6TH EDITION

How Things Work

THE PHYSICS OF EVERYDAY LIFE

Louis A. Bloomfield

The University of Virginia

WILEY

To Karen for being such a wonderful friend and companion,

to Aaron, Elana, and Rich for being everything a father could want,

to Max and Rosie for being so cheerful and attentive,

and to the students of the University of Virginia for making teaching, research, and writing fun.

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The Goals of This Book

As they read this book, students should:

1. Begin to see science in everyday life. Science is everywhere; we need only open our eyes to see it. We're surrounded by things that can be understood in terms of science, much of which is within a student's reach. Seeing science doesn't mean that when viewing an oil painting they should note only the selective reflection of incident light waves by organic and inorganic molecules. Rather, they should realize that there's a beauty to science that complements aesthetic beauty. They can learn to look at a glorious red sunset and appreciate both its appearance and why it exists.

2. Learn that science isn't frightening. The increasing technological complexity of our world has instilled within most people a significant fear of science. As the gulf widens between those who create technology and those who use it, their ability to understand one another and communicate diminishes. The average person no longer tinkers with anything and many modern devices are simply disposable, being too complicated to modify or repair. To combat the anxiety that accompanies unfamiliarity, this book shows students that most objects can be examined and understood, and that the science behind them isn't scary after all. The more we understand how others think, the better off we'll all be.

3. Learn to think logically in order to solve problems. Because the universe obeys a system of well-defined rules, it permits a logical understanding of its behaviors. Like mathematics and computer science, physics is a field of study where logic reigns supreme. Having learned a handful of simple rules, students can combine them logically to obtain more complicated rules and be certain that those new rules are true. So the study of physical systems is a good place to practice logical thinking.

4. Develop and expand their physical intuition. When you're exiting from a highway, you don't have to consider velocity, acceleration, and inertia to know that you should brake gradually—you already have physical intuition that tells you the consequences of doing otherwise. Such physical intuition is essential in everyday life, but it ordinarily takes time and experience to acquire. This book aims to broaden a student's physical intuition to situations they normally avoidor have yet to encounter. That is, after all, one of the purposes of reading and scholarship: to learn from other people's experiences.

5. Learn how things work. As this book explores the objects of everyday life, it gradually uncovers most of the physical laws that govern the universe. It reveals those laws as they were originally discovered: while trying to understand real objects. As they read this book and learn these laws, students should begin to see the similarities between objects, shared mechanisms, and recurring themes that are reused by nature or by people. This book reminds students of these connections and is ordered so that later objects build on their understanding of concepts encountered earlier.

6. Begin to understand that the universe is predictable rather than magical. One of the foundations of science is that effects have causes and don't simply occur willy-nilly. Whatever happens, we can look backward in time to find what caused it. We can also predict the future to some extent, based on insight acquired from the past and on knowledge of the present. And where predictability is limited, we can understand those limitations. What distinguishes the physical sciences and mathematics from other fields is that there are often absolute answers, free from inconsistency, contraindication, or paradox. Once students understand how the physical laws govern the universe, they can start to appreciate that perhaps the most magical aspect of our universe is that it is not magic; that it is orderly, structured, and understandable.

7. Obtain a perspective on the history of science and technology. None of the objects that this book examines appeared suddenly and spontaneously in the workshop of a single individual who was oblivious to what had been done before. These objects were developed in the context of history by people who were generally aware of what they were doing and usually familiar with any similar objects that already existed. Nearly everything is discovered or developed when related activities make their discoveries or developments inevitable and timely. To establish that historical context, this book describes some of the history behind the objects it discusses.

Visual Media

Because this book is about real things, its videos, illustrations, and photographs are about real things, too. Whenever possible, these visual materials are built around familiar objects so that the concepts they are meant to convey become associated with objects students already know. Many students are visual learners—if they see it, they can learn it. By superimposing the abstract concepts of physics onto simple realistic visuals, this book attempts to connect physics with everyday life. That idea is particularly evident at the opening of each section, where the object examined in that section appears in a carefully rendered drawing. This drawing provides students with something concrete to keep in mind as they encounter the more abstract physical concepts that appear in that section. By lowering the boundaries between what the students see in the book and what they see in their environment, the rich visual media associated with this book makes science a part of their world.

Features

This printed book contains 40 sections, each of which discusses how something works. The sections are grouped together in 15 chapters according to the major physical themes developed. In addition to the discussion itself, the sections and chapters include a number of features intended to strengthen the educational value of this book. Among these features are:

- **Chapter introductions, experiments, and itineraries.** Each of the 15 chapters begins with a brief introduction to the principal theme underlying that chapter. It then presents an experiment that students can do with household items to observe firsthand some of the issues associated with that physical theme. Lastly, it presents a general itinerary for the chapter, identifying some of the physical issues that will come up as the objects in the chapter are discussed.
- **Section introductions, questions, and experiments.** Each of the 40 sections explains how something works. Often that something is a specific object or group of objects, but it is sometimes more general. A section begins by introducing the object and then asks a number of questions about it, questions that might occur to students as they think about the object and that are answered by the section. Lastly, it suggests some simple experiments that students can do to observe some of the physical concepts that are involved in the object.
- **Check your understanding and check your figures.** Sections are divided into a number of brief segments, each of which ends with a "Check Your Understanding" question. These questions apply the physics of the preceding segment to new situations and are followed by answers and explanations. Segments that introduce important equations also end with a "Check Your Figures" question. These questions show how the equations can be applied and are also followed by answers and explanations.
- **Chapter epilogue and explanation of experiment.** Each chapter ends with an epilogue that reminds the students of how the objects they studied in that chapter fit within the chapter's physical theme. Following the epilogue is a brief explanation of the experiment suggested at the beginning of the chapter, using physical concepts that were developed in the intervening sections.
- **Chapter summary and laws and equations.** The sections covered in each chapter are summarized briefly at the end of the chapter, with an emphasis on how the objects work. These summaries are followed by a restatement of the important physical laws and equations encountered within the chapter.
- **Chapter exercises and problems.** Following the chapter summary material is a collection of questions dealing with the physics concepts in that chapter. Exercises ask the students to apply those concepts to new situations. Problems ask the students to apply the equations in that chapter and to obtain quantitative results.
- **Three-way approach to the equation of physics.** The laws and equations of physics are the groundwork on which everything else is built. But because each student responds differently to the equations, this book presents them carefully and in context. Rather than making one size fit all, these equations are presented in three different forms. The first is a word equation, identifying each physical quantity by name to avoid any ambiguities. The second is a symbolic equation, using the standard format and notation. The third is a sentence that conveys the meaning of the equation in simple terms and often by example. Each student is likely to find one of these three forms more comfortable, meaningful, and memorable than the others.
- **Glossary.** The key physics terms are assembled into a glossary at the end of the book. Each glossary term is also marked in bold in the text when it first appears together with its contextual definition.
- **Historical, technical, and biographical asides.** To show how issues discussed in this book fit into the real world of people, places, and things, a number of brief asides have been placed in the margins of the text. An appropriate time at which to read a particular aside is marked in the text by a color-coded mark such as ■.

Organization

The 40 sections that make up this book are ordered so that they follow a familiar path through physics: mechanics, heat and thermodynamics, resonance and mechanical waves, electricity and magnetism, light, optics, and electronics, and modern physics. Because there are too many topics here to cover in a single semester, the book is designed to allow shortcuts through the material. In general, the final sections in each chapter and the final chapters in each of the main groups mentioned above can be omitted without serious impact on the material that follows. The only exceptions to that rule are the first two chapters, which should be covered in their entirety as the introduction to any course taught from this book. The book also divides neatly in half so that it can be used for two independent one-semester courses—the first covering Chapters 1–9 and the second covering Chapters 1, 2, and 10–15. That two-course approach is the one I use myself. A detailed guide to shortcuts appears on the instructor's website.

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- **Computer simulations of the book's objects.** One of the best ways to learn how a violin or nuclear reactor works is to experiment with it, but that's not always practical or safe. Computer simulations are the next best thing and the student website includes many simulations of the book's objects. Associated with each simulation is a sequence of interactive questions that turn it into a virtual laboratory experiment. In keeping with the *How Things Work* concept, the student is then able to explore the concepts of physics in the context of everyday objects themselves.
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The real test of this book, and of any course taught from it, is its impact on students' lives long after their classroom days are done. Theirs' is a time both exciting and perilous; one in which physics will play an increasingly important and multifaceted role. It is my sincere hope that their encounter with this book will leave those students better prepared for what lies ahead and will help them make the world a better place in the years to come.

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1 The Laws of Motion
PART 1

The aim of this book is to broaden your perspectives on familiar objects and situations by helping you understand the science that makes them work. Instead of ignoring that science or taking it for granted, we'll seek it out in the world around us, in the objects we encounter every day. As we do so, we'll discover that seemingly "magical" objects and effects are quite understandable 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 examine 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.

ACTIVE LEARNING EXPERIMENTS

Removing a Tablecloth from a Table

One famous "magical" effect allows a tablecloth to be removed from a set table without breaking the dishes. The person performing this stunt pulls the tablecloth sideways in one lightning-fast motion. The smooth, slippery tablecloth slides out from under the dishes, leaving them behind and nearly unaffected.

With some practice, you too can do this stunt. Choose a slick, unhemmed tablecloth, one with no flaws that might catch on the dishes. A supple fabric such as silk helps because you can then pull the cloth slightly downward at the edge of the table. When you get up the nerve to try—with unbreakable dishes, of course—make sure that you pull suddenly and swiftly, so as to minimize the time it takes for the cloth to slide out from under the dishes. Leaving a little slack in the cloth at first helps you get your hands up to speed before the cloth snaps taut and begins to slide off the table. Don't make the mistake of starting slowly or you'll decorate the floor.

Courtesy Lou Bloomfield

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rate at which your position is changing with time. Its magnitude is your **speed**, the distance you travel in a certain amount of time,

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

and its direction is the direction in which you're heading.

For example, if you move 2 meters (6.6 feet) west in 1 second, then your velocity is 2 meters per second (6.6 feet per second) toward the west. If you maintain that velocity, your position moves 20 meters west in 10 seconds, 200 meters west in 100 seconds, and so on. Even when you're motionless, you still have a velocity—zero. A velocity of zero is special, however, because it has no direction.

When you're gliding freely, however, with nothing pushing you horizontally, your velocity is particularly easy to describe. Since you travel at a steady speed along a straight-line path, your velocity is constant—it never changes. In a word, you **coast**. And if you happen to be at rest with nothing pushing you horizontally, you remain at rest. Your velocity is constantly zero.

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 [3]. The outside influences referred to in this law are called **forces**, a technical term for pushes and pulls. An object that moves in accordance with Newton's first law is said to be **inertial**.

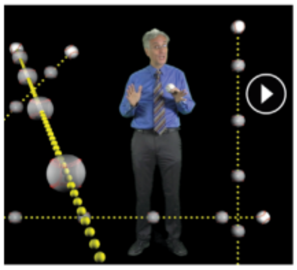


Fig. 1.1.2 These baseballs are in deep space and free from outside influences. Each ball moves according to inertia alone, following a straight-line path at a steady pace.

[3] 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.

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.

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. Mass has no direction, so it's not a vector quantity. It is a **scalar quantity**—that is, a quantity that has only an amount.

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 the rate at which your velocity is changing with time (Fig. 1.1.3). *Any* change in your velocity is acceleration, whether you're speeding up, slowing down, or 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

Fig. 1.1.3 A rightward force is causing this baseball to accelerate toward the right. Its velocity is increasing toward the right so that it travels farther with each passing second.

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.)

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, but this time in the backward 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 position or velocity. You can determine a skater's position in a single glance and her velocity by comparing her positions in two separate glances. To observe her acceleration, however, you need at least three glances because you are looking for how her velocity is changing with time. If her speed isn't steady or her path isn't straight, then she's 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 it starts 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

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 have only 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. 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 among 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:

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

and in everyday language:

Throwing a baseball is much easier than throwing a bowling ball (Fig. 1.1.4).

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 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

Fig. 1.1.4 A baseball accelerates easily because of its small mass. A bowling ball has a large mass and is harder to accelerate.

corresponding 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. 1.1.5).

So far we've explored five principles:

1. Your position indicates exactly where you're located.
2. Your velocity measures the rate at which your position is changing with time.
3. Your acceleration measures the rate at which your velocity is changing with time.
4. 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.

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.

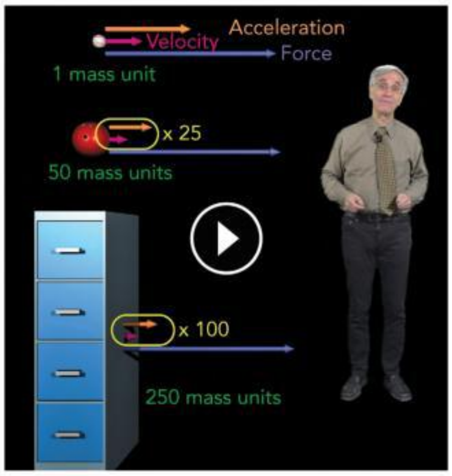


Fig. 1.1.5 A baseball, bowling ball, and file cabinet have different masses and accelerate quite differently in response to equal rightward forces. Arrows representing the accelerations and velocities of the bowling ball and file cabinet are magnified to make them visible.

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 2 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, online, 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; 1 meter is about the length of a long stride; 1 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 squared**, abbreviated m/s^2). One meter per second is a healthy walking speed; 1 meter per second^2 is about the acceleration of an elevator after the door closes and it begins to move 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. Conveniently, 1 newton is about the weight of a small apple; that is, if you hold that apple 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 I 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-mass and pound-force.

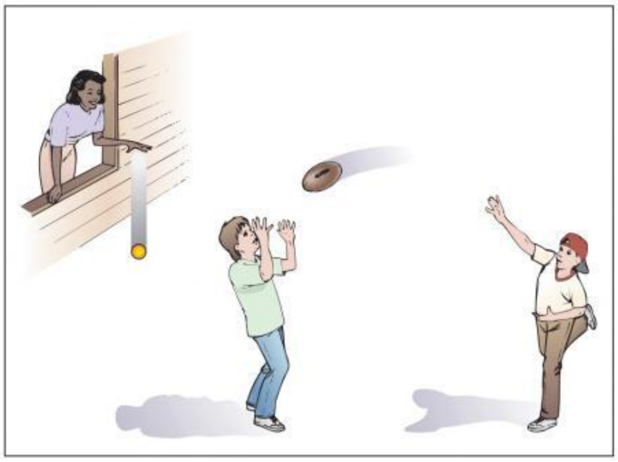
Check Your Understanding #5: Going for a Walk

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

Answer: About 2.24 miles.

Why: There are many different units in this example, so we must do some converting. First, an hour is 3600 s, so in an hour of walking at 1 m per second you will have walked 3600 m. Second, a mile is about 1609 m, so each time you travel 1609 m you have traveled 1 mile. By walking 3600 m, 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, Earth. Gravity weakens with distance; the moon and sun are so far away that we notice their gravities only through such subtle effects as the ocean tides.

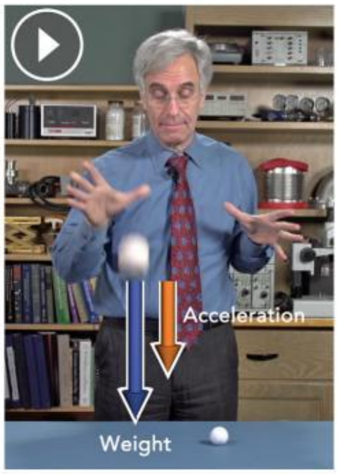


Fig. 1.2.1 A dropped baseball experiences only its weight—the force due to gravity. It accelerates downward.

Earth's gravity exerts a downward force on any object near its surface. That object is attracted directly toward the center of 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 back and forth!

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 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 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 Earth's atmosphere encounters additional forces due to the air, let's ignore those forces for the time being. Doing so costs us only a little in terms of accuracy—the air's forces on the ball 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

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

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 Earth's surface experiences a downward acceleration of 9.8 m/s^2 (32 ft/s^2), regardless of its mass (Fig. 1.2.2). 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 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 forces due to the air 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 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 Earth, or about 1.6 m/s^2.

Fig. 1.2.2 A baseball (left) and a golf ball (right) both accelerate downward at the acceleration due to gravity. Their differences in weight and mass perfectly compensate for one another.

The Velocity of a Falling Ball

We're now ready to examine the motion of a falling ball near Earth's surface. A falling ball is one that has only its weight, the force due to 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 s, 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 acceleration times the time that 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:

$$\mathbf{v}_\text{f} = \mathbf{v}_\text{i} + \mathbf{a} \cdot t,$$

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. 1.2.3). After 1 s, the ball has a downward velocity of 9.8 m/s (32 ft/s). After 2 s, the ball has a downward velocity of 19.6 m/s (64 ft/s). After 3 s, its downward velocity is 29.4 m/s (96 ft/s), and so on.

Because a ball falls in a three-dimensional world, Eq. 1.2.2 is a relationship among *vector* quantities. When a ball is dropped from rest, however, its motion is strictly vertical and all of those vector quantities point either up or down. In that special case of motion along a vertical line, we can represent vector quantities that point up by ordinary positive values and vector quantities that point down by ordinary negative values. The acceleration due to gravity is then -9.8 m/s^2, and a ball that has been falling from rest for 2 s has a velocity of -19.6 m/s. As we'll see later in this section, those simplified values are actually the *upward components* of the ball's acceleration and velocity.

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: 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 #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-s 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 m (402 ft or as high as 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 s, 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 s, 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-s free fall is pretty unrealistic. Try for a 2- or 3-s free fall instead.

Tossing the Ball Upward

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 its weight and it accelerates downward at 9.8 m/s^2 (32 ft/s^2).

Equation 1.2.2 still describes how the ball's velocity depends on the fall time, but now the initial velocity isn't zero. If you toss the ball straight up in the air, it leaves your hand with a large upward velocity (Fig. 1.2.4). 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 1 s 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. 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.

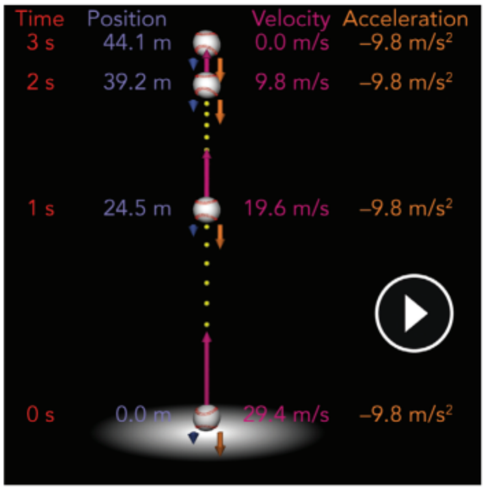


Fig. 1.2.4 The moment you let go of a ball thrown straight upward, it begins to accelerate downward at 9.8 m/s^2. The ball rises but its upward velocity diminishes steadily until it momentarily comes to a stop. It then descends with its downward velocity increasing steadily. In this example, the ball rises for 3 s and comes to rest. It then descends for 3 s before returning to your hand in a very symmetrical flight.

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.

Check Your Understanding #4: A Toss-Up

You toss a coin straight up, and it rises well above your head. At the moment the coin reaches its peak height, what is its velocity? Is that velocity constant or changing with time? Is the coin's acceleration constant or changing with time?

Answer: The coin's velocity is momentarily zero at its peak, but that velocity is changing with time. The coin's acceleration, however, is constant—the acceleration due to gravity.

Why: Once the coin leaves your hand, it's a falling object and constantly accelerates downward at the acceleration due to gravity. Because it begins its fall traveling upward, it rises at a gradually decreasing speed, is momentarily motionless at its peak, and then descends at a gradually increasing speed.

How a Thrown Ball Moves: Projectile Motion

What happens if you don't toss the ball exactly straight up? Suppose you throw the ball upward at some angle. The ball still rises to a peak height and then descends, but 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 you 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. 1.2.5). For example, the upward component of an object's position is that object's altitude.

A ball's altitude, however, is only part of its position; you still need to know where it is in relation to your right or left 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 to one another. This means that you can completely specify the ball's position by its distance to your right, its distance in front of you, and its altitude above you. If it's to your left, behind you, or below you, the corresponding components have negative values. For example, the ball might be 3 m to your right, −3 m in front of you (which is 3 m behind you), and 2 m above you.

When you drop the ball from rest or toss it straight up, its motion is entirely vertical and only the upward components of its position, velocity, and acceleration are important. When the falling ball is also moving horizontally, however, you'll need to pay attention to the rightward and forward components of those vector quantities. Throwing the ball forward helps because it eliminates any rightward components of the motion. The ball then arcs forward with a position specified at each moment by its altitude (its upward component) and its distance *downfield* (its forward component).

Although Eqs. 1.2.2 and 1.2.3 were introduced to describe a ball's vertical motion, they also describe its horizontal motion. More generally, they relate three vector quantities—the ball's position, velocity, and constant acceleration—to one another and describe how the ball's position and velocity change with time when that ball undergoes constant acceleration in any direction. Of course, since we're concerned now with falling balls, the relevant constant acceleration is the downward acceleration due to gravity.

These equations also apply to the *components* of the ball's position, velocity, and constant acceleration. If you add the words *upward component of* in front of each vector quantity

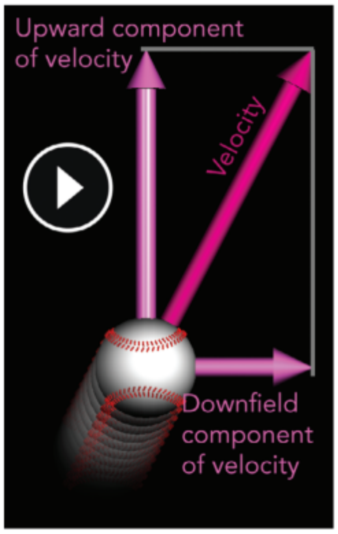


Fig. 1.2.5 Even if the ball has a velocity that is neither purely vertical nor purely horizontal, its velocity may nonetheless be viewed as having an upward component and a downfield component. Part of its total velocity acts to move this ball upward, and part of its total velocity acts to move this ball downfield.

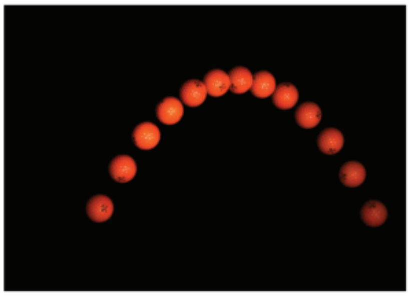


Fig. 1.2.6 This golf ball drifts steadily to the right after being thrown because gravity affects only the ball's upward component of velocity.

in Eqs. 1.2.2 and 1.2.3, the equations correctly describe the ball's vertical motion. Now it's time to add the words *forward component of* to those equations so that they describe the ball's horizontal motion.

Once you've thrown the ball forward and are no longer touching it, its motion can be broken into two parts: its upward motion and its forward motion (Fig. 1.2.5). Part of the ball's initial velocity is in the upward direction, and that upward component of velocity determines the object's ascent and descent. Part of the ball's initial velocity is in the forward direction, and that forward component of velocity determines the ball's progress downfield.

Because the ball is accelerating straight downward, the forward component of its acceleration is zero and the forward component of its velocity thus remains constant. The ball travels downfield at a steady rate throughout its flight (Fig. 1.2.6). Overall, the upward 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 forward component of the initial velocity determines how quickly the ball travels downfield during its time aloft (Fig. 1.2.7).

Just before the ball hits the ground it still has its original forward component of velocity, but its upward component of velocity is now negative—the ball is moving downward. The total velocity of the ball is composed of these two components. The ball starts with its velocity directed up and forward, and finishes with its velocity directed 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 forward component of velocity; in other words, you must achieve a good balance between the upward and forward components of velocity (Fig. 1.2.8). These components of velocity together determine the ball's flight path, its **trajectory**. If you throw the ball straight up, it will stay aloft for a long time but will not travel downfield at all (and you will need to wear a helmet). If you throw the ball directly forward, it will travel downfield quickly but hit the ground almost immediately.

Neglecting air resistance and the altitude difference between your throwing arm and the ground that the ball will eventually hit, your best choice is to throw the ball forward at an angle of 45° above horizontal. At that angle, the initial upward component of velocity will be the same as the initial forward component of velocity. The ball will stay aloft for a reasonably long time and will make good use of that time to move downfield. Other angles won't make such good use of the initial speed to move the ball downfield. (A discussion of how to determine the upward and forward components of velocity appears in Appendix A, online.)

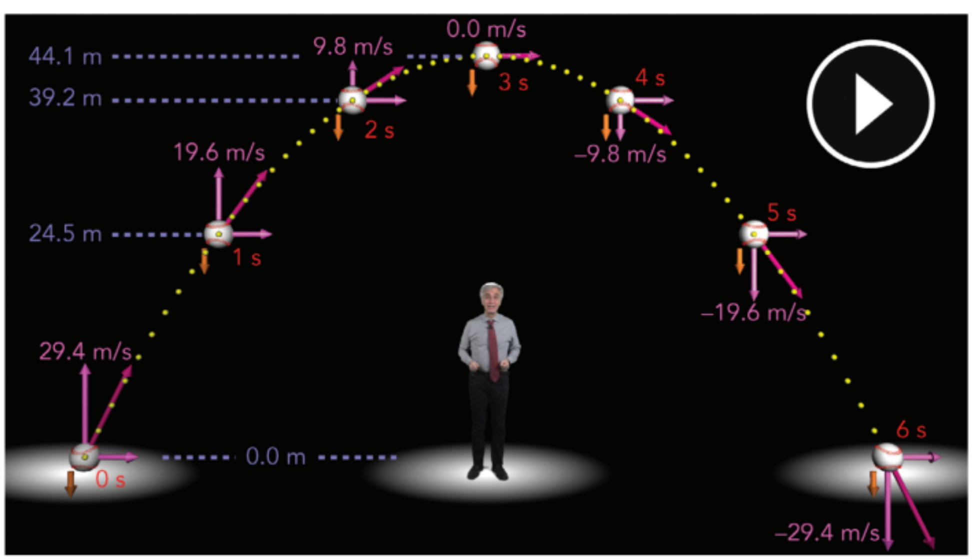


Fig. 1.2.7 If you throw a ball upward, at an angle, part of the initial velocity will be in the upward direction and part will be in the downfield direction. The vertical and horizontal motions will take place independently of one another. The ball will rise and fall just as it did in Figs. 1.2.3 and 1.2.4; at the same time, however, it will move downfield. Because there is no horizontal component of acceleration (gravity acts only in the vertical direction), the downfield component of velocity remains constant during the ball's 6-s trip.

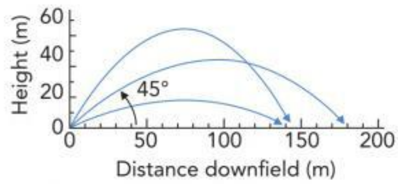


Fig. 1.2.8 If you want the ball to hit the ground as far from your feet as possible, given a certain initial speed, throw the ball at 45° above horizontal. Halfway between horizontal and vertical, such a throw gives the ball equal initial upward and downfield components of velocity. The ball then stays aloft for a relatively long time and makes good use of that flight time to travel downfield.

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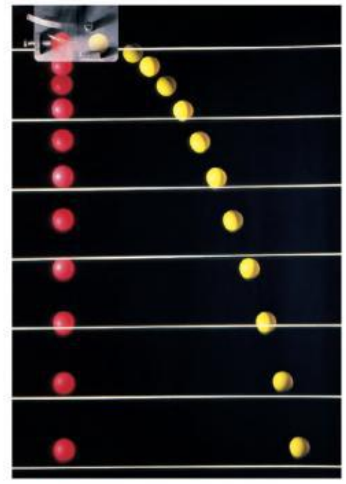


Fig. 1.2.9 When these two balls were dropped, they accelerated downward at the constant rate of 9.8 m/s^2 and their velocities increased steadily in the downward direction. Even though one of them was initially moving to the right, they descended together.

These same ideas apply to two baseballs, one dropped from a cliff and the other thrown directly forward from that same cliff. If both leave your hands at the same time, they will both hit the ground below at the same time (Fig. 1.2.9). The fact that the second ball has an initial forward velocity doesn't affect the time it takes to descend to the ground because the horizontal and vertical motions are independent. Of course, the ball thrown directly forward will strike the ground far from the base of the cliff, while the dropped ball will land directly below your hand.

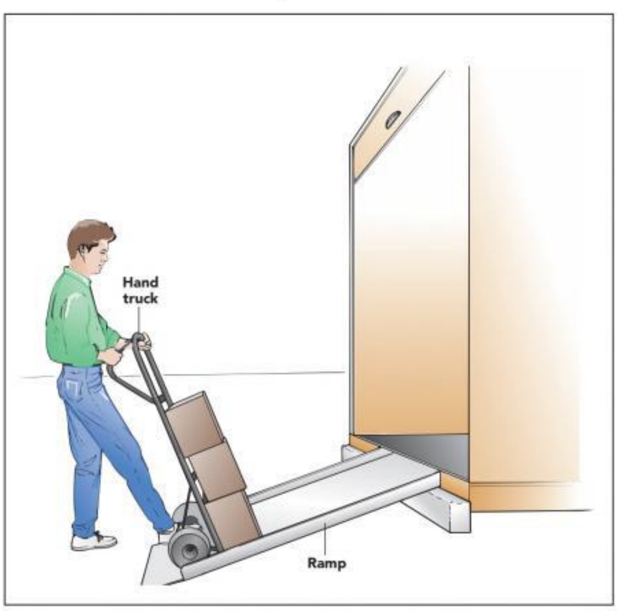
Check Your Understanding #5: **Aim High**

Why must a sharpshooter or an archer aim somewhat above her target? Why can't she simply aim directly at the bull's-eye to hit it?

Answer: The bullet or arrow will fall in flight, so she must compensate for its loss of height.

Why: To hit the bull's-eye, the sharpshooter or archer must aim above the bull's-eye because the projectile will fall in flight. Even if the target is higher or lower than the sharpshooter, the projectile will fall below the point at which she is aiming. The longer the bullet or arrow is in flight, the more it will fall and the higher she must aim. As the distance to the target increases, the flight time increases and her aim must move upward.

SECTION 1.3 Ramps



In the previous section, we looked at what happens to an object experiencing only a single force, its weight. 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 its downward weight 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 an unbreakable water bottle on a level table or board. Hold the bottle steady for a second and then let go of it without pushing on it. Why does the bottle remain motionless?

Now, equip yourself with a pencil. Have a friend tilt the surface of the table or board slightly so that the bottle begins to roll downhill. Can you stop the bottle by pushing on it with the pencil? Place the bottle 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 bottle from rolling downhill? Now try to push the bottle uphill with the pencil (1) when the table is slightly tilted and (2) 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 is 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 forces due to the air; they will needlessly complicate our discussion. Besides, as long as the piano is on wheels, friction is negligible.

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.

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

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.

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 #2: 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 your downward 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 do things—to break the board, to produce motion, and to squash whatever is 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 what's contained in a so-called "energy drink"; 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 that can be transferred between objects or, in the case of energy, be 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 Earth and undergoes an increase in **gravitational potential energy**, energy stored in the gravitational forces between the rock and 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 #3: **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 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* of the object's motion that lies 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 #4: **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 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:

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

in symbols:

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

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 1500-watt hairdryer needs 1500 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 #5: 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: 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 through the air, which slows it to about 40 km/h or 25 mph.

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 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.

Fig. 1.3.4 When a piano is on a ramp, its weight and the ramp's support force don't cancel. Instead, they sum to a downhill ramp force. If no other forces act on the piano, the ramp force is its net force and it accelerates downhill.

How Falling Balls Work: Any ball that's subject only to its weight—the force due to 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 a ramp force that's 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 ramp 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 ramp 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 a mechanical advantage, allowing you to do work that would require an unrealistically large force by instead exerting a smaller force for a longer distance.

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. Velocity of an object experiencing constant acceleration: The object's present velocity differs from its initial velocity by 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. Position of an object experiencing constant acceleration: The object's present position differs from its initial position by 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. Definition of work: The work done on an object is equal to 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

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

2 The Laws of Motion

PART 2

In the previous chapter, we saw how things move from place to place and encountered energy, an important conserved quantity. But motion doesn't always involve a change of position, and energy isn't nature's only conserved quantity. In this chapter, we'll take a look at a second type of motion—rotation—and at two other conserved quantities—momentum and angular momentum. Spinning objects are quite common, and we'll do well to explore their laws of motion before proceeding much further. With those additional concepts under our belts, we'll be ready to explore the physics behind a broad assortment of mechanical objects.

ACTIVE LEARNING EXPERIMENTS

A Spinning Pie Dish

Spinning a dish on the top of a narrow post seems like a simple activity. But don't let its uncomplicated appearance deceive you: there are lots of physics involved in keeping the dish turning, in gradually slowing it down, and in preventing it from falling off the post.

An easy way to experiment with a spinning dish is to tape a pencil vertically to the edge of a table or chair so that its eraser projects several inches upward into the air. To avoid wobbling problems, the tape should hold the pencil rigidly in place, and the table or chair should be sturdy and stable.

Now prepare to balance a metal pie dish on the eraser before giving it a twist. If you don't have a pie dish, you can use a Frisbee, a deep plastic plate, or a shallow plastic bowl instead. Be creative. You probably have something that will work; just don't use Grandma's heirloom porcelain unless you're willing to face the possible consequences.

The first thing you'll need to do is to balance the dish on the eraser. Why is it easiest to balance the dish when it's upside down? Now give the dish a gentle spin. What sort of influence do you have to exert on the dish to start it rotating? If the dish doesn't wobble and the pencil remains stationary, the dish should spin for a while before coming to a stop. Once you're no longer touching the dish, what keeps it turning? On the other hand, why doesn't it keep turning forever?

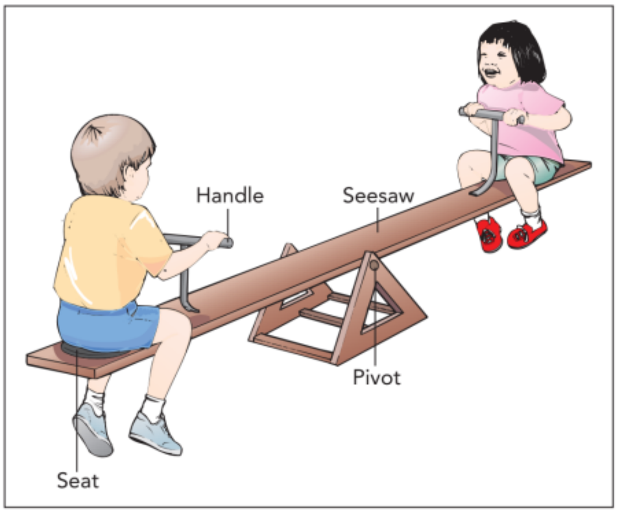
Now flip the pencil over so that its sharp point projects upward. What will happen when you place the dish on that point? Will the dish still balance? When you spin the dish, will it turn for a longer or shorter time than on the bare eraser? If the dish is soft and the point digs into it, protect the dish's bottom by taping a coin to it. How does this improved pivot affect the dish's rotation? Can you prolong the spin by taping weights around the outer edge of the dish? Is there a way to get the dish spinning just by blowing on it? Can you relate this motion to that of a spinning skater or a bicycle wheel?

Courtesy Lou Bloomfield

Chapter Itinerary

We're going to explore the laws of rotational motion and two new conserved quantities in the context of three everyday objects: (1) *seesaws*, (2) *wheels*, and (3) *bumper cars*. In Seesaws, we look at twists and turns, and see how two children manage to rock a seesaw back and forth. In Wheels, we examine how friction affects motion and learn how wheels make a vehicle more mobile. In Bumper Cars, we learn the physics behind collisions and uncover some of the simple rules that govern what initially appear to be complicated motions. For a more complete preview of what we examine in this chapter, flip ahead to the Chapter Summary and Important Laws and Equations at the end of the chapter.

SECTION 2.1 Seesaws



The ramp that we examined in Section 1.3 is only one tool that provides mechanical advantage. In this section, we'll look at another such device: the type of lever known as a seesaw. Although seesaws move, their motion differs from that of the objects in Chapter 1. Seesaws don't go anywhere; they rotate. In this section, we'll revisit many of the laws of motion that we encountered previously, but this time we'll see these laws in a new context—rotational motion.

Questions to Think About: A playground seesaw balances only when the children riding it are properly situated. What do we mean by a balanced seesaw? Why does it matter just where the children sit on the seesaw? What must the children do to start the seesaw turning? To keep it turning? Who is doing work on whom as they rock back and forth?

Experiments to Do: To get a feel for how rotating objects work, find a rigid ruler with a hole in its center—the kind that can be clipped into a three-ring binder. If you support the ruler by putting the tip of an upright pencil into the central hole, you'll find that the ruler exhibits rotational inertia; that is, it either remains stationary, at whatever orientation you choose, or rotates steadily about the central hole. (Eventually, the ruler comes to rest because of friction, a detail that we'll continue to ignore for now.) Now, push on one end of the ruler. What happens? Try pushing the ruler's end toward its central hole. What happens then? What is the most effective way to make the ruler spin?

Now lay the pencil on a table and place the ruler flat on top of it so that the pencil and the ruler are at right angles, or perpendicular, to each other. If you center the ruler on the pencil, the ruler will balance. How is this balanced ruler similar to the freely turning, inertial ruler of the previous paragraph? What role does gravity play in balancing the ruler? Load the two ends of the ruler with coins or other small weights, trying as you do so to keep the ruler balanced. Try placing the coins at different positions relative to the pencil. Is there any way you can balance a light weight on one end with a heavy weight on the other end?

The Seesaw

Any child who has played on a seesaw with friends of different sizes knows that the toy works best for two children of roughly the same weight (Fig. 2.1.1*a*). Evenly matched riders balance each other, and this balance allows them to rock back and forth easily. In contrast, when a light child tries to play seesaw with a heavy child, the heavy child's side of the seesaw drops rapidly and hits the ground with a thud (Fig. 2.1.1*b*). The light child is tossed into the air.

There are several solutions to the heavy child-light child problem. Of course, two light children could try to balance one heavy child. But most children eventually figure out that if the heavy child sits closer to the seesaw's pivot, the seesaw will balance (Fig. 2.1.1*c*). The children can then make the seesaw tip back and forth easily, just as it does when two evenly matched children ride at its ends. This is a pretty useful trick, and we'll explore it later in this section. First, though, we'll need to look carefully at the nature of rotational motion.

For simplicity, let's ignore the mass and weight of the seesaw itself. There are then only three forces acting on the occupied seesaw shown in Fig. 2.1.1: two downward forces (the weights of the two children) and one upward force (the support force of the central pivot). Seeing those three forces, we may immediately think about net forces and begin to look for some overall acceleration of this toy and its riders. But we know that the seesaw remains where it is in the playground and isn't likely to head off for Kalamazoo or the center of Earth anytime soon. Because the seesaw's fixed pivot always provides just enough upward and sideways force to keep the seesaw from accelerating as a whole, the seesaw always experiences zero net force and never leaves the playground. Overall movement of an object from one place to another is called **translational motion**. Although the seesaw never experiences translational motion, it can turn around the pivot, and thus it experiences a different kind of motion. Motion around a fixed point (which prevents translation) is called **rotational motion**.

Rotational motion is what makes a seesaw interesting—the whole point of a seesaw is that it can rotate so that one child rises and the other descends. (You may not think of going up and down as rotating, but if the ground weren't there, the seesaw would be able to rotate in a big circle.) But what causes the seesaw to rotate, and what observations can we make about the process of rotation?

To answer those questions, we'll need to examine several new physical quantities associated with rotation and explore the laws of rotational motion that relate them to one another. We'll do these things both by studying the workings of seesaws and other rotating objects and by looking for analogies between translational motion and rotational motion.

Imagine holding onto the seesaw in Fig. 2.1.1*a* to keep it level for a moment while the child on the left climbs off the seesaw. Now imagine letting go of the seesaw. As soon as you let go, the seesaw begins to rotate clockwise, and the child on the right descends toward the ground. The seesaw's motion is fairly slow at first, but it moves more and more quickly until that child strikes the ground with a teeth-rattling thump. We could describe the seesaw being twisted from rest in the following way:

> "The seesaw starts out not rotating at all. When we release the seesaw, it begins to rotate clockwise. The seesaw's rate of rotation increases continuously in the clockwise direction until the seesaw strikes the ground."

This description sounds a lot like the description of a falling ball released from rest:

> "The ball starts out not moving at all. When we release the ball, it begins to move downward. The ball's rate of translation increases steadily in the downward direction until the ball strikes the ground."

The statement about the seesaw involves rotational motion, while the statement about the ball involves translational motion. Their similarity isn't a coincidence; the concepts and laws of rotational motion have many analogies in the concepts and laws of translational motion. The familiarity that we've acquired with translational motion will help us examine rotational motion.

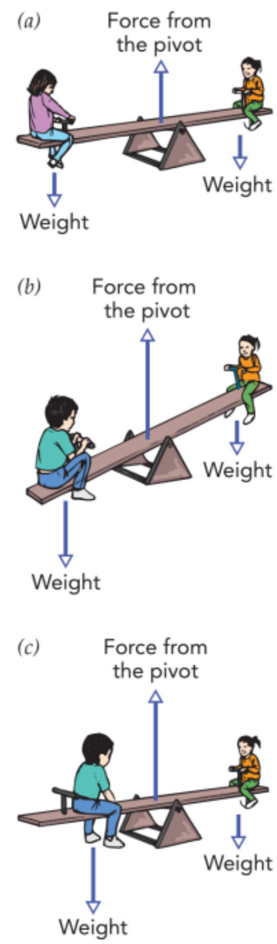


Fig. 2.1.1 (*a*) When two children of equal weight sit at opposite ends of a seesaw, it balances. (*b*) When their weights are not equal, the heavy child descends. (*c*) If the heavy child moves closer to the pivot, the seesaw can balance.

Check Your Understanding #1: Wheel of Fortune Cookies

The guests at a large table in a Chinese restaurant use a revolving tray, a lazy Susan, to share the food dishes. How does the motion of the lazy Susan differ from that of the passing dessert cart?

Answer: The lazy Susan undergoes rotational motion, while the dessert cart undergoes translational motion.

Why: The lazy Susan has a fixed pivot at its center. This pivot never goes anywhere, no matter how you rotate the lazy Susan. In contrast, the dessert cart moves about the room and has no fixed point. The server can rotate the dessert cart when necessary, but its principal motion is translational.

The Motion of a Dangling Seesaw

In the previous chapter we looked at the concept of translational inertia, which holds that a body in motion tends to stay in motion and a body at rest tends to stay at rest. This concept led us to Newton's first law of translational motion. Inserting the word *translational* here is a useful revision because we're about to encounter the corresponding concepts associated with rotational motion. We'll begin that encounter by observing a seesaw that's free of outside rotational influences. We'll then examine how the seesaw responds to outside influences such as its pivot or a handful of young riders. Because of the similarities between rotational and translational motions, this section closely parallels our earlier examinations of skating and falling balls.

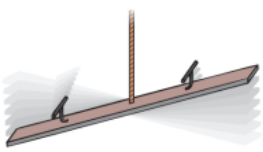


Fig. 2.1.2 A seesaw that's dangling from a rope at its middle. Since nothing twists it, the seesaw rotates steadily about a fixed line in space.

Let's suppose that your local playground is installing a new seesaw and that this seesaw is presently dangling from a rope (Fig. 2.1.2). The rope is attached to the middle of the seesaw, where it supports the seesaw's weight but exerts no other influences on the seesaw. Most important, let's suppose that the dangling seesaw can spin and pivot with complete freedom—nothing pushes on it or twists it—and that the rope doesn't get tangled or in the way. This dangling seesaw is free to turn in any direction, even completely upside down. You, the observer, are standing motionless near the seesaw. When you look over at the seesaw, what does it do?

If the seesaw is stationary, then it will remain stationary. However, if it's rotating, it will continue rotating at a steady pace about a fixed line in space. What keeps the seesaw rotating? Its **rotational inertia**. A body that's rotating tends to remain rotating; a body that's not rotating tends to remain not rotating. That's how our universe works.

To describe the seesaw's rotational inertia and rotational motion more accurately, we'll need to identify several physical quantities associated with rotational motion. The first is the seesaw's orientation. At any particular moment, the seesaw is oriented in a certain way—that is, it has an **angular position**. Angular position describes the seesaw's orientation relative to some reference orientation; it can be specified by determining how far the seesaw has rotated away from its reference orientation and the axis or line about which that rotation has occurred. The seesaw's angular position is a vector quantity, pointing along the rotation axis with a magnitude equal to the rotation angle (Fig. 2.1.3). Because *changes* in orientation are usually more interesting than orientation itself, angular position is a relatively little-used physical quantity.

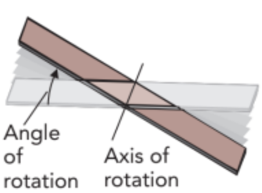


Fig. 2.1.3 You can specify this seesaw's angular position, relative to its horizontal reference orientation, as the axis about which it was rotated to reach its new orientation and the angle through which it was rotated.

The SI unit of angular position is the **radian**, the natural unit for angles. It's a natural unit because it follows directly from geometry, not from an arbitrary human choice or convention the way most units do. Geometry tells us that a circle of radius 1 has a circumference of 2π. By letting arc lengths around that circle's circumference specify angles, we are using radians. For example, there are 2π radians (or 360°) in a full circle and $\pi/2$ radians (or 90°) in a right angle. Since the radian is a natural unit, it is often omitted from calculations and derived units.

Check Your Understanding #3: Tracking the High Dive

When a diver does a rigid, open somersault off a high diving board, his motion appears quite complicated. Can this motion be described simply? How?

Answer: Yes. His center of mass falls smoothly, obeying the rules governing falling objects. As he falls, his body rotates at constant angular velocity about his center of mass.

Why: Like a thrown football or tossed baton, the diver is a rigid, rotating object. His motion can be separated into translational motion of his center of mass (it falls) and rotational motion about his center of mass (he rotates about it at constant angular velocity). While the diver may never think of his motion in these terms, he is aware intuitively of the need to handle both his rotational and translational motions carefully. Hitting the water with his chest because he mishandled his rotation isn't much more fun than hitting the board because he mishandled his translation.

How the Seesaw Responds to Torques

The workers are eating lunch, so the seesaw is still hanging from the rope. Why can't this dangling seesaw change its rotational speed or axis of rotation? Because it has rotational mass [1]. **Rotational mass** is the measure of an object's *rotational* inertia, its resistance to changes in its *angular* velocity. An object's rotational mass depends both on its ordinary mass and on how that mass is distributed within the object. The SI unit of rotational mass is the **kilogram-meter²** (abbreviated $kg \cdot m^2$). Because the seesaw has rotational mass, its angular velocity will change only if something twists it or spins it. In other words, it must experience a torque.

[1] For clarity and simplicity, this book refers to the measure of an object's rotational inertia as *rotational mass*. However, this quantity is known more formally as **moment of inertia**.

Torque—our second important vector quantity of rotational motion—has both a magnitude and a direction. The more torque you exert on the seesaw, the more rapidly its angular velocity changes. Depending on the direction of the torque, you can make the seesaw turn more rapidly or less rapidly or even make it rotate about a different axis. How do you determine the direction of a particular torque? One way is to imagine exerting this torque on a stationary ball floating in water (Fig. 2.1.8*a*,*b*). The ball will begin to rotate, acquiring a nonzero angular velocity (Fig. 2.1.8*c*). The direction of this angular velocity is that of the torque. The SI unit of torque is the **newton-meter** (abbreviated $N \cdot m$).

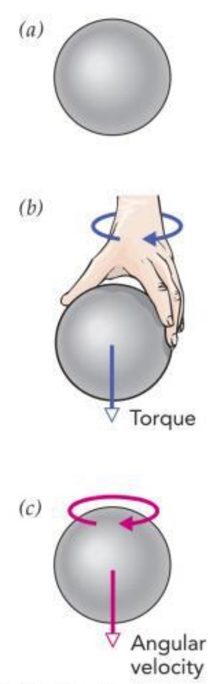


Fig. 2.1.8 If you start with a ball that's not spinning (*a*) and twist it with a torque (*b*), the ball will acquire an angular velocity (*c*) that's in the same direction as that torque.

The larger an object's rotational mass, the more slowly its angular velocity changes in response to a specific torque (Fig. 2.1.9). You can easily spin a basketball with the tips of your fingers, but it's much harder to spin a bowling ball. The bowling ball's larger rotational mass comes about primarily because it has a greater ordinary mass than the basketball.

However, rotational mass also depends on an object's shape, particularly on how far each portion of its ordinary mass is from the axis of rotation. The farther a portion of mass is from that axis, the more rapidly it must accelerate as the entire object undergoes angular acceleration and the more leverage it has with which to oppose that acceleration. We'll examine levers shortly, but the consequence of these two effects of distance from the rotation axis is that each portion of mass contributes to the object's rotational mass in proportion to the square of its distance from that axis. That's why an object that has most of its mass located near the axis of rotation will have a much smaller rotational mass than an object of the same mass that has most of its mass located far from that axis. Thus a ball of pizza dough has a smaller rotational mass than the finished pizza. The bigger the pizza gets, the harder it is to start or stop spinning.

Because an object's rotational mass depends on how far its mass is from the axis of rotation, its rotational mass may change when its axis of rotation changes, even if it's rotating about its center of mass. For example, less torque is required to spin a tennis racket about its handle (Fig. 2.1.10*a*) than to flip the racket head-over-handle (Fig. 2.1.10*b*). When you spin the tennis racket about its handle, the axis of rotation runs right through the handle so that most of the racket's mass is fairly close to the axis and the

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Fig. 2.1.9 Spinning a merry-go-round is difficult because of its large rotational mass. Despite the large torque exerted by this boy, the merry-go-round's angular velocity increases slowly.

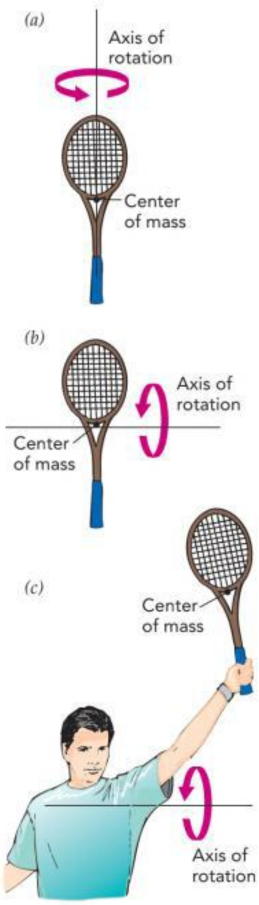


Fig. 2.1.10 A tennis racket's rotational mass depends on the axis about which it rotates. Its rotational mass is small (*a*) when it rotates about its handle and large (*b*) when it rotates head-over-handle. (*c*) If you make it rotate about your shoulder, its rotational mass becomes even larger.

rotational mass is small. When you flip the tennis racket head-over-handle, the axis of rotation runs across the handle so that both the head and the handle are far away from the axis and the rotational mass is large. The tennis racket's rotational mass becomes even larger when you hold it in your hand and make it rotate about your shoulder rather than about its center of mass (Fig. 2.1.10*c*).

When something exerts a torque on the dangling seesaw, its angular velocity changes; in other words, it undergoes angular acceleration, our third important vector quantity of rotational motion. **Angular acceleration** measures the rate at which the seesaw's *angular* velocity is changing with time. It's analogous to acceleration, which measures the rate at which an object's *translational* velocity is changing with time. Just as with acceleration, angular acceleration involves both a magnitude and a direction. An object undergoes angular acceleration when its angular speed increases or decreases or when its angular velocity changes directions. The SI unit of angular acceleration is the **radian per second²** (abbreviated $1/s^2$).

If the seesaw is experiencing several torques at once, it can't respond to them individually. Instead, it undergoes angular acceleration in response to the **net torque** it experiences, the sum of all the individual torques being exerted on it.

There is a simple relationship between the net torque exerted on the seesaw, its rotational mass, and its angular acceleration. The seesaw's angular acceleration is equal to the net torque exerted on it divided by its rotational mass or, as a word equation,

$$\text{angular acceleration} = \frac{\text{net torque}}{\text{rotational mass}}. \qquad (2.1.1)$$

The seesaw's angular acceleration, as we've seen, is in the same direction as the net torque exerted on it.

This relationship is **Newton's second law of rotational motion**. Structuring the relationship this way distinguishes the causes (net torque and rotational mass) from their effect (angular acceleration). Nonetheless, it has become customary to rearrange the relationship to eliminate the division. In its traditional form, the relationship can be written in a word equation:

$$\text{net torque} = \text{rotational mass} \cdot \text{angular acceleration}, \qquad (2.1.2)$$

in symbols:

$$\tau_{\text{net}} = I \cdot \alpha,$$

and in everyday language:

Spinning a marble is much easier than spinning a merry-go-round.

It's like Newton's second law of translational motion (net force = mass · acceleration), except that net torque has replaced net force, rotational mass has replaced mass, and angular acceleration has replaced acceleration. This new law doesn't apply to nonrigid or wobbling objects, however, because nonrigid objects can change their rotational masses and wobbling ones are affected by more than one rotational mass simultaneously (see the earlier discussion of tennis rackets).

NEWTON'S SECOND LAW OF ROTATIONAL MOTION

The net torque exerted on a rigid object that is not wobbling is equal to that object's rotational mass times its angular acceleration. The angular acceleration points in the same direction as the net torque.

Because it's an equation, the two sides of Eq. 2.1.1 are equal. Any change in the net torque you exert on the seesaw must be accompanied by a proportional change in its angular acceleration. As a result, the harder you twist the seesaw, the more rapidly its angular velocity changes.

We can also compare the effects of a specific torque on two different rotational masses. Equation 2.1.1 indicates that a decrease in rotational mass must be accompanied by a corresponding increase in angular acceleration. If we replace the playground seesaw with one from a dollhouse, the rotational mass will decrease and the angular acceleration will increase. The angular velocity of the doll's seesaw thus changes more rapidly than the angular velocity of a playground seesaw when the two experience identical net torques.

In summary:

1. Your angular position indicates exactly how you're oriented.
2. Your angular velocity measures the rate at which your angular position is changing with time.
3. Your angular acceleration measures the rate at which your angular velocity is changing with time.
4. For you to undergo angular acceleration, you must experience a net torque.
5. The more rotational mass you have, the less angular acceleration you experience for a given net torque.

This summary of the physical quantities of rotational motion is analogous to the summary for translational motion in Section 1.1. Take a moment to compare the two.

Quantity	SI Unit	English Unit	SI → English	English → SI
Angular position	radian (1)	radian (1)		
Angular velocity	radian per second (1/s)	radian per second (1/s)		
Angular acceleration	radian per second^2 (1/s^2)	radian per second^2 (1/s^2)		
Torque	newton-meter (N · m)	foot-pound (ft · lbf)	1 N · m = 0.73757 ft · lbf	1 ft · lbf = 1.3558 N · m
Rotational mass	kilogram-meter^2 (kg · m^2)	pound-foot^2 (lbm · ft^2)	1 kg · m^2 = 23.730 lbm · ft^2	1 lbm · ft^2 = 0.042140 kg · m^2

Check Your Understanding #4: **The Merry-Go-Round**

The merry-go-round is a popular playground toy (see Fig. 2.1.9). Already challenging to spin empty, a merry-go-round is even harder to start or stop when there are lots of children on it. Why is it so difficult to change a full merry-go-round's angular velocity?

Answer: The full merry-go-round has a huge rotational mass.

Why: Starting or stopping a merry-go-round involves angular acceleration. As the pusher, you exert a torque on the merry-go-round, and it undergoes angular acceleration. This angular acceleration depends on the merry-go-round's rotational mass, which in turn depends on how much mass it has and how far that mass is from the axis of rotation. With many children adding to the merry-go-round's rotational mass, its angular acceleration tends to be small.

Check Your Figures #1: **Hard to Turn**

Automobile tires are normally hollow and filled with air. If they were made of solid rubber, their rotational masses would be about 10 times as large. With the wheel lifted off the ground, how much more torque would an automobile have to exert on a solid tire to make it undergo the same angular acceleration as a hollow tire?

Answer: It would need about 10 times as much torque.

Why: To keep the angular acceleration in Eq. 2.1.1 unchanged while increasing the rotational mass by a factor of 10, the torque must also increase by a factor of 10. Solid tires are extremely difficult to spin or to stop from spinning, which is why automobiles use hollow tires.

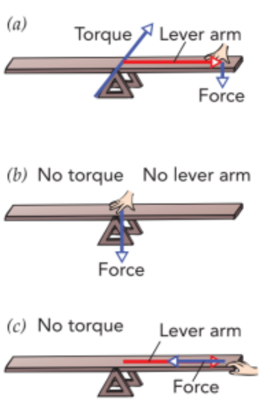


Fig. 2.1.11 (*a*) When you push on the seesaw, perpendicular to the lever arm, you produce a torque on the seesaw. But when you (*b*) push at the pivot or (*c*) push parallel to the lever arm, you produce no torque.

Forces and Torques

The workers have finally installed the seesaw. Because the pivot supporting the seesaw passes directly through the seesaw's center of mass, the seesaw rotates about its own natural pivot. Moreover, the pivot supports the seesaw's weight in a manner that leaves it free to obey Newton's first law of rotational motion. That is, when unoccupied and not influenced by anything else, the seesaw is either motionless or rotates with constant angular velocity about its pivot.

To change the seesaw's angular velocity, you have to exert a torque on it. But how do you actually exert a torque? To find out, you put your hand on one end of the seesaw and push that end down (Fig. 2.1.11*a*). If the seesaw was motionless, it starts turning. If it was already turning, its rate of rotation changes. You have indeed exerted a torque on the seesaw.

You started by exerting a *force* on the seesaw—you pushed on it—so forces and torques must be related somehow. Sure enough, a force can produce a torque and a torque can produce a force. To help us explore their relationship, let's think of all the ways *not* to produce a torque by pushing on the seesaw.

What happens if you push on the seesaw exactly where the pivot passes through it (Fig. 2.1.11*b*)? Nothing happens—there is no angular acceleration. If you move a little away from the pivot, you can get the seesaw rotating, but you have to push hard. You do much better if you push on the end of the seesaw, where even a small force can start the seesaw rotating. The shortest distance and direction from the pivot to the place where you push on the seesaw is a vector quantity called the **lever arm**; in general, the longer the lever arm, the less force it takes to cause a particular angular acceleration. Our first observation about producing a torque with a force is this: you obtain more torque by exerting that force farther from the pivot or axis of rotation. In other words, the torque is proportional to the length of the lever arm.

Another ineffective way to start the seesaw rotating is to push its end directly toward or away from the pivot (Fig. 2.1.11*c*). When your force is directed parallel to the lever arm, as it is in this case, it produces no torque on the seesaw. Our second observation about producing a torque with a force is that your force must have a component that is perpendicular to the lever arm and only that perpendicular component contributes to the torque.

We can summarize these two observations as follows: the torque produced by a force is equal to the lever arm times that force, where we include only the component of the force that is perpendicular to the lever arm. This relationship can be written as a word equation:

$$\text{torque} = \text{lever arm} \cdot \text{force perpendicular to lever arm}, \qquad (2.1.3)$$

in symbols:

$$\tau = r \cdot F_{\perp},$$

and in everyday language:

When twisting an unyielding object, it helps to use a long wrench.

The directions of the force and lever arm also determine the direction of the torque. The three directions follow another right-hand rule (Fig. 2.1.12). If you point your right index finger in the direction of the lever arm and your bent middle figure in the direction of the force, then your thumb will point in the direction of the torque. Thus in Fig. 2.1.12*a*, the lever arm points to the right, the force points downward, and the resulting torque points into the page so that the seesaw undergoes angular acceleration in the clockwise direction. In Fig. 2.1.12*b*, the lever arm has reversed directions and so has the torque.

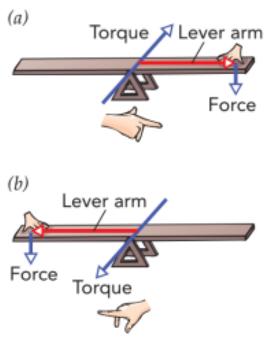


Fig. 2.1.12 The torque on a seesaw obeys a right-hand rule: if your index finger points along the lever arm and your middle finger points along the force, your thumb points along the torque.

Check Your Understanding #5: **Cutting Up Cardboard**

When you cut cardboard with a pair of scissors, it's best to move the cardboard as close as possible to the scissors' pivot. Explain.

Answer: The closer the cardboard is to the pivot, the more force it must exert on the scissors to produce enough torque to keep the scissors from rotating closed. When the cardboard is unable to produce enough torque, the scissors cut through it.

Why: When you place paper close to the pivot of a pair of scissors, you are requiring that paper to exert enormous forces on the scissors to keep them from rotating closed. Rotations are started and stopped by torques, and forces exerted close to the pivot exert relatively small torques.

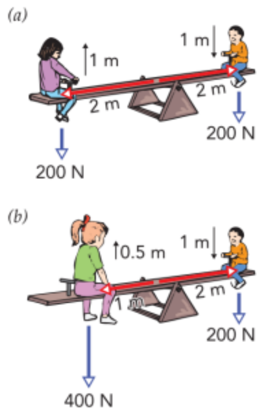


Fig. 2.1.13 When two children ride a balanced seesaw, the work the descending child does on the board is equal to the work the board does on the rising child. (*a*) When their weights are equal, those two works involve equal forces exerted over equal distance. (*b*) When one child is heavier than the other, those two works involve different forces exerted over different distances.

Levers and Mechanical Advantage

While discussing how to balance a seesaw, it was helpful to view the board and its riders as a single rotating seesaw, subject to various gravitational and other torques, and undergoing angular acceleration when those torques don't sum to zero. But we can also view the seesaw board individually as a lever that allows two children to do work on one another as it rotates. Most interestingly, that lever provides the mechanical advantage (see Section 1.3) necessary for a light child sitting far from the pivot to do the work of lifting a heavy child sitting near the pivot.

When two children sit on a motionless horizontal seesaw board (Fig. 2.1.13), each child pushes down on the board with a force equal to that child's weight. The force is directed perpendicular to the lever arm from the pivot to the force, so it produces a torque on the board about the pivot. If the children are properly situated on opposite sides of the board, their torques cancel and the seesaw board experiences zero net torque. The seesaw is balanced.

If the board is rotating steadily near horizontal, the forces and angles get a little complicated but the basic story doesn't change. Both children still push down on the board and their torques still sum to zero. Now, however, the descending child does work on the board by pushing it downward as it moves downward, and the board does work on the rising child by pushing that child upward as the child moves upward. Because the seesaw is balanced, the work done on the board by the descending child is equal to the work done by the board on the rising child. In effect, the board transfers energy perfectly from the descending child to the rising child.

To see this effect, suppose two 5-year-olds, each weighing 200-N (45 lbf), are sitting at opposite ends of the seesaw (Fig. 2.1.13*a*). By exerting a 200-N downward force on the seesaw board, 2 m (6.6 ft) from its pivot, each child produces a torque of 400 N · m (300 ft · lbf) on the board (200 N · 2 m = 400 N · m). Since those torques are in opposite directions, they sum to zero.

Now suppose the seesaw rotates clockwise, so that the girl rises 1 m and the boy descends 1 m. Since the boy exerted a 200-N downward force on the board as the board moved downward 1 m, he did 200-N · 1 m = 200 J of work on the board. Simultaneously, the board exerted a 200-N upward force on the girl as the girl moved upward 1 m, so the board did 200 J of work on the girl. Overall, the board has transferred 200 J of energy from the boy to the girl.

Now let's replace the 5-year-old girl with a 400-N (90-lbf) teenager (Fig. 2.1.13*b*). To balance the seesaw, she must sit halfway to the pivot. She exerts a 400-N downward force on the board, 1 m (3.3 ft) from its pivot, leaving the torque unchanged (400 N · 1 m = 400 N · m). As before, the children's torques are in opposite directions and sum to zero. This effect explains how a small boy at the end of the seesaw can balance a large girl nearer the pivot.

Again, the seesaw rotates clockwise, but now the girl rises only 0.5 m when the boy descends 1 m. As before, the boy did 200 J of work on the board. The board exerted a 400-N upward force on the girl as the girl moved upward 0.5 m, so the board did 400 N · 0.5 m = 200 J of work on the girl. Once again, the board has transferred 200 J of energy from the boy to the girl, even though the girl weighs more than the boy.

The seesaw's mechanical advantage allows even the tiniest child sitting at its end to lift the heaviest adult sitting near its pivot. Because the child travels much farther than the adult, the child's work on the seesaw equals the seesaw's work on the adult. This effect—a small force exerted for a long distance on one part of a rotating system producing a large force exerted for a short distance elsewhere in that system—is an example of the mechanical advantage associated with levers.

Check Your Understanding #7: Pulling Nails

Some hammers have a special claw designed to remove nails from wood. When you slide the claw under the nail's head and rotate the hammer by pulling on its handle, the claw pulls the nail out of the wood. The hammer's head contacts the wood to form a pivot that's about 10 times closer to the nail than to the handle. The torque you exert on the hammer twists it in one direction, while the torque that the nail exerts on the hammer twists it in the opposite direction. The hammer isn't undergoing any significant angular acceleration, so the torques must nearly balance. If you're exerting a force of 100 N (22 lbf) on the hammer's handle, how much force is the nail exerting on the hammer's claw?

Answer: The nail is exerting about 1000 N (220 lbf).

Why: Since the nail is 10 times closer to the pivot, the nail must exert 10 times the force on the hammer to create the same magnitude of torque as you do pulling on the handle. As the nail pulls on the hammer, the hammer pulls on the nail. Although the wood exerts frictional forces on the nail to keep it from moving, the extracting force overwhelms this friction and the nail slides slowly out of the wood.

Children Support Each Other

While we're thinking about the two children on a balanced seesaw as individual objects, using the seesaw board to exchange energy, we may notice something else about those children: they're using the seesaw board to support one another. In other words, each child is using the board to exert a torque on the other child about the pivot, and that torque cancels the other child's gravitational torque. For example, the boy in Fig. 2.1.13*a* experiences a clockwise torque due to gravity and a counterclockwise torque from the girl on the other end of the seesaw. Since those two torques sum to zero, the boy rotates at constant angular velocity about the pivot. Likewise, the boy exerts a torque on the girl so that she, too, rotates at constant angular velocity.

Since the girl is exerting a torque on the boy and the boy is exerting a torque on the girl, you might wonder if those two torques are related. It should come as no great surprise that they are equal in amount but oppositely directed. Just as there is a Newton's third law for translational motion, so there is a **Newton's third law of rotational motion**: if one object exerts a torque on a second object, then the second object will exert an equal but oppositely directed torque on the first object. The girl's torque on the boy and the boy's torque on the girl are a Newton's third law pair.

NEWTON'S THIRD LAW OF ROTATIONAL MOTION

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

It's worth noting that not all equal but oppositely directed torques are Newton's third law pairs. On a balanced seesaw, each child experiences two torques that *happen* to be equal but oppositely directed: a torque due to gravity and a torque due to the other child. Those two torques form a matched pair because the seesaw is balanced, not because of Newton's third law. In fact, if the seesaw weren't balanced, those two torques would not be equal but oppositely directed and the children would both be undergoing angular acceleration.

COMMON MISCONCEPTIONS: Newton's Third Law or Not?

Misconception: Every pair of equal but oppositely directed forces or torques is associated with Newton's third law.

Resolution: Newton's third law applies only to pairs of forces or torques that two objects exert on one another. In such cases only, the forces or torques must be equal but oppositely directed. Two forces or torques exerted on the same object are never a Newton's third law pair and can have any values, including equal but oppositely directed.

SUMMARY OF NEWTON'S LAWS OF ROTATIONAL MOTION

1. **A rigid object that is not wobbling and is not subject to any outside torques rotates at a constant angular velocity, turning equal amounts in equal times about a fixed axis of rotation.**
2. **The net torque exerted on a rigid object that is not wobbling is equal to that object's rotational mass times its angular acceleration. The angular acceleration points in the same direction as the torque.**
3. **For every torque that one object exerts on a second object, there is an equal but oppositely directed torque that the second object exerts on the first object.**

***Note:* These laws are the rotational analogs of the translational laws in Section 1.3.**

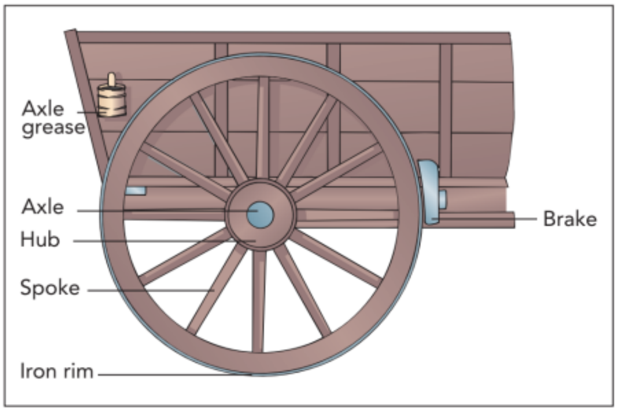
Check Your Understanding #8: **Turning on Ice**

A light at your skating rink needs replacing, so you stand on the slippery ice and reach up overhead to unscrew the light. As you twist the light, you begin to rotate. What caused you to rotate?

Answer: The light exerted a torque on you.

Why: To unscrew the light, you must exert a torque on it. In accordance with Newton's third law of rotational motion, that light exerts an equal but opposite torque on you. The ice is too slippery to exert a torque on you, so you undergo angular acceleration and begin to rotate.

SECTION 2.2 Wheels



Like ramps and levers, wheels are simple tools that make our lives easier. But a wheel's main purpose isn't mechanical advantage, it's overcoming friction. Up until now, we've ignored friction, looking at the laws of motion as they apply only in idealized situations. However, our real world does have friction, and most objects in motion tend to slow down and stop because of it. One of our first tasks in this section will therefore be to understand friction—though, for the time being, we'll continue to neglect air resistance.

Questions to Think About: If objects in motion tend to stay in motion, why is it so hard to drag a heavy box across the floor? If objects should accelerate downhill on a ramp, why won't a plate slide off a slightly tilted table? What makes the wheels of a cart rotate as you pull the cart forward? How does spinning its wheels propel a car forward?

Experiments to Do: To observe the importance of wheels in eliminating friction, try sliding a book along a flat table. Give the book a push and see how quickly it slows down and stops. Which way is friction pushing on the book? Does the force that friction exerts on the book depend on how fast the book is moving? Let the book come to a stop. Is friction still pushing on the book when it isn't moving? If you push gently on the stationary book, what force does friction exert on it?

Lay three or four round pencils on a table, parallel to one another and a few inches apart. Rest the book on top of the pencils and give the book a push in the direction that the pencils can roll. Describe how the book now moves. What do you think has caused the difference?

Moving a File Cabinet: Friction

When we imagined moving your friend's piano into a new apartment back in Section 1.3, we neglected a familiar force—friction. Luckily for us, your friend's piano had wheels on its legs, and wheels facilitate motion by reducing the effects of friction. We'll focus on wheels in this section. First, though, to help us understand the relationship between wheels and friction, we'll look at another item that needs to be moved—your friend's file cabinet.

The file cabinet is resting on a smooth and level hardwood floor; it's full of sheet music and weighs about 1000 N (225 lbf). Despite its large mass, you know that it should accelerate in response to a horizontal force, so you give it a gentle push toward the door. Nothing happens. Of course, the file cabinet accelerates in response to the net force it experiences, not to each individual force acting on it. Something else must be pushing on the file cabinet in just the right way to cancel your force and keep it from accelerating. Undaunted, you push harder and harder until finally, with a tremendous shove, you manage to get the file cabinet sliding across the floor. However, the cabinet moves slowly even though you continue to push on it. Something else is pushing on the file cabinet, trying to stop it from moving.

That something else is **friction**, a phenomenon that opposes the relative motion of two surfaces in contact with one another. Two surfaces that are in **relative motion** are traveling with different velocities so that a person standing still on one surface will observe the other surface as moving. In opposing relative motion, friction exerts forces on both surfaces in directions that tend to bring them to a single velocity.

For example, when the file cabinet slides by itself toward the left, the floor exerts a rightward frictional force on it (Fig. 2.2.1). The frictional force exerted on the file cabinet, *toward the right*, is in the direction opposite the file cabinet's velocity, *toward the left*. Since the file cabinet's acceleration is in the direction opposite its velocity, the file cabinet slows down and eventually comes to a stop.

According to Newton's third law of motion, an equal but oppositely directed force must be exerted by the file cabinet on the floor. Sure enough, the file cabinet does exert a leftward frictional force on the floor. However, the floor is rigidly attached to Earth, so it accelerates very little. The file cabinet does almost all the accelerating, and soon the two objects are traveling at the same velocity.

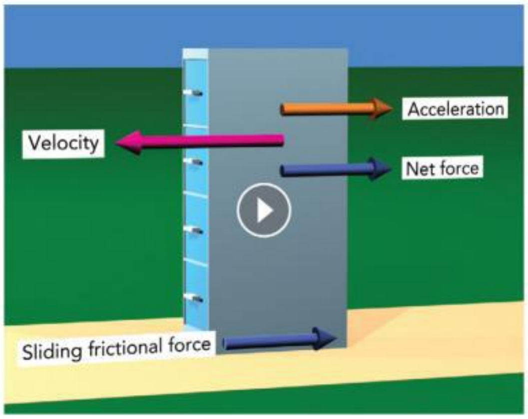


Fig. 2.2.1 A file cabinet sliding to the left across a sidewalk experiences a frictional force from the sidewalk to the right. Since that sliding frictional force is the net force on the file cabinet, the cabinet accelerates opposite its velocity and gradually slows to a stop.

Frictional forces always oppose relative motion, but they vary in strength according to (1) how tightly the two surfaces are pressed against one another, (2) how slippery the surfaces are, and (3) whether the surfaces are actually moving relative to one another. First, the harder you press two surfaces together, the larger the frictional forces they experience. For example, an empty file cabinet slides more easily than a full one. Second, roughening the surfaces generally increases friction, while smoothing or lubricating them generally reduces it. Riding a toboggan down the driveway is much more interesting when the driveway is covered with snow or ice than when the driveway is bare asphalt. We'll examine the third issue later on.

Check Your Understanding #1: The One That Got Away

Your table at the restaurant isn't level, and your water glass begins to slide slowly downhill toward the edge. Which way is friction exerting a force on it?

Answer: Friction is pushing the glass uphill.

Why: The glass is sliding downhill across the top of the stationary table. Since friction always opposes relative motion, it pushes the glass uphill, in the direction opposite its motion.

A Microscopic View of Friction

As the file cabinet slides by itself across the floor, it experiences a horizontal frictional force that gradually brings it to a stop. From where does this frictional force come? The obvious forces on the file cabinet are both vertical, not horizontal; the cabinet's weight is downward, and the support force from the floor is upward. How can the floor exert a horizontal force on the file cabinet?

The answer lies in the fact that neither the bottom of the file cabinet nor the top of the floor is perfectly smooth. They both have microscopic hills and valleys of various sizes. The file cabinet is actually supported by thousands of tiny contact points, where the file cabinet directly touches the floor (Fig. 2.2.2). As the file cabinet slides, the microscopic projections on the bottom of the file cabinet pass through similar projections on the top of the floor. Each time two projections collide, they experience horizontal forces. These tiny forces oppose the relative motion and give rise to the overall frictional forces experienced by the file cabinet and floor. Because even an apparently smooth surface still has some microscopic surface structure, all surfaces experience friction as they rub across one another.

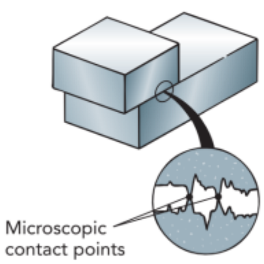


Fig. 2.2.2 Two surfaces that are pressed against one another actually touch only at specific contact points. When the surfaces slide across one another, these contact points collide, producing sliding friction and wear.

Increasing the size or number of these microscopic projections by roughening the surfaces generally leads to more friction. If you put sandpaper on the bottom of the file cabinet, it would experience larger frictional forces as it slides across the floor. On the other hand, a microscopically smoother "nonstick" surface, like that used in modern cookware, would let the file cabinet slide more easily.

Increasing the number of contact points by squeezing the two surfaces more tightly together also leads to more friction. The microscopic projections simply collide more often. That's why adding more sheet music to the file cabinet would make it harder to slide. Doubling the file cabinet's weight would roughly double the number of contact points and make it about twice as hard to move across the floor. A useful rule of thumb is that the frictional forces between two firm surfaces are proportional to the forces pressing those two surfaces together.

Friction also causes wear when the colliding contact points break one another off. With time, this wear can remove large amounts of material so that even seemingly indestructible stone steps are gradually worn away by foot traffic. The best way to reduce wear between two surfaces (other than to insert a lubricant between them) is to polish them so that they are extremely smooth. The smooth surfaces will still touch at contact points and experience friction as they slide across one another, but their contact points will be broad and round and will rarely break one another off during a collision.

rest, its gravitational potential energy decreases and its kinetic energy increases, but its total energy remains unchanged.

We measure energy in many common units: joules (J), calories, food Calories (also called kilocalories), and kilowatt-hours, to name only a few. All these units measure the same thing, and they differ from one another only by numerical conversion factors, some of which can be found in Appendix B. For example, 1 food Calorie is equal to 1000 calories or 4187 J. A jelly donut with about 250 food Calories thus contains about 1,000,000 J of energy. Since a joule is the same as a newton-meter, 1,000,000 J is the energy you'd use to lift your friend's file cabinet into the second-floor apartment 200 times (1000 N times 5 m upward equals 5000 J of work per trip). No wonder eating donuts is hard on your physique!

Let's return now to thermal energy. Thermal energy is actually a mixture of ordinary kinetic and potential energies. But unlike the kinetic energy in a moving ball or the potential energy in an elevated piano, the kinetic and potential energies in thermal energy are contained entirely within those objects. Any object has **internal energy,** energy held entirely within that object by its individual particles and forces between those particles; *thermal energy* is the portion of internal energy that's associated with temperature. Thermal energy makes every microscopic particle in the object jiggle randomly and independently; at any moment, each particle has its own tiny supply of potential and kinetic energies, and this dispersed and disordered energy is collectively referred to as thermal energy.

As you push the file cabinet across the floor, you do work on it, but it doesn't pick up speed. Instead, sliding friction converts your work into thermal energy, and the cabinet and floor become hotter as the energy you transfer to them disperses among their particles. But although sliding friction easily turns work into thermal energy, there's no easy way to turn thermal energy back into work. Disorder not only makes things harder to use, but it also is difficult to undo. When you drop your favorite coffee mug on the floor and it shatters into a thousand pieces, the cup is still all there; however, it's disordered and thus much less useful. Just as dropping the pieces on the floor a second time isn't likely to reassemble your cup, energy converted into thermal energy can't easily be reassembled into useful, ordered energy.

Check Your Understanding #4: **Burning Rubber**

If you push too hard on your car's accelerator pedal when the traffic light turns green, your wheels will slip and you'll leave a black trail of rubber behind. Such a "jackrabbit start" can cause as much wear on your tires as 50 km (31 miles) of normal driving. Why is skidding so much more damaging to the tires than normal driving?

Answer: Normal driving involves mostly static friction because the surfaces of the tires don't slide across the pavement. Skidding involves sliding friction as the tire surfaces move independently of the pavement. Because it involves sliding friction, skidding creates thermal energy and damages the tires.

Why: The expression "burning rubber" is an appropriate name for skidding during a jackrabbit start. Substantial thermal energy is produced, and a trail of hot rubber is left on the pavement behind the car. At drag races, the frictional heating that results from skidding at the start can be so severe that the tires actually catch on fire.

Wheels

You've wrestled your friend's file cabinet out the door of the old apartment and are now dragging it along the sidewalk. You're doing work against sliding friction the whole way, producing large amounts of thermal energy in both the bottom of the cabinet and the surface of the sidewalk. You're also damaging both objects, since sliding friction is wearing out their surfaces. The four-drawer file cabinet may be down to three drawers by the time you arrive at the new apartment.

Fortunately, there are mechanical systems that can help you move one object across another without sliding. The classic example is a roller (Fig. 2.2.3). If you place the file cabinet on rollers, those rollers will rotate as the file cabinet moves so that their surfaces

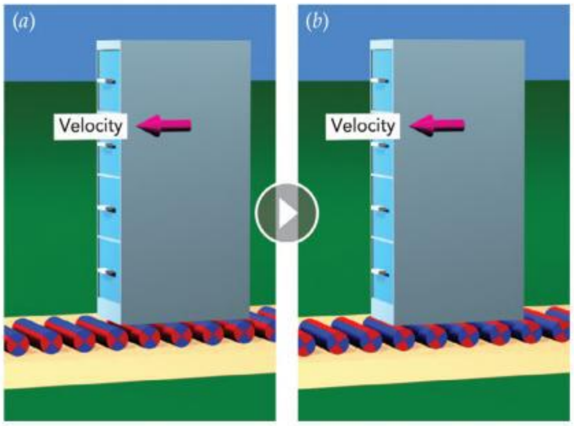


Fig. 2.2.3 (*a*) A file cabinet that's supported on turning rollers experiences no sliding friction. (*b*) Since the top surface of a roller moves forward with the file cabinet, while its bottom surface stays behind with the sidewalk, the roller moves only half as fast as the file cabinet. As a result, the rollers are soon left behind.

never slide across the bottom of the cabinet or the top of the sidewalk. To see how the rollers work, make a fist with one hand and roll it across the palm of your other hand. The skin of one hand doesn't slide across the skin of the other hand; since this silent motion doesn't convert work into thermal energy, your skin remains cool. Now slide your two open palms across one another; this time, sliding friction warms your skin.

Although the rollers don't experience sliding friction, they can experience static friction. The top of each roller is touching the bottom of the cabinet, and the two surfaces move along together even when the file cabinet is accelerating because of static friction; they grip one another tightly until the roller's rotation pulls them apart. A similar process takes place between the rollers and the top of the sidewalk; static friction can exert torques on the rollers and cause them to rotate in the first place. Again, you can illustrate this behavior with your hands. Try to drag your fist across your open palm. Just before your fist begins to slide, you'll feel a torque on it. Static friction between the skins of your two hands, acting to prevent sliding, causes your fist to begin rotating just like a roller.

Once you get the file cabinet moving on rollers, you can keep it rolling along the level sidewalk indefinitely. Without any sliding friction, the cabinet doesn't lose kinetic energy, so it continues at constant velocity without your having to push it. However, the rollers move out from under the file cabinet as it travels, and you frequently have to move a roller from the back of the cabinet to the front. In fact, you need at least three rollers to ensure that the file cabinet never falls to the ground when a roller pops out the back. Although the rollers have eliminated sliding friction, they've created another headache—one that makes the prospect of a long trip unappealing. Is there another device that can reduce sliding friction without requiring constant attention?

One alternative would be a four-wheeled cart. The simplest cart rests on fixed poles or axles that pass through central holes or hubs in the four wheels (Fig. 2.2.4). The ground exerts upward support forces on the wheels, the wheels exert upward support forces on the axles, and the axles support the cart and its contents. As the cart moves forward, its wheels

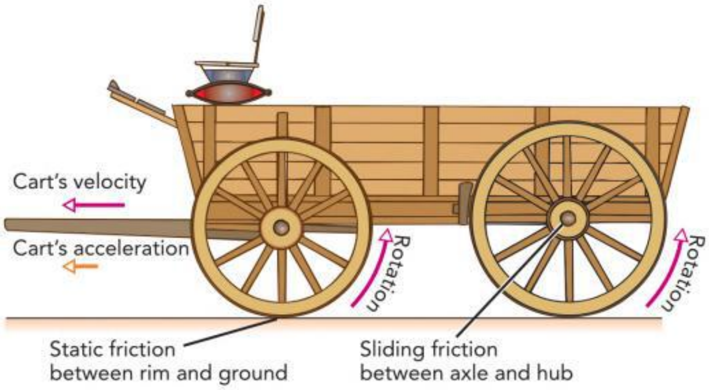


Fig. 2.2.4 As this cart accelerates toward the left, its wheels roll counterclockwise. Although the wheel rims experience only static friction with the ground, the wheel hubs slide around the axles and convert the cart's kinetic energy into thermal energy. To reduce this wasted energy, the cart has narrow axles that are lubricated with axle grease.

roll. Their bottom surfaces don't slide or skid across the ground; instead, each wheel lowers a portion of its surface onto the sidewalk, leaves it there briefly so that it may experience static friction, and then raises it back off the sidewalk, with a new portion of wheel surface taking its place. Because of the touch-and-release character of rolling, there is no sliding friction between the cart's wheels and the ground.

Unfortunately, as each wheel rotates, its hub slides across the stationary axle at its center. This sliding friction wastes energy and causes wear to both hub and axle. However, the narrow hub moves relatively slowly across the axle so that the work and wear done each second are small. Still, this sliding friction is undesirable and can be reduced significantly by lubricating the hub and axle with axle grease.

A better solution is to insert rollers between the hub and axle (Fig. 2.2.5). The result is a roller bearing, a mechanical device that eliminates sliding friction between a hub and an axle. A complete bearing consists of two rings separated by rollers that keep those rings from rubbing against one another. In this case, the bearing's inner ring is attached to the stationary axle, while its outer ring is attached to the spinning wheel hub. The nondriven wheels of an automobile are supported by roller bearings on essentially stationary axles. The nondriven wheels of lighter vehicles, such as bicycles and wagons, are similarly supported on stationary axles, but their bearings use balls instead of rollers—ball bearings. When a vehicle with free wheels starts forward, static friction from the ground pushes backward on the bottoms of those free wheels to keep them from skidding forward. Those frictional forces also produce torques that cause the wheels to begin turning and they roll forward (Fig. 2.2.6*a*).

A car's engine-powered or driven wheels are also supported by roller bearings, but these bearings act somewhat differently. Because the engine must be able to exert a torque on each driven wheel, those wheels are rigidly connected to their axles. As the engine spins these axles, the axles spin their wheels (Fig. 2.2.6*b*). A bearing prevents each spinning axle from rubbing against the car's frame. This bearing's outer ring is attached to the stationary car frame while its inner ring is attached to the spinning axle. When a vehicle begins to spin its driven wheels, static friction from the ground pushes forward on the bottoms of those driven wheels to keep them from skidding backward. Since those forward frictional forces are the only horizontal forces on the vehicle, the vehicle accelerates forward and the driven wheels roll forward.

Recognizing a good idea when you think of it, you load the file cabinet into the passenger seat of your red convertible sports car and start the engine. The car isn't quite as responsive as usual because of the added mass, but it's still able to accelerate respectably. In a few seconds, you're cruising down the road toward the new apartment and a very grateful friend.

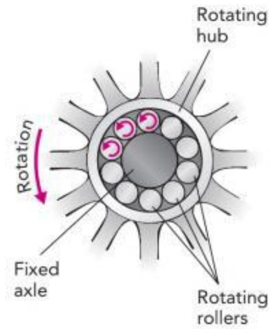


Fig. 2.2.5 In a roller bearing, the hub of the wheel doesn't touch the axle directly. Instead, the two are separated by a set of rollers that turn with the hub. The bottom few rollers bear most of the load since the hub pushes up on them and they push up on the axle. As the wheel turns, the rollers recirculate, traveling up to the right and over the top of the axle before returning down to the left to bear the load once again. The rollers, wheel, and axle can experience only static friction, not sliding friction. In a ball bearing, the cylindrical rollers are replaced by spherical balls.

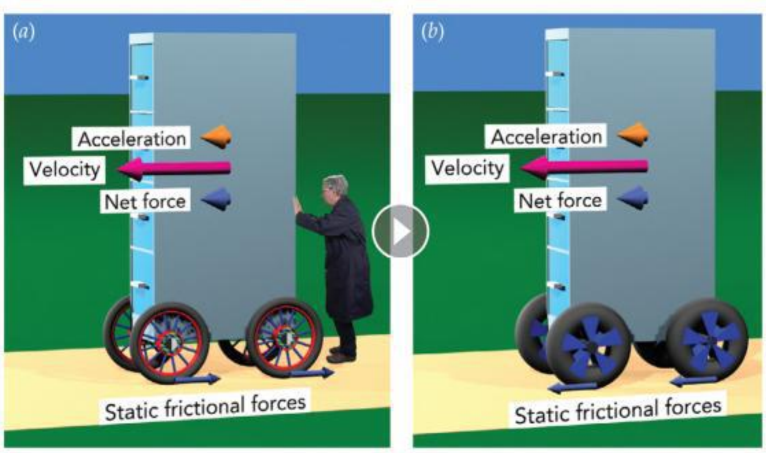


Fig. 2.2.6 (*a*) When my assistant pushes a cart forward and it accelerates forward, static friction from the ground pushes the wheel bottoms backward to prevent them from skidding. That same frictional force causes the wheels to roll forward. (*b*) When the engine of a go-cart twists its wheels forward, static friction from the ground pushes the wheel bottoms forward to prevent them from skidding. That same frictional force causes the vehicle to accelerate forward.

Check Your Understanding #5: Jewel Movements

Many antique mechanical watches and clocks proudly proclaim that they have "jewel movements." Gears in these timepieces turn on axles that are pointed at either end and are supported at those ends by very hard, polished gemstones. What is the advantage of having needlelike ends on an axle and supporting those needles with smooth, hard jewels?

Answer: Because all the supporting forces are very close to the axis of rotation, the jewels exert almost zero torque on the axle. The axle turns remarkably freely.

Why: Mechanical timepieces need almost ideal motion to keep accurate time. One of the best ways to allow a rotating object free movement is to support it exactly on the axis of rotation, where the support can't exert torque on the object.

Power and Rotational Work

It's a beautiful afternoon, and you thrill to the power of your car as it drives swiftly up a steep hill. In this situation, power means more than just a sense of exhilaration and freedom; **power** is also the physical quantity that measures the rate at which your car's engine does work—the amount of work it does in a certain amount of time, or

$$\text{power} = \frac{\text{work}}{\text{time}}.$$

The SI unit of power is the **joule per second**, also called the **watt** (abbreviated W). Other units of power include Calories per hour and horsepower; like the units for energy, these units differ only by numerical factors, which are listed in Appendix B online. For example, 1 horsepower is equal to 745.7 W, so the engine of your 200-horsepower roadster can supply about 150,000 W of power. With you and the file cabinet on board, the car weighs about 15,000 N (3400 lbf), so the car engine can lift it about 10 m upward each second. No wonder it's climbing the hill so easily!

Up to now, we've considered work only in the context of *translation* motion, where work involves force and distance. For example, you do work on the file cabinet by exerting a force on it as it moves a distance in the direction of that force. The car's engine, however, does work on each of its powered wheels in the context of *rotational* motion, where work involves torque and angle. Specifically, the engine does work on a wheel by exerting a torque on the wheel as the wheel rotates through an angle in the direction of the torque.

To do work on an object via rotational motion, you must twist it as it rotates through an angle in the direction of your twist. The work you do on it is equal to the torque you exert on its times the angle through which it rotates in the direction of your torque, where that angle is measured in radians, the natural unit of angles. We can express this relationship as a word equation:

$$\text{work} = \text{torque} \cdot \text{angle(in radians)} \tag{2.2.1}$$

in symbols:

$$W = \boldsymbol{\tau} \cdot \boldsymbol{\theta},$$

and in everyday language:

If you're not twisting or it's not turning, then you're not working.

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

As the engine does work on its wheels via rotational motion, those wheels do work on the car via translational motion. Because each wheel grips the pavement with static friction, its contact point with the ground can't move. Instead, the rotating wheel pushes the axle and car forward as they move forward. So energy that flows into the wheels via rotational motion returns to the car via translational motion and keeps the car climbing steadily up the hill.

Like work itself, power can be supplied by translational motion or rotational motion. When you're pushing the file cabinet across the floor, you're using translational motion to supply power to it. Since translational work is force times distance (Eq. 1.3.1) and power is work divided by time, translational power is force times distance divided by time, or

$$\text{power} = \text{force} \cdot \text{velocity}.$$

You can thus supply more power to the file cabinet either by pushing it harder or by having it move faster in the direction of your push.

As your car drives up the hill, the car engine is using rotational motion to supply power to its wheels. Since rotational work is torque times angle, rotational power is torque times angle divided by time, or

$$\text{power} = \text{torque} \cdot \text{angular velocity}.$$

The car can therefore supply more power to its wheels either by twisting them harder or by having them rotate faster in the direction of that twist.

Check Your Understanding #6: Going Nowhere One Foot at a Time

You're pedaling a stationary bicycle when your shoelace comes undone. While you retie the lace, you can pedal with only one foot and exert half as much torque on the pedals as before. The pedals are still turning just as quickly, so are you still exercising as hard?

Answer: No.

Why: By halving the torque you exert on the pedals, you halve the work that you do on those pedals each time they complete a rotation.

Check Your Figures #1: We All Knead Energy

When your kitchen mixer is kneading a loaf of sourdough bread, it exerts a torque of 20 newton-meters on its mixing blade, and that blade completes 500 rotations. How much energy does the mixer supply to its blade and the dough?

Answer: It supplies about 63,000 joules.

Why: According to Eq. 2.2.1, the energy that the mixer transfers to its blade is equal to the torque it exerts on the blade times the angle through which the blade turns. Since there are 2π radians per complete rotation, the blade turns approximately 3140 radians. The work that the mixer does is 20 N-m times 3140, or about 63,000 J.

Kinetic Energy

As you near your destination, you begin thinking about the car's brakes. They're designed to stop the car by turning its kinetic energy into thermal energy. They'll perform their task by rubbing stationary brake pads against spinning metal discs. Although you're confident that those brakes are up to the task, just how much kinetic energy are they going to have to convert into thermal energy?

One way to determine the car's kinetic energy is to calculate the work its engine did on it while bringing it from rest to its current speed. The result of that calculation is that the strikes the stationary coin squarely. What happens? Try this experiment again, but now use two coins with different masses. How is the collision different? Does it matter which coin you crash into the other?

Now line up several identical coins so that they touch, and slide another coin into one end of this line. How does the collision affect the coin that was originally moving? How does it affect the line of coins? What was transferred among the coins by the collision?

Now stand a coin on its edge and flick it so that it spins rapidly. Did you give it something that keeps it spinning? Why does the coin eventually stop spinning?

Coasting Forward: Linear Momentum

Bumper cars are small, electrically powered vehicles that can turn on a dime and are protected on all sides by rubber bumpers. Each car has only two controls: a pedal that activates its motor and a steering wheel that controls the direction in which the motor pushes the car. Since the car itself is so small, its occupants account for much of the car's total mass and rotational mass.

Imagine that you have just sat down in one of these cars and put on your safety strap. The other people also climb into their cars, usually one person per car, and the ride begins.

With your car free to move or turn, you quickly become aware of its translational and rotational inertias. The car's translational inertia makes it hard to start or stop, and its rotational inertia makes it difficult to spin or stop from spinning. While we've seen these two types of inertia before, let's take another look at them and at how they affect your bumper car. This time, we'll see that they're associated with two new conserved quantities: linear momentum and angular momentum. As promised, energy isn't the only conserved quantity in nature!

When fast-moving bumper cars crash into one another, they exchange more than just energy. Energy is a scalar rather than vector quantity, so it's directionless and can't account for the fact that these cars seem to be exchanging some physical quantity that incorporates both speed and direction of travel. For example, if your car is hit squarely by a car speeding toward the right, then your car's motion shifts rightward in response. What your car is receiving from the other car is a rightward-directed dose of a conserved vector quantity known as linear momentum.

Linear momentum, usually just called **momentum**, is the measure of an object's translational impetus or tenacity—its determination to keep moving the way it's currently moving. Roughly speaking, your car's momentum indicates the effort it took to get the car moving with its present speed and direction of motion. To distinguish it from energy and angular momentum, you can think of momentum as the *conserved quantity of moving*.

The car's momentum is equal to its mass times its velocity and can be written as a word equation:

$$\text{momentum} = \text{mass} \cdot \text{velocity}, \tag{2.3.1}$$

in symbols:

$$\mathbf{p} = m \cdot \mathbf{v},$$

and in everyday language:

It's hard to stop a fast-moving truck.

Note that momentum is a vector quantity and that it has the same direction as the velocity. As we might expect, the faster your car is moving or the more mass it has, the more momentum it has in the direction of its velocity. The SI unit of momentum is the **kilogram-meter per second** (abbreviated kg · m/s).

To physicists, conserved quantities are rare treasures that make it easier to understand otherwise complicated motions. Like all conserved quantities, momentum can't be created or destroyed. It can only be transferred between objects. Momentum plays a very basic role in bumper cars; the whole point of crashing them into one another is to enjoy the momentum

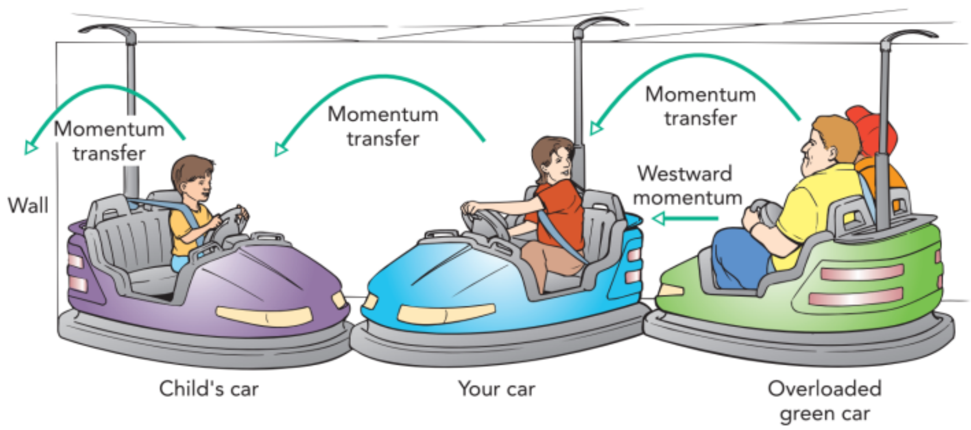


Fig. 2.3.1 Your car is hit by a fast-moving, massive car with westward momentum. Much of that westward momentum is transferred to your car. You crash into a child's car, transferring the westward momentum to it. It then crashes into the wall, transferring the westward momentum to the wall. Although that wall doesn't appear to move, it and the Earth, to which it's attached, actually accelerate westward a tiny amount as they receive the westward momentum.

transfers. During each collision, momentum shifts from one car to the other so that they abruptly change their speeds or directions or both. As long as these momentum transfers aren't too jarring, everyone has a good time.

You've stopped your car, so it has zero velocity and zero momentum. To begin moving again, something must transfer momentum to your car. While you could press the pedal and let the motor gradually transfer momentum from the ground to your car, that's not much fun. Instead, you let two grinning couch potatoes in an overloaded green car slam into you at breakneck speed (Fig. 2.3.1).

The green car was heading westward, and in a few moments your car is moving westward, too, while the green car has slowed significantly. Before you recover from the jolt, your car pounds a child's car westward and your car slows down abruptly. Finally, its impact with a wall stops the child's car. Despite disapproving looks from the child's parents, there's no harm done. Overall, westward momentum has flowed from the spudmobile to your car, to the child's car, and into the wall. No momentum has been created or destroyed; you've all simply enjoyed passing it along from car to car.

Check Your Understanding #1: **Stuck on the Ice**

Suppose you're stuck in the middle of a frozen lake, with a surface so slippery that you can't get any traction. You take off a shoe and throw it toward the southern shore. You find yourself coasting toward the northern shore and soon escape from the lake. Why did this scheme work?

Answer: By transferring southward momentum to the shoe, you obtained northward momentum.

Why: Initially, both you and your shoe have zero momentum. But when you throw the shoe southward, you give it southward momentum. Since the only source of that southward momentum is you, you must have lost southward momentum. A negative amount of southward momentum is actually northward momentum, and thus you coast northward. Interestingly enough, the total momentum of you and the shoe hasn't changed. It's still zero, as it must be because momentum is conserved. It has simply been redistributed.

Check Your Figures #1: **Follow That Train!**

The bad guys are getting away in a four-car train, and you're trying to catch them. The train has a mass of 20,000 kg and it's rolling forward at 22 m/s (80 km/h or 50 mph). What is the train's momentum?

Answer: The train's momentum is 4400,000 kg · m/s, in the forward direction.

Why: You can use Eq. 2.3.1 to calculate the train's momentum from its mass and velocity:

$$\begin{aligned}\text{linear momentum} &= 20{,}000\text{ kg}\cdot 22\text{ m/s}\\ &= 440{,}000\text{ kg}\cdot\text{m/s}.\end{aligned}$$

That momentum is in the same direction the train is moving, the forward direction.

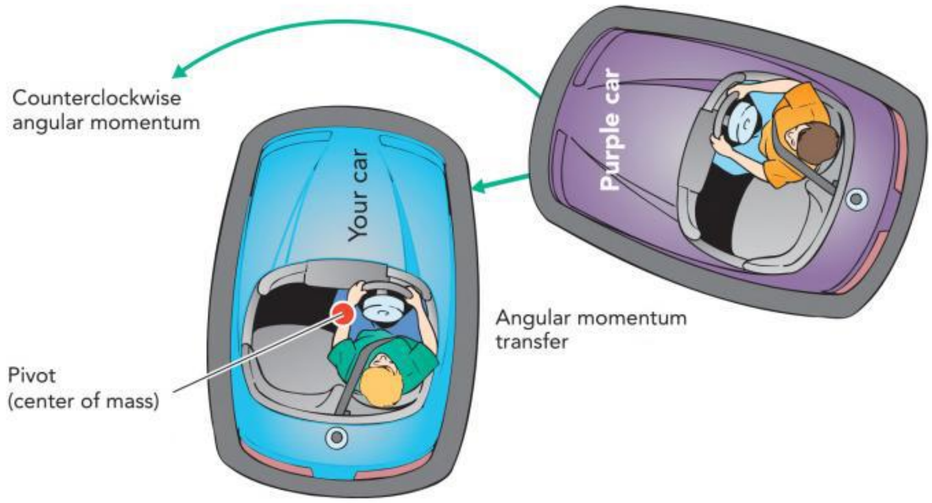


Fig. 2.3.2 Since the purple car is circling your car counterclockwise, it has counterclockwise angular momentum. When it hits your car, it transfers some of that angular momentum to your car. Because of this transfer, the purple car stops circling quickly as your car begins to spin counterclockwise.

Check Your Figures #3: Want to Go for a Spin?

Spinning satellites are particularly stable. Suppose that the astronauts launching a particular satellite decide to increase its angular velocity by a factor of 5. How will that change affect the satellite's angular momentum?

Answer: The angular momentum will increase by a factor of 5.

Why: Because the satellite's angular momentum is proportional to its angular velocity, spinning it five times faster will increase its angular momentum by that same factor.

Glancing Blows: Angular Impulses

Angular momentum is transferred to a bumper car by giving it an **angular impulse**, that is, a torque exerted on it for a certain amount of time. When the purple car hits your car and exerts a torque on it briefly, it gives your car an angular impulse and transfers angular momentum to it. This angular impulse is the change in your car's angular momentum and is equal to the torque exerted on your car times the duration of that torque. This relationship can be written as a word equation:

$$\text{angular impulse} = \text{torque} \cdot \text{time}, \qquad (2.3.5)$$

in symbols:

$$\Delta \mathbf{L} = \boldsymbol{\tau} \cdot t,$$

and in everyday language:

To get a merry-go-round spinning rapidly, you must twist it hard and for a long time.

The more torque is exerted or the longer that torque is exerted, the larger the angular impulse and the more your car's angular momentum changes. Once again, an angular impulse is a vector quantity and points in the same direction as the torque. Had the purple car been circling your car clockwise when it struck the glancing blow, its angular impulse would have been in the opposite direction and you'd be spinning the other way.

Different torques exerted for different amounts of time can transfer the same angular momentum to a car:

$$\begin{aligned}\text{angular impulse} &= \text{large torque} \cdot \text{short time}\\ &= \text{small torque} \cdot \text{long time.}\end{aligned} \quad (2.3.6)$$

Thus you can get your car spinning with a certain angular momentum either by letting the motor and floor twist it with a small torque of long duration or by letting the colliding purple car twist it with a large torque of short duration. As with linear momentum, sudden transfers of angular momentum can break things, so the cars are designed to limit their *impact torques* to reasonable levels. Even so, you may find yourself reaching for the motion sickness bag after a few spinning collisions.

Angular momentum is conserved because of Newton's third law of rotational motion. When the purple car exerts a torque on your car for a certain amount of time, your car exerts an equal but oppositely directed torque on the purple car for exactly the same amount of time. Because of the equal but oppositely directed nature of the two torques, the cars receive angular impulses that are equal in amount but opposite in direction. Since the angular momentum gained by one car is exactly equal to the angular momentum lost by the other car, we say that angular momentum is transferred from one car to the other.

Because a car's angular momentum depends on its rotational mass, two different cars may end up rotating at different angular velocities even though they have identical angular momenta. For example, when the purple car hits the overloaded green car and transfers angular momentum to it, the green car's enormous rotational mass makes it spin relatively slowly. The same sort of behavior occurs with linear momentum, where a car's mass affects how fast it travels when it's given a certain amount of linear momentum. But while a bumper car can't change its mass, it can change its rotational mass. If it does so while it's spinning, its angular *momentum* won't change, but its angular *velocity* will!

To see this change in angular velocity, consider the overloaded green car. Its two large occupants are disappointed with the ride because their huge mass and rotational mass prevent them from experiencing the intense jolts and spins that you've been enjoying. Suddenly they get a wonderful idea. As their car slowly spins, one of them climbs into the other's lap and the two sit very close to the car's center of mass. By rearranging the car's mass this way, they have reduced the car's overall rotational mass and the car actually begins to spin faster than before.

As the green car's mass is being redistributed, it's not a freely turning rigid object covered by Newton's first law of rotational motion. However, it is freely turning and thus covered by a more general and equally useful rule: an object that is not subject to any outside torques has constant angular momentum. As the car's rotational mass becomes smaller, its angular velocity must increase to keep its angular momentum constant. That's just what happens. This effect of changing one's rotational mass explains how an ice skater can achieve an enormous angular velocity by pulling herself into a thin, spinning object on ice (Fig. 2.3.3).

Fig. 2.3.3 When skater Sarah Hecken pulls in her arms, she reduces her rotational mass. Since she is experiencing zero net torque, her angular momentum must remain constant and she begins to spin more rapidly.

CONSERVED QUANTITY: ANGULAR MOMENTUM | **TRANSFERRED BY: ANGULAR IMPULSE**

Angular momentum: **The measure of an object's rotational motion, its tendency to continue spinning about a particular axis. Angular momentum is a vector quantity, meaning that it has a direction. It has no potential form and therefore cannot be hidden; angular momentum = rotational mass · angular velocity.**

Angular impulse: **The mechanical means for transferring angular momentum; angular impulse = torque · time.**