the piano's downward push: the sidewalk pushes upward on the piano! You can feel this response by leaning over and pushing down on the sidewalk with your hand—the sidewalk will push back. Those two forces, your downward push on the sidewalk and its upward push on your hand, are exactly equal in magnitude but opposite in direction.

This observation—that two things exert equal but opposite forces on one another—isn't unique to sidewalks, pianos, or hands; in fact, it's always true. If you push on any object, that object will push back on you with an equal amount of force in exactly the opposite direction. This rule—often expressed as "for every action, there is an equal but opposite reaction"—is known as **Newton's third law of motion**, the last of his three laws.

Newton's Third Law of Motion

For every force that one object exerts on a second object, there is an equal but oppositely directed force that the second object exerts on the first object.

The universality of this law is astounding. Whether an object is large or small, hard or soft, stationary or faster than a rocket, if you can push on it, it *will* push back on you with an equal but oppositely directed force.

In the present case, the sidewalk and piano push on one another with equal but oppositely directed forces. Of this pair of equal-but-opposite forces, only one force acts *on the piano*: the sidewalk's upward push. This upward push on the piano is what keeps the piano from falling. We've solved the mystery.

Intuition Alert: Action and Reaction

Intuition says that when you push an object that's moving away from you, it pushes back more gently on you than you push on it, and when you push an object that's moving toward you, it pushes back harder on you than you push on it.

Physics says that when you push on an object, it always pushes back on you exactly as hard as you push on it.

Resolution: It's difficult to push on an object that's moving away from you, so you naturally push on it more gently than you expect. The gentle force it exerts on you is simply an equal but oppositely directed response to your gentle force on it. In contrast, it's difficult not to push strongly on an object that's moving toward you, so you naturally push on it harder than you expect. The strong force it exerts on you is again an equal but oppositely direct response to your strong force on it.

Summary of Newton's Laws of Motion

1. An object that is not subject to any outside forces moves at a constant velocity, covering equal distances in equal times along a straight-line path.
2. The net force exerted on an object is equal to the product of that object's mass times its acceleration. The acceleration is in the same direction as the force.
3. For every force that one object exerts on a second object, there is an equal but oppositely directed force that the second object exerts on the first object.

Check Your Understanding #2: Swinging

You are pushing a child on a playground swing. If you exert a 50-N (11-lbf) force on him as he is swinging away from you, how much force will he exert back on you?

Answer: He will exert 50 N (11 lbf).

Why: Whenever you exert a 50-N force on an object, whether it's moving or stationary, it will exert a 50-N force back on you. There are no exceptions. If that object is a friend, it doesn't matter whether she is stationary or moving or wearing roller skates or even sound asleep: she will push back with 50 N of force. She has no choice in the matter. Similarly, if someone pushes on you, you will feel yourself pushing back. That's how Newton's third law works.

Looking for Support and Adding Up the Forces

Although we've figured out why the piano isn't falling, we still don't know what type of force the sidewalk is using to hold it up or why that upward force so perfectly balances the piano's downward weight.

Let's begin with the type of force: since two objects can't occupy the same space at the same time, their surfaces push apart whenever they're in contact. They exert **support forces** on one another, each pushing the other directly away from its surface—the direction *normal* or *perpendicular* to its surface (see ■). Since the sidewalk is horizontal, the support force it exerts on the piano is vertical—straight up (Fig. 1.3.2).

■ Forces that are directed exactly away from surfaces are called **normal forces,** since the term **normal** is used by mathematicians to describe something that points exactly away from a surface—at right angles or perpendicular to that surface.

How large is that support force? To answer this question, suppose the sidewalk's support force were strong enough to make the piano accelerate upward. The piano would soon lift off the sidewalk and, as their surfaces stopped touching, the sidewalk's support force on the piano would grow weaker. Alternatively, suppose the sidewalk's support force was weak enough to let the piano accelerate downward. The piano would soon drop into the sidewalk and, as their surfaces overlapped more, the sidewalk's support force on the piano would grow stronger.

Because of these behaviors, the sidewalk's upward support force on the piano adjusts automatically until it exactly balances the piano's downward weight and the piano accelerates neither up nor down. When you sit on the piano during a break, the sidewalk's upward support force quickly readjusts to balance your weight as well.

Another way to state that the upward support force on the piano exactly balances the piano's downward weight is to say that the net force on the piano is zero, meaning that

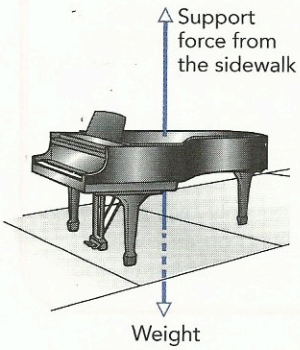


Fig. 1.3.2 A piano resting on the sidewalk. The sidewalk exerts an upward support force that exactly balances the piano's downward weight. The net force on the piano is zero, so the piano doesn't accelerate.

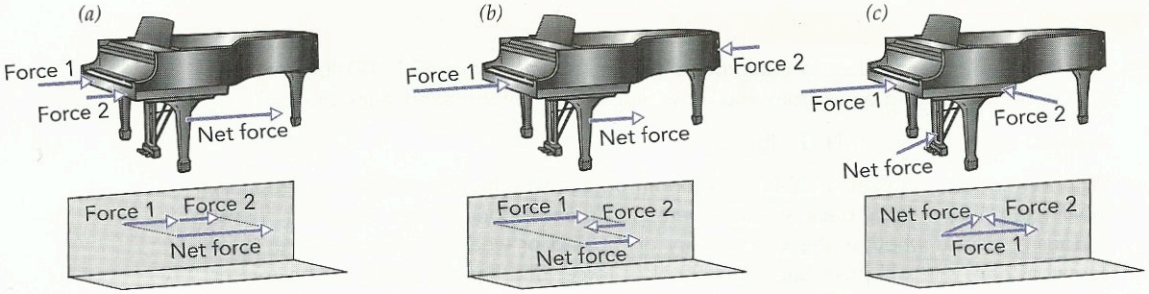


Fig. 1.3.3 When several forces act simultaneously on an object, the object responds to the sum of the forces. This sum is called the net force, and it has both a magnitude and a direction. You can sum the forces graphically by arranging the force arrows in sequence, head to tail. The net force arrow then points from the tail of the first arrow to the head of the last arrow. Some of the force arrows are shown displaced slightly for clarity, a shift that doesn't affect the summing process. Here, as elsewhere in this book, the length of each force arrow indicates its magnitude.

the sum of all the forces on the piano is zero. Objects often experience more than one force at a time, and it's the net force, together with the object's mass, that determines how it accelerates. When you and your friend push the piano in the same direction, your forces add up, assisting one another so that the piano accelerates in that direction (Fig. 1.3.3*a*). When the two of you push the piano in opposite directions, your forces oppose and at least partially cancel one another (Fig. 1.3.3*b*).

When the two of you push the piano at an angle with respect to one another, the net force points somewhere in between. For example, if you push the piano eastward while your friend pushes it northward, the net force will point to the northeast and the piano will accelerate in that direction (Fig. 1.3.3*c*). The precise angle of the net force and the piano's subsequent acceleration depends on exactly how hard each person pushes. For most of the following discussion, we'll need only a rough estimate of the net force's magnitude and direction, and we'll obtain that estimate using common sense.

Apart from direction, there's one crucial difference between the force gravity exerts on the piano and the support force the sidewalk exerts on it. While the piano's weight is dispersed throughout the piano, the sidewalk's upward support force acts only on the piano's wheels. Even when the net force on the piano is zero, having individual forces act on it at different locations can lead to considerable stress within the piano. If it weren't built so well, the piano might lose a leg or two during the move.

Common Misconceptions: Newton's Third Law and Balanced Forces

Misconception: When you push on an object and it pushes back on you, those two equal-but-opposite forces somehow cancel one another perfectly and therefore have no effect on either you or the object.

Resolution: The two forces described by Newton's third law always act on *two different things*. Your push acts on the object while the object's push acts on you. Since the object accelerates in response to the net force it experiences—the sum of all the individual forces acting *on it*—it is affected only by your force *on it*, not by its force *on you*. If you are the only thing pushing on it, it will accelerate. If the object is the only thing pushing on you, you'll accelerate, too!

Check Your Understanding #3: Riding the Elevator

As you ride upward in an elevator at a constant velocity, what two forces act on your body and what is the net force on you?

Answer: The two forces are the downward force of gravity (your weight) and an upward support force from the floor. They balance, so that the net force on you is zero.

Why: Whenever anything is moving with constant velocity, it's not accelerating and thus has zero net force on it. Although the elevator is moving upward, the fact that you are not accelerating means that the car must exert an upward support force on you that exactly balances your weight. You experience zero net force.

What the Piano Needs: Energy

As you approach the task of lifting your friend's piano into her apartment, you might begin to worry about safety. There is clearly a difference between the piano resting on the sidewalk and the piano suspended on a board just outside the second floor apartment. After all, which one would you rather be sitting beneath? The elevated piano has something that the piano on the sidewalk doesn't have: the ability to produce motion and even to break itself and the things beneath it. This capacity to make things happen is called *energy*, and the process of making them happen is called *work*.

Energy and work are both important physical *quantities*, meaning that both are measurable. For example, you can measure the amount of energy in the suspended piano, and the amount of work the piano does when the board breaks and it falls to the sidewalk. As you may suspect, the physical definitions of energy and work are somewhat different from those of common English. Physical **energy** isn't the exuberance of a child at the amusement park or the contents of a large cup of coffee; instead, it's defined as the capacity to do work. Similarly, physical **work** doesn't refer to activities at the office or in the yard; instead, it refers to the process of transferring energy.

Energy is what's transferred, and work does the transferring. The most important characteristic of energy is that it's conserved. In physics, a **conserved quantity** is one that can't be created or destroyed but can be transferred between objects or, in the case of energy, converted from one form to another. Conserved quantities are very special in physics; there are only a few of them. An object that has energy can't simply make that energy disappear; it can only get rid of energy by giving it to another object, and it makes this transfer by doing work on that object.

The relationship between energy and work is analogous to the relationship between money and spending: money is what is transferred, and spending does the transferring. Sensible, law-abiding citizens don't create or destroy money; instead they transfer it among themselves through spending. Just as the most interesting aspect of money is spending it, so the most interesting aspect of energy is doing work with it. We can define money as the capacity to spend, just as we define energy as the capacity to do work.

So far we've been using a circular definition: work is the transfer of energy and energy is the capacity to do work. But what is involved in doing work on an object? You do work on an object by exerting a force on it as it moves in the direction of that force. As you throw a ball, exerting a forward force on the ball as the ball moves forward, you do work on the ball; as you lift a rock, pushing the rock upward as it moves upward, you do work on the rock. In both cases, you transfer energy from yourself to an object by doing work on it.

This transferred energy is often apparent in the object. When you throw a ball, it picks up speed and undergoes an increase in **kinetic energy**—energy of motion that allows the ball to do work on whatever it hits. When you lift a rock, it shifts farther from the earth and undergoes an increase in **gravitational potential energy**—energy stored in the gravitational forces between the rock and the earth that allows the rock to do work on whatever it falls on. In general, **potential energy** is energy stored in the forces between or within objects.

Returning to the task at hand, it's now apparent that raising the piano to the second floor apartment is going to increase the piano's gravitational potential energy by a substantial amount. Since energy is a conserved quantity, this additional energy must come from something else. Unfortunately, that something is you! To deliver the piano, you are going to have to provide it with the gravitational potential energy it needs by doing exactly that amount of work on it. As we'll see, you can do that work the hard way by carrying it up a ladder or the easy way by pushing it up a ramp.

Check Your Understanding #4: No Shortage of Energy

Do any of these objects have energy they can spare: a compressed spring, an inflated toy balloon, a stick of dynamite, and a falling ball?

Answer: Yes, they all do.

Why: Each of these four objects can easily do work on you and thereby give you some of its spare energy. It does this work by pushing on you as you move in the direction of that push.

Lifting the Piano: Doing Work

To do work on an object, you must push on it while it moves in the direction of your push. The work you do on it is the product of the force you exert on it times the distance it travels along the direction of your force. We can express this relationship as a word equation:

$$\text{work} = \text{force} \cdot \text{distance}, \tag{1.3.1}$$

in symbols:

$$W = \mathbf{F} \cdot \mathbf{d},$$

and in everyday language:

If you're not pushing or it's not moving, then you're not working.

This simple relationship assumes that your force is constant while you're doing the work. If your force varies, the calculation of work will have to recognize that variation and may require the use of calculus.

Calculating the work you do is easy if the object moves exactly in the direction of your constant push: you simply multiply your force times the distance the object travels. However, if the object doesn't move in the direction of your push, you must multiply your force times the *component* (i.e., the portion) of the object's motion along the direction of your force.

As long as the angle between your force and the object's motion is small, you can often ignore this complication. However, as the angle becomes larger, the work you do on the object decreases. When the object moves at right angles to your force, the work you do on it drops to zero—it's not moving along the direction of your force at all. And for angles larger than 90°, the object moves *opposite* your force and the work you do on it actually becomes negative!

Recalling that forces always come in equal but oppositely directed pairs, we can now explain why energy is conserved: whenever you do work on an object, that object simultaneously does an equal amount of negative work on you! After all, if you push an object and it moves along the direction of your force, then it pushes back on you and you move along the direction opposite its force. You do positive work on it and it does negative work on you.

For example, when you lift the piano to judge its weight, you push it up as it moves up and thus do work on it. At the same time, the piano pushes your hand down but your hand moves up, so it does negative work on your hand. Overall, the piano's energy increases by exactly the same amount that your energy decreases—a perfect transfer! The energy that you're losing is mostly food energy, a form of chemical potential energy, and the energy the piano is gaining is mostly gravitational potential energy.

When you lower the piano after realizing that it's too heavy to carry up a ladder, the process is reversed and the piano transfers energy back to you. Now the piano does work on you and you do an equal amount of negative work on the piano. The piano is losing mostly gravitational potential energy and you are gaining mostly thermal energy—a disordered form of energy that we'll examine in Section 2.2. Unlike a rubber band, your body just isn't good at storing work done on it, so it simply gets hotter. Nonetheless, it's usually easier to have work done on you than to do work on something else. That's why it's easier to lower objects than to lift them.

Finally, when you hold the piano motionless above the pavement, while waiting for your friend to reinstall the wheel that fell off, you and the piano do no work on one another. You are simply converting chemical potential energy from your last meal into thermal energy in your muscles and getting overheated, probably in more ways than one.

Conserved Quantity: Energy **Transferred By: Work**

Energy: The capacity to do work. Energy has no direction. It can be hidden as potential energy.

Kinetic Energy: The form of energy contained in an object's motion.

Potential Energy: The form of energy stored in the forces between or within objects.

Work: The mechanical means for transferring energy; work = force · distance.

Check Your Understanding #5: Pitching

When you throw a baseball horizontally, you're not pushing against gravity. Are you doing any work on the baseball?

Answer: Yes.

Why: Any time you exert a force on an object and the object moves in the direction of that force, you are doing work on the object. Since gravity doesn't affect horizontal motion, the work you do on the baseball as you throw it ends up in the baseball as kinetic energy (energy of motion). As anyone who has been hit by a pitch can attest, a moving baseball has more energy than a stationary baseball.

Check Your Figures #1: Light Work, Heavy Work

You are moving books to a new shelf, 1.20 m (3.94 ft) above the old shelf. The books weigh 10.0 N (2.25 lbf) each and you have 10 of them to move. How much work must you do on them as you move them? Does it matter how many you move at once?

Answer: It takes 120 N · m (88.6 ft · lbf), no matter how many you lift at once.

Why: To keep each book from accelerating downward, you must support its weight with an upward force of 10.0 N. You must then move it upward 1.20 m. The work you do pushing upward on the book as it moves upward is given by Eq. 1.3.1:

$$\text{work} = \text{force} \cdot \text{distance} = 10.0\ \text{N} \cdot 1.20\ \text{m} = 12.0\ \text{N} \cdot \text{m}.$$

It takes 12.0 N · m of work to lift each book, whether you lift it together with other books or all by itself. The total work you must do on all 10 books is 120 N · m.

Gravitational Potential Energy

How much work would you do on the piano while lifting it straight up a ladder to the apartment? Apart from a little extra shove to get the piano moving upward, lifting it would entail supporting the piano's weight while it coasted upward at constant velocity from the sidewalk to the second floor. Since you would be pushing upward on the piano with a force equal in amount to its weight, the work you would do on it would be the product of its weight times the distance you lifted it.

As the piano rises in this scenario, its gravitational potential energy increases by an amount equal to the work you do on it. If we agree that the piano has zero gravitational potential energy when it rests on the sidewalk, then the suspended piano's gravitational potential energy is simply its weight times its height above the sidewalk. Since the piano's weight is equal to its mass times the acceleration due to gravity, its gravitational potential energy is its mass times the acceleration due to gravity times its height above the sidewalk.

These ideas aren't limited to pianos. You can determine the gravitational potential energy of any object by multiplying its mass times the acceleration due to gravity times its height above the level at which its gravitational potential energy is zero. This relationship can be expressed as a word equation:

$$\text{gravitational potential energy} = \text{mass} \cdot \text{acceleration due to gravity} \cdot \text{height}, \quad (1.3.2)$$

in symbols:

weight

$$U = (m \cdot g) \cdot h,$$

and in common language:

The higher it was, the harder it hit.

Of course, if you know the object's weight, you can use it in place of the object's mass times the acceleration due to gravity.

So what is the piano's gravitational potential energy when it reaches the second floor? If it weighs 2000 N (450 lbf) and the second floor is 5 m (16 ft) above the sidewalk, you will have done 10,000 N · m (about 7200 ft · lbf) of work in lifting it up there, and the piano's gravitational potential energy will thus be 10,000 N · m. The **newton-meter** is

the SI unit of energy and work; it's so important that it has its own name, the **joule** (abbreviated J). At the second floor, the piano's gravitational potential energy is 10,000 J.

A few everyday examples should give you a feeling for how much energy a joule is. Lifting a liter bottle of water 10 centimeters (4 inches) upward requires about 1 J of work. A 100-watt lightbulb needs 100 J every second to operate. Your body is able to extract about 2,000,000 J from a slice of cherry pie. When you're bicycling or rowing hard, your body can do about 1000 J of work each second. A typical flashlight battery has about 10,000 J of stored energy.

Quantity	*SI Unit*	*English Unit*	*SI → English*	*English → SI*
Energy	joule (J) = newton-meter (N · m)	foot-pound (ft · lbf)	1 J = 0.73757 ft · lbf	1 ft-lbf = 1.3558 J

Check Your Understanding #6: **Mountain Biking**

Bicycling to the top of a mountain is much harder than rolling back down to the bottom. At which place do you have the most gravitational potential energy?

Answer: You have the most at the top of the mountain.

Why: Bicycling up the mountain is hard because you must do work against the force of gravity. This work is stored as an increasing gravitational potential energy on your way uphill. Gravity then does work on you as you roll downhill and your gravitational potential energy decreases.

Check Your Figures #2: **Watch Out Below**

If you carry a U.S. penny (0.0025 kg) to the top of the Empire State Building (443.2 m or 1453.7 ft), how much gravitational potential energy will it have?

Answer: It will have about 11 J.

Why: The penny's gravitational potential energy is given by Eq. 1.3.2:

$$\text{gravitational potential energy} = 0.0025\ \text{kg} \cdot 9.8\ \text{N/kg} \cdot 443.2\ \text{m} = 11\ \text{N} \cdot \text{m} = 11\ \text{J}.$$

This 11-J increase in energy would be quite evident if you were to drop the penny. In principle, the penny could accelerate to very high speed (up to 340 km/h or 210 mph) and do lots of damage when it hit the ground. Fortunately, a falling penny actually tumbles and is slowed so much by the air that it isn't particularly dangerous.

Lifting the Piano with a Ramp

Unfortunately, you probably can't carry a grand piano up a ladder by yourself. You need a ramp, both to help you support the piano and to make it easier for you to raise the piano to the second floor.

Like the sidewalk, a ramp exerts a support force on the piano to prevent the piano from passing through its surface. However, since the ramp isn't exactly horizontal, that support force isn't exactly vertical (Fig. 1.3.4). The piano's weight still points straight

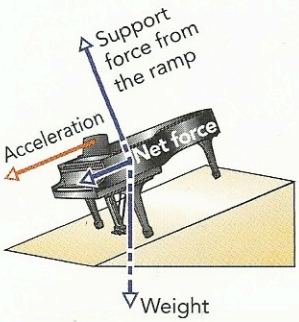


Fig. 1.3.4 A piano sliding on a frictionless ramp while experiencing a force due to gravity. It accelerates down the ramp more slowly than it would if it were falling freely.

down, but since the ramp's support force doesn't point straight up, the two forces can't balance one another. There is a nonzero net force on the piano.

This net force can't point into or out of the ramp. If it did, the piano would accelerate into or out of the ramp and the two objects would soon either lose contact or travel through one another. Instead, the net force points exactly along the surface of the ramp—a direction *tangent* or *parallel* to the surface. More specifically, it points directly downhill so the piano accelerates down the ramp!

However, because this net force is much smaller than the piano's weight, the piano's acceleration down the ramp is slower than if it were falling freely. This effect is familiar to anyone who has bicycled downhill or watched a cup slip slowly off a tilted table. Although gravity is still responsible, these objects accelerate more slowly than they would if falling and in the direction of the downward slope.

Therein lies the beauty of the ramp. By putting the piano on a ramp, you let the ramp support most of the piano's weight. The piano only experiences a small residual net force pushing it downhill along the ramp. If you now push uphill on the piano with a force that exactly balances that downhill force, the net force on the piano drops to zero and the piano stops accelerating. If you push uphill a little harder, the piano will accelerate up the ramp!

How does the ramp change the job of moving the piano? Suppose that you build a ramp 50 m (164 ft) long that extends from the sidewalk to the apartment's balcony, 5 m (16.4 ft) above the pavement. This ramp is sloped so that traveling 50 m uphill along its surface lifts the piano only 5 m upward (Fig. 1.3.5). Because of the ramp's 10 to 1 ratio between distance traveled along its surface and altitude change, you can push the 2000-N (450-lbf) piano up it at constant velocity with a force of only 200 N (45 lbf). Most people can push that hard, so the moving job is now realistic. To reach the apartment, you must push the piano 50 m along this ramp with a force of 200 N so that you will do a total of 10,000 J of work.

By pushing the piano up the ramp, you've used physical principles to help you perform a task that would otherwise have been nearly impossible. You didn't get something for nothing, however. The ramp is much longer than the ladder, and you have had to push the piano for a longer distance in order to raise it to the second floor. Of course, you have had to push with less force.

Remarkably, the amount of work you do in either case is 10,000 J. In carrying the piano up the ladder, the force you exert is large but the distance the piano travels in the direction of that force is small. In pushing the piano up the ramp, the force is small but the distance is large. Either way, the final result is the same: the piano ends up on the second floor with an additional 10,000 J of gravitational potential energy and you have

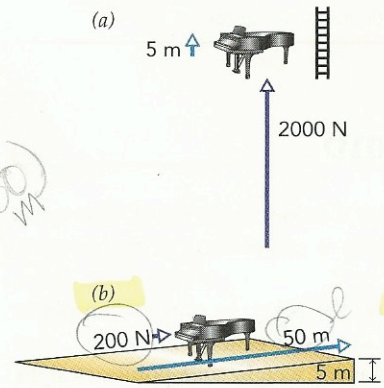


Fig. 1.3.5 To lift a piano weighing 2000 N, you can either (*a*) push it straight up or (*b*) push it along a ramp. To keep the piano moving at a constant velocity, you must make sure it experiences a net force of zero. If you lift it straight up the ladder in (*a*), you must exert an upward lifting force of 2000 N to balance the piano's downward weight. If you push it up the ramp shown in (*b*), you will only have to push the piano uphill with a force of 200 N in order to give the piano a net force of zero.

done 10,000 J of work. Expressed graphically in an equation, this relationship would appear as follows:

$$\text{work} = \text{large force} \cdot \text{small distance} = \text{small force} \cdot \text{large distance.}$$

In the absence of friction, the amount of work you do on the piano to get it to the second floor doesn't depend on how you raise it. No matter how you move that piano up to the second floor, its gravitational potential energy will increase by 10,000 J so you'll have to do 10,000 J of work on it. Even if you disassemble the piano into parts, carry them individually up the stairs, and reconstruct the piano in your friend's living room, you will have done 10,000 J of work lifting the piano.

Unless you're an experienced piano tuner, you'll probably be better off sticking with the ramp. It offers an easy method for one person to lift a baby grand piano. The ramp provides **mechanical advantage**—the process whereby a mechanical device redistributes the amounts of force and distance that go into performing a specific amount of mechanical work. In moving the piano with the help of the ramp, you've performed a task that would normally require a large force over a small distance by supplying a small force over a large distance. You might wonder whether the ramp itself does any work on the piano; it doesn't. Although the ramp exerts a support force on the piano and the piano moves along the ramp's surface, this force and the distance traveled are at right angles to one another. The ramp does no work on the piano.

Mechanical advantage occurs in many situations involving ramps. For example, it appears when you ride a bicycle up a hill. Climbing a gradual hill takes far less uphill force than climbing a steep hill of the same height. Since your pedaling ultimately provides the uphill force, it's much easier to climb the gradual hill than the steep one. Of course, you must travel a longer distance along the road as you climb the gradual hill than you do on the steep hill, so the work you do is the same in either case.

Ramps and inclined planes show up in many devices, where they reduce the forces needed to perform otherwise difficult tasks. They also change the character of certain activities. Skiing wouldn't be very much fun if the only slopes available were horizontal or vertical. By choosing ski slopes of various grades, you can select the net forces that set you in motion. Gentle slopes leave only small net forces and small accelerations; steep slopes produce large net forces and large accelerations.

Finally, our observation about mechanical advantage is this: mechanical advantage allows you to do the same work, but you must make a trade-off—you must choose whether you want a large force or a large distance. The product of the two parts, force times distance, remains the same.

Check Your Understanding #7: Access Ramps

Ramps for handicap entrances to buildings are often quite long and may even involve several sharp turns. A shorter, straighter ramp would seem much more convenient. What consideration leads the engineers designing these ramps to make them so long?

Answer: The engineers must limit the amount of force needed to propel a wheelchair steadily up the ramp. The steeper the ramp, the more force is required.

Why: A person traveling in a wheelchair on a level surface experiences little horizontal force and can move at constant velocity with very little effort. However, climbing a ramp at constant velocity requires a substantial uphill force equal in magnitude to the downhill force from gravity. The steeper the ramp, the more uphill force is needed to maintain constant velocity. A 12 to 1 grade (12 meters of ramp surface for each meter of rise in height) is the accepted limit to how steep such a long ramp can be.

Epilogue for Chapter 1

In this chapter we examined three everyday things and explored the basic physical laws that govern their behaviors. In *skating*, we looked at the concept of inertia and observed that objects accelerate only in response to forces. In *falling balls*, we introduced an important type of force—weight—and saw how weight causes unsupported objects to fall with equal downward accelerations.

In *ramps*, we encountered another type of force—support force. We also saw how the work done in changing an object's altitude doesn't depend on how you raise the object, since work is actually the mechanical means for transferring energy from one object to another. Energy, we noted, is one of the conserved physical quantities that govern the motion of objects in our universe. The particular type of energy we studied in *ramps* was gravitational potential energy—the potential energy associated with the force of gravity.

Explanation: Removing a Tablecloth from a Table

The dishes remain in place because of their inertia. As we've seen, an object in motion tends to remain in motion, while an object at rest tends to remain at rest.

Before you pull on the tablecloth, the dishes sit motionless on its surface and they tend to remain that way. By sliding the tablecloth off the table as quickly and smoothly as possible, you ensure that whatever force the tablecloth exerts on each dish occurs only for a very short time. As a result, the dishes undergo only the tiniest changes in velocity and remain essentially stationary on the tabletop.

Chapter Summary

How Skating Works: When you're gliding forward on frictionless skates, you experience no horizontal forces and move at a constant velocity. Inertia alone carries you forward. To change your velocity—to accelerate—something must exert a horizontal force on you. A forward force speeds you up while a backward force slows you down. Since sideways forces change your direction of travel, they, too, make you accelerate.

How Falling Balls Work: Any ball that's subject only to the force of gravity is a falling ball. It accelerates downward at a steady rate. Gravity affects only the ball's vertical motion, causing the ball's vertical component of velocity to increase steadily in the downward direction. If the ball were initially moving horizontally, it would continue that horizontal motion and drift steadily downfield as it falls.

A falling ball that's initially rising soon stops rising and begins to descend. The larger its initial upward component of velocity, the longer the ball rises and the greater its peak height. When the ball then begins to descend, the peak height determines how long it takes for the ball to reach the ground.

When you throw a ball, the vertical component of initial velocity determines how long the ball remains aloft. The horizontal component of initial velocity determines how quickly the ball moves downfield. A thrower intuitively chooses an initial speed and direction for a ball so that it moves just the right distance downfield by the time it descends to the desired height.

How Ramps Work: An object at rest on level ground experiences two forces: its downward weight and an upward support force from the ground that exactly balances that weight. The net force on the object is thus zero. If the ground is replaced with a ramp, however, the support force is no longer directly upward and the net force on the object isn't zero. Instead, the net force points downhill along the ramp and is equal to the weight of the object multiplied by the ratio of the ramp's rise to the ramp's length. If a 10-m-long ramp rises 1 m in height, then this ratio is 1 m divided by 10 m or 0.10. The net force downhill along this ramp is thus only 10% of the object's weight.

To stop an object from accelerating down a ramp, you must balance the downhill force by pushing equally hard uphill. In fact, if you exert more force up the ramp than it experiences down the ramp, the object will begin to accelerate up the ramp.

It takes less force to push an object up a ramp than to lift it directly upward, but you must push that object a longer distance along the ramp. Overall, the work you do in raising the object from one height to another is the same, whether or not you use the ramp. However, the ramp gives you mechanical advantage, allowing you to do work that would require an unrealistically large force by instead exerting a much smaller force for a much longer distance.

Important Laws and Equations

1. Newton's First Law of Motion: An object that is free from all outside forces travels at a constant velocity, covering equal distances in equal times along a straight-line path.

2. Newton's Second Law of Motion: An object's acceleration is equal to the net force exerted on that object divided by the object's mass, or

$$\text{net force} = \text{mass} \cdot \text{acceleration}. \qquad (1.1.2)$$

3. Relationship Between Mass and Weight: An object's weight is equal to its mass times the acceleration due to gravity, or

$$\text{weight} = \text{mass} \cdot \text{acceleration due to gravity}. \qquad (1.2.1)$$

4. The Velocity of an Object Experiencing Constant Acceleration: The object's present velocity differs from its initial velocity by the product of its acceleration times the time since it was at that initial velocity, or

$$\text{present velocity} = \text{initial velocity} + \text{acceleration} \cdot \text{time}. \qquad (1.2.2)$$

5. The Position of an Object Experiencing Constant Acceleration: The object's present position differs from its initial position by the product of its average velocity since it was at that initial position times the time since it was at that initial position, or

$$\text{present position} = \text{initial position} + \text{initial velocity} \cdot \text{time} + \tfrac{1}{2} \cdot \text{acceleration} \cdot \text{time}^2. \qquad (1.2.3)$$

6. Newton's Third Law of Motion: For every force that one object exerts on a second object, there is an equal but oppositely directed force that the second object exerts on the first object.

7. The Definition of Work: The work done on an object is equal to the product of the force exerted on that object times the distance that object travels in the direction of the force, or

$$\text{work} = \text{force} \cdot \text{distance}. \qquad (1.3.1)$$

8. Gravitational Potential Energy: An object's gravitational potential energy is its mass times the acceleration due to gravity times its height above a zero level, or

$$\text{gravitational potential energy} = \text{mass} \cdot \text{acceleration due to gravity} \cdot \text{height}. \qquad (1.3.2)$$

Exercises

1. A dolphin can leap several meters above the ocean's surface. Why doesn't gravity stop the dolphin from leaving the water?

2. As you jump across a small stream, does a horizontal force keep you moving forward? If so, what is that force?

3. Why does stamping your feet clean the snow off them?

4. Why does tapping your toothbrush on the sink dry it off?

5. The back of your car seat has a headrest to protect your neck during a collision. What type of collision causes your head to press against the headrest?

6. An unseatbelted driver can be injured by the steering wheel during a head-on collision. Why does the driver hit the steering wheel when the car suddenly comes to a stop?

7. Why do loose objects on the dashboard slide to the right when the car turns suddenly to the left?

8. Why is your velocity continuously changing as you ride on a carousel?

9. When you apply the brakes on your bicycle, which way do you accelerate?

10. One type of home coffee grinder has a small blade that rotates very rapidly and cuts the coffee beans into powder. Nothing prevents the coffee beans from moving, so why don't they get out of the way when the blade begins to push on them?

11. A blacksmith usually hammers hot metal on the surface of a massive steel anvil. Why is this more effective than hammering the hot metal on the surface of a thin steel plate?

12. A sprinter who is running a 200-m race travels the second 100 m in much less time than the first 100 m. Why?

13. If you pull slowly on the top sheet of a pad of paper, the whole pad will move. But if you yank suddenly on that sheet, it will tear away from the pad. What causes these different behaviors?

14. A ball falls from rest for 5 seconds. Neglecting air resistance, during which of the 5 seconds does the ball's speed increase most?

15. If you drop a ball from a height of 4.9 m, it will hit the ground 1 s later. If you fire a bullet exactly horizontally from a height of 4.9 m, it will also hit the ground 1 s later. Explain.

16. An acorn falls from a branch located 9.8 m above the ground. After 1 second of falling, the acorn's velocity will be 9.8 m/s downward. Why hasn't the acorn hit the ground?

17. A diver leaps from a 50-m cliff into the water below. The cliff is not perfectly vertical, so the diver must travel forward several meters in order to avoid the rocks beneath him. In fact, he leaps directly forward rather than upward. Explain why a forward leap allows him to miss the rocks.

18. The kicker in a sporting event isn't always concerned with how far downfield the ball travels. Sometimes the ball's flight time is more important. If he wants to keep the ball in the air as long as possible, which way should he kick it?

19. The heads of different golf clubs are angled to give the golf ball different initial velocities. The golf ball's speed remains almost constant, but the angle changes with the different clubs. Neglecting any air effects, how does changing the initial angle of the ball affect the distance the ball travels?

20. A speedboat is pulling a water-skier with a rope, exerting a large forward force on her. The skier is traveling forward in a straight line at constant speed. What is the net force she experiences?

21. Your suitcase weighs 50 N. As you ride up an escalator toward the second floor, carrying that suitcase, you are traveling at a constant velocity. How much upward force must you exert on the suitcase to keep it moving with you?

22. What is the net force on (a) the first car, (b) the middle car, and (c) the last car of a metro train traveling at constant velocity?

23. Two teams are having a tug-of-war with a sturdy rope. It has been an even match so far, with neither team moving. What is the net force on the left team?

24. When you kick a soccer ball, which pushes on the other harder: your foot or the soccer ball?

25. The earth exerts a downward force of 850 N on a veteran astronaut as he works outside the space shuttle. What force (if any) does the astronaut exert on the earth?

26. A car passes by, heading to your left, and you reach out and push it toward the left with a force of 50 N. Does this moving car push on you and, if so, with what force?

27. Which is larger: the force the earth exerts on you or the force you exert on the earth?

28. Comic book superheroes often catch a falling person only a hairsbreadth from the ground. Why would this rescue actually be just as fatal for the victim as hitting the ground itself?

29. You accidentally miss the doorway and run into the wall. You suddenly experience a backward force that is several times larger than your weight. What's the origin of this force?

30. When you fly a kite, there is a time when you must do (positive) work on the kite. Is that time when you let the kite out or when you pull it in?

31. Which does more work in lifting a grain of rice over its head: an ant or a person? Use this result to explain how insects can perform seemingly incredible feats of lifting and jumping.

32. Are you doing work while kneading bread? If so, when?

33. While hanging a picture, you accidentally dent the wall with a hammer. Did the hammer do work on the wall?

34. You're cutting wood with a handsaw. You have to push the saw away from you as it moves away from you and pull the saw toward you as it moves toward you. When are you doing work on the saw?

35. The steel ball in a pinball game rolls around a flat, tilted surface. If you flick the ball straight uphill, it gradually slows to a stop and then begins to roll downhill. Which way is the ball accelerating as it rolls uphill? Downhill?

36. Why do less snow and other debris accumulate on a steep roof than on a flatter roof?

37. You roll a marble down a playground slide that starts level, then curves downward, and finally curves very gradually upward so that it's level again at the end. Where along its travel does the marble experience its greatest acceleration? Its greatest speed?

38. When you're roller skating on level pavement, you can maintain your speed for a long time. But as soon as you start up a gradual hill, you begin to slow down. What slows you?

39. When the brakes on his truck fail, the driver steers it up a runaway truck ramp. As the truck rolls up the ramp, it slows to a stop. What happens to the truck's kinetic energy, its energy of motion?

Problems

1. If your car has a mass of 800 kg, how much force is required to accelerate it forward at 4 m/s^2?

2. If your car accelerates from rest at a steady rate of 4 m/s^2, how soon will it reach 88.5 km/h (55.0 mph or 24.6 m/s)?

3. On Mars, the acceleration due to gravity is 3.71 m/s^2. What would a rock's velocity be 3 s after you dropped it on Mars?

4. How far would a rock fall in 3 s if you dropped it on Mars? (See Problem 3.)

5. How would your Mars weight compare to your earth weight? (See Problem 3.)

6. A basketball player can leap upward 0.5 m. What is his initial velocity at the start of the leap?

7. How long does the basketball player in Problem 6 remain in the air?

8. A sprinter can reach a speed of 10 m/s in 1 s. If the sprinter's acceleration is constant during that time, what is the sprinter's acceleration?

9. If a sprinter's mass is 60 kg, how much forward force must be exerted on the sprinter to make the sprinter accelerate at 0.8 m/s^2?

10. How much does a 60-kg person weigh on earth?

11. If you jump upward with a speed of 2 m/s, how long will it take before you stop rising?

12. How high will you be when you stop rising in Problem 11?

13. How much force must a locomotive exert on a 12,000-kg boxcar to make it accelerate forward at 0.4 m/s^2?

14. How long will it take the boxcar in Problem 13 to reach its cruising speed of 100 km/h (62 mph or 28 m/s)?

15. The builders of the pyramids used a long ramp to lift 20,000-kg (22-ton) blocks. If a block rose 1 m in height while traveling 20 m along the ramp's surface, how much uphill force was needed to push it up the ramp at constant velocity?

16. How much work was done in raising one of the blocks in Problem 15 to a height of 50 m?

17. What is the gravitational potential energy of one of the blocks in Problem 15 if it's now 75 m above the ground?

18. As water descends from the top of a tall hydroelectric dam, its gravitational potential energy is converted to electric energy. How much gravitational potential energy is released when 1000 kg of water descends 200 m to the generators?

19. The tire of your bicycle needs air so you attach a bicycle pump to it and begin to push down on the pump's handle. If you exert a downward force of 25 N on the handle and the handle moves downward 0.5 m, how much work do you do?

20. You're using a wedge to split a log. You are hitting the wedge with a large hammer to drive it into the log. It takes a force of 2000 N to push the wedge into the wood. If the wedge moves 0.2 m into the log, how much work have you done on the wedge?

21. The wedge in Problem 20 acts like a ramp, slowly splitting the wood apart as it enters the log. The work you do on the wedge, pushing it into the log, is the work it does on the wood, separating its two halves. If the two halves of the log only separate by a distance of 0.05 m while the wedge travels 0.2 m into the log, how much force is the wedge exerting on the two halves of the log to rip them apart?

22. You're sanding a table. You must exert a force of 30 N on the sandpaper to keep it moving steadily across the table's surface. You slide the paper back and forth for 20 minutes, during which time you move it 1000 m. How much work have you done?