CHAPTER 3

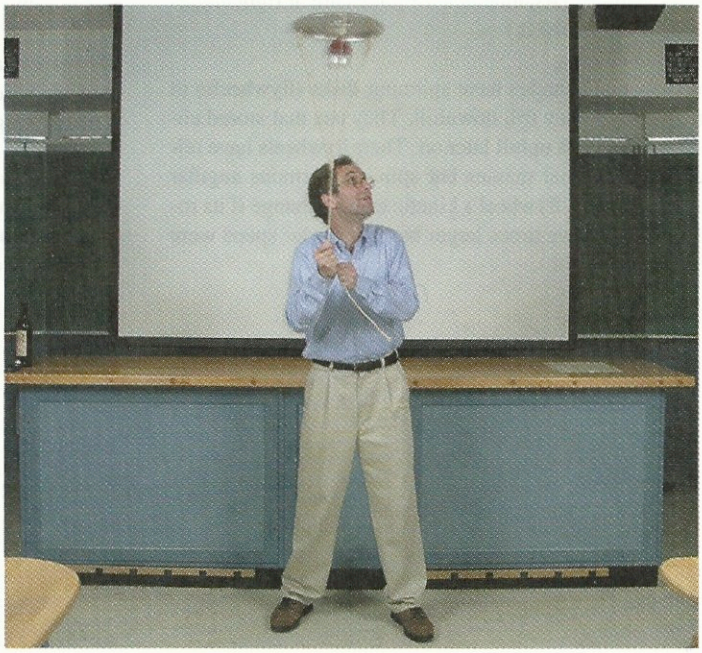
Mechanical Objects Part 1

Now that we've surveyed the laws of motion, we can begin using those laws to explain the behaviors of everyday objects. But while we can already address some of the central features at work in a toy wagon, a weight machine, or a ski lift, we're still missing a number of mechanical concepts that are important in the world around us. In this chapter, we'll look at some of those additional concepts.

One of the most important new concepts will be the feeling of acceleration. If we treat acceleration passively, it can be fairly uninteresting: we push on the cart and the cart accelerates. If we think of it more actively, though—for example, if we envision ourselves on a roller coaster as it plummets down that first big hill—then the experience of acceleration becomes much more intriguing. In fact, we might even need to hold on to our hats.

EXPERIMENT: Swinging Water Overhead

To examine some of the novel effects of acceleration, try experimenting with a bucket of water. If you're careful, you can swing the bucket over your head and upside down without spilling a drop. In the process, you'll be demonstrating a number of important physical concepts.



Courtesy Lou Bloomfield

To do this experiment, you'll need a bucket with a handle. (You might substitute some equivalent container; even a plastic cup will do in a pinch.) Fill the bucket partway full of water and then hold it by the handle so that it hangs down by your side.

Now swing the bucket backward about an eighth of a turn and bring it forward rapidly. In one smooth, fluid motion, swing it forward, up, and over your head. Continue this motion all the way around behind you and then bring the bucket forward again. You'll need to swing the bucket quickly to avoid getting wet. As you swing the bucket around and around, you'll notice that the water stays in it even when it travels over your head and is upside down. Why doesn't the water fall out?

You can carry this experiment a step further by swinging the bucket at various speeds—that is, if you don't mind getting wet. What will happen if you swing the bucket less rapidly or more rapidly? Is the pull stronger or weaker when you swing less rapidly? More rapidly? Is there any relationship between the upward pull you feel from the inverted bucket and the water's tendency to remain inside?

You might vary this experiment in several ways. Try swinging a plastic cup held in your fingers, or try placing a full wine glass in the bucket and swinging the two objects together. In the latter case, you'll find that the wine will stay in the glass and the glass will stay at the bottom of the bucket, even when the bucket is upside down.

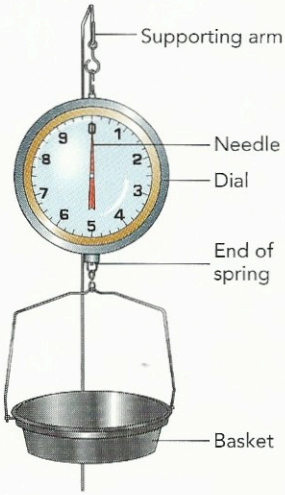
By the way, the hardest part of all these tricks is stopping. To avoid a catastrophe, you'll need to do the same thing you did to get started, only in reverse. Come to a smooth, gradual stop about an eighth of a turn in front of you, and then let the bucket loosely drop back to your side. If you stop moving the bucket too abruptly, the water, wine, or glass will spill or smash. Why do you suppose that happens?

Chapter Itinerary

In this chapter, we'll examine three types of everyday objects: (1) *spring scales*, (2) *bouncing balls*, and (3) *carousels and roller coasters*. In *spring scales*, we'll review the relationship between mass and weight and explore how the distortion of a spring can be used to measure an object's weight. In *bouncing balls*, we'll study how balls store and return energy and how their bouncing depends both on their own characteristics and on those of the objects they hit. And in *carousels and roller coasters*, we'll look at how acceleration gives rise to gravity-like apparent forces that can make us scream with delight at the amusement park. For a more complete preview of what we'll examine in this chapter, skip ahead to the Chapter Summary at the end of the chapter.

The concepts these objects illustrate can explain other phenomena as well. Almost any solid object, from a mattress to a diving board to a tire, behaves like a spring scale's spring when you push on it. Bouncing balls offer a view of collisions that will help you comprehend what happens when two cars crash or when a hammer hits a nail. And the sensations associated with acceleration that you experience on a roller coaster are also present when you ride in airplanes, on subways, or on swing sets. When it comes to the physics of everyday objects, there really is nothing new under the sun.

SECTION 3.1 Spring Scales



How much of you is there? From day to day, depending on how much you eat, the amount of you stays approximately the same. But how can you tell how much that is? The best measure of quantity is mass: kilograms of gold, grain, or you. Mass is the measure of an object's inertia and, as we saw in Section 1.1, doesn't depend on the object's environment or on gravity. A kilogram box of cookies always has a mass of 1 kilogram, no matter where in the universe you take it.

But mass is difficult to measure directly. Moreover, the very concept of mass is only about 300 years old. Consequently, people began quantifying the material in an object by measuring its weight. Spring scales eventually became one of the simplest and most practical tools for accomplishing this task, and they are still found in bathrooms and grocery stores today. They really do contain springs, although these are normally hidden from view.

Questions to Think About: *How is your weight related to your mass? If the earth's gravity became twice as strong, how would your mass be affected? What about your weight? Does jumping up and down change either your mass or your weight? If you stand on a strong spring, how does your weight affect the shape of the spring? Why should there be a relationship between your weight and how much the spring bends?*

Experiments to Do: *Find a hanging spring scale of the type used in the produce section of a grocery store and watch the scale's basket and weight indicator as you put objects in the basket. What happens to the basket as you fill it up? Can you find a relationship between the basket's height and the weight reported by the scale? If you drop something into the basket, instead of lowering it gently, how does the scale respond? Why does the weight indicator bounce back and forth rhythmically? What happens to the gravitational potential energy of the dropped item?*

Now find a spring bathroom scale—the short, flat kind with a rotating dial. Stand on it. Why does it read your correct weight only when you are standing still? If you jump upward, how does the scale's reading change? What about if you let yourself drop? Bounce up and down gently. How does the scale's average reading compare with your normal weight? Does bouncing really change your weight? You can also change the scale's reading by pushing on the floor, wall, or other nearby objects. Which way must you push to increase the scale's reading? To decrease it? When you change the reading in these ways, are you actually changing your weight?

Why You Must Stand Still on a Scale

Whenever you stand on a scale in your bathroom or place a melon on a scale at the grocery store, you are measuring weight. An object's weight is the force exerted on it by gravity, usually the earth's gravity. When you stand on a bathroom scale, the scale measures just how much upward force it must exert on you in order to keep you from moving downward toward the earth's center. As in most scales you'll encounter, the bathroom scale uses a spring to provide this upward support. If you're stationary, you're not accelerating, so your downward weight and the upward force from the spring must cancel one

another; that is, they must be equal in magnitude but opposite in direction so that they sum to zero net force. Consequently, although the scale actually displays how much upward force it's exerting on you, that amount is also an accurate measure of your weight.

This subtle difference between your actual weight and what the scale is reporting is important. While an object's weight depends only on its gravitational environment, not on its motion, the weighing process itself is extremely sensitive to motion. If anything accelerates during the weighing process, the scale may not report the object's true weight. For example, if you jump up and down while you're standing on a scale, the scale's reading will vary wildly. You're accelerating and, since the net force exerted on you is no longer zero, your downward weight and the upward force from the scale no longer cancel. If you want an accurate measurement of your weight, therefore, you have to stand still.

Even if you stand still, weighing is not a perfect way to quantify the amount of material in your body. That's because your weight depends on your environment. If you always weigh yourself in the same place, the readings will be pretty consistent, as long as you don't routinely eat a dozen jelly doughnuts for lunch. But if you moved to the moon, where gravity is weaker, you'd weigh only about one-sixth as much as on the earth. Even a move elsewhere on the earth will affect your weight: the earth bulges outward slightly at the equator, and gravity there is about 0.5% weaker than at the poles. That change, together with a small acceleration effect due to the earth's rotation, means that a scale will read 1.0% less when you move from the north pole to the equator. Obviously, moving south is not a useful weight-loss plan.

Check Your Understanding #1: Space Merchants

You're opening a company that will export gourmet food from the earth to the moon. You want the package labels to be accurate at either location. How should you label the amount of food in each package—by mass or by weight?

Answer: You should sell by mass—for example, by kilogram or pound-mass.

Why: If you label your product by weight, you are specifying the force that gravity exerts on it near the earth's surface. When it's exported to the moon, such a product will weigh just ⅙ as much, and your company may be fined for selling underweight groceries. If you label the packages according to their masses, that labeling will remain correct no matter where you ship the packages. Mass is the measure of inertia and depends only on the object, not on its environment.

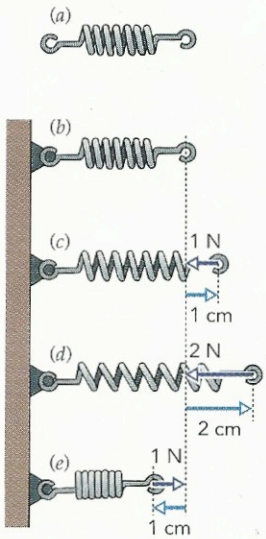


Fig. 3.1.1 Five identical springs. The ends of spring (*a*) are free so that it can adopt its equilibrium length. The left ends of the other springs are fixed so that only their right ends can move. When the free end of spring (*b*) is moved away from its original equilibrium position (*c, d,* and *e*), the spring exerts a restoring force on that end that is proportional to the distance between its new position and the original equilibrium position.

Stretching a Spring

So you know now that when you put a melon in the basket of a scale at the grocery store and read its weight from the scale's dial, the scale is actually reporting just how much upward force its spring is exerting on the melon. While your shopping cart could support the melon equally well, there's no simple way to determine just how much upward force the cart exerts on the melon. Therein lies the beauty, and the utility, of a spring: a simple relationship exists between its length and the forces it's exerting on its ends. The spring scale can therefore determine how much force it's exerting on the melon by measuring the length of its spring.

The springs shown in Fig. 3.1.1 consist of a wire coil that pulls inward on its ends when it's stretched and pushes outward on them when it's compressed. If a coil spring is neither stretched nor compressed, it exerts no forces on its ends.

The top spring (Fig. 3.1.1*a*) is neither stretched nor compressed, so that when it lies on a table to keep it from falling, its ends remain motionless. Those ends are in **equilibrium**—experiencing zero net force. As the phrase "zero net force" suggests, equilibrium occurs whenever the forces acting on an object sum perfectly to zero so that the object doesn't accelerate. When you sit still in a chair, for example, you are in equilibrium.

The spring in Fig. 3.1.1*a* is also at its equilibrium length, its natural length when you leave it alone. No matter how you distort this spring, it tries to return to this equilibrium length. If you stretch it so that it's longer than its equilibrium length, it will pull inward on its ends. If you compress it so that it's shorter than its equilibrium length, it will push outward on its ends.

Let's attach the left end of our spring to a post (Fig. 3.1.1*b*) and look at the behavior of its free right end. With nothing pushing or pulling on the spring, this free end will be in equilibrium at a particular location—its **equilibrium position**. Since the spring's end naturally returns to this equilibrium position if we stretch or compress it and then let go, the end is in a **stable equilibrium**.

What happens if we pull the free end to the right and don't let go? The spring now exerts a steady inward force on that end, trying to return it to its original equilibrium position. The more we stretch the spring, the more inward force it exerts on the end. Remarkably, this inward force is exactly proportional to how far we stretch the end away from its original equilibrium position. Since the end of the spring in Fig. 3.1.1*c* has been pulled 1 cm to the right of its original equilibrium position, the spring now pulls this end to the left with a force of 1 N; if the end is instead pulled 2 cm to the right, as it has been in Fig. 3.1.1*d*, the spring pulls it to the left with a force of 2 N. This proportionality continues to work even when we compress the spring: in Fig. 3.1.1*e*, the end has been pushed 1 cm to the left, and the spring is pushing it to the right with a force of 1 N.

The force exerted by a coil spring thus has two interesting properties. First, this force is always directed so as to return the spring to its equilibrium length. We call this kind of force a **restoring force** because it acts to restore the spring to equilibrium. Second, the spring's restoring force is proportional to how far it has been distorted (stretched or compressed) from its equilibrium length.

These two observations are expressed in **Hooke's law**, named after the Englishman Robert Hooke, who discovered it in the late seventeenth century. This law can be written in a word equation:

$$\text{restoring force} = -\text{spring constant} \cdot \text{distortion}, \tag{3.1.1}$$

in symbols:

$$\mathbf{F} = -k \cdot \mathbf{x},$$

and in everyday language:

The stiffer the spring and the farther you stretch it, the harder it pulls back.

Here the **spring constant**, k, is a measure of the spring's stiffness. The larger the spring constant—that is, the firmer the spring—the larger the restoring force the spring exerts for a given distortion. The negative signs in these equations indicate that a restoring force always points in the direction opposite the distortion.

Hooke's Law
The restoring force exerted by an elastic object is proportional to how far it has been distorted from its equilibrium shape.

Springs are distinguished by their stiffness, as measured by their spring constants. Some springs are **soft** and have small spring constants—for example, the one that pops the toast out of your toaster, which you can easily compress with your hand. Others, like the large springs that suspend an automobile chassis above the wheels, are **firm** and have large spring constants. But no matter the stiffness, all springs obey Hooke's law.

Hooke's law is remarkably general and isn't limited to the behavior of coil springs. Almost anything you distort will pull or push back with a force that's proportional to how far you've distorted it away from its equilibrium length—or, in the case of a complicated object, its equilibrium shape. Equilibrium shape is the shape an object adopts when it's not subject to any outside forces. If you bend a tree branch, it will push back with a force proportional to how far it has been bent. If you pull on a rubber band, it will pull back with a force proportional to how far it has been stretched, up to a point. If you squeeze a ball, it will push outward with a force proportional to how far it has been compressed. If a heavy truck bends a bridge downward, the bridge will push upward with a force proportional to how far it has been bent (Fig. 3.1.2).

There is a limit to Hooke's law, however. If you distort an object too far, it will usually begin to exert less force than Hooke's law demands. This is because you will have exceeded the **elastic limit** of the object and will probably have permanently deformed it in the process. If you pull on a spring too hard, you'll stretch it forever; if you push on a branch too hard, you'll break it. But as long as you stay within the elastic limit, almost everything obeys Hooke's law—a rope, a ruler, an orange, and a trampoline.

Distorting a spring requires work. When you stretch a spring with your hand, pulling its end outward, you transfer some of your energy to the spring. The spring stores this energy as **elastic potential energy**. If you reverse the motion, the spring returns most of this energy to your hand, while a small amount is converted to thermal energy by frictional effects inside the spring itself. Work is also required to compress, bend, or twist a spring. In short, a spring that is distorted away from its equilibrium shape always contains elastic potential energy.

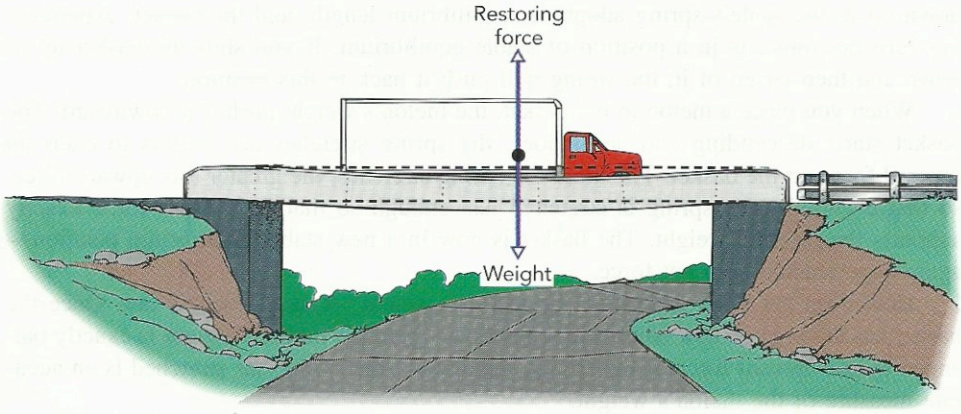


Fig. 3.1.2 A steel bridge sags under the weight of a truck. The bridge bends downward until the upward restoring force it exerts on the truck exactly balances the truck's weight.

Check Your Understanding #2: **Going Down, Anyone?**

As you watch people walk off the diving board at a pool, you notice that it bends downward by an amount proportional to each diver's weight. Explain.

Answer: The diving board is behaving as a spring, bending downward in proportion to the weight of each diver.

Why: The heavier the diver, the more the board bends downward before exerting enough upward force on the diver to balance the diver's weight.

Check Your Figures #1: **A Sinking Sensation**

You're hosting a party in your third-floor apartment. When the first 10 guests begin standing in your living room, you notice that the floor has sagged 1 centimeter in the middle. How far will the floor sag when 20 guests are standing on it? When 100 guests are standing on it?

Answer: It will sag 2 centimeters and 10 centimeters (assuming that the floor doesn't break).

Why: A floor, like most suspended surfaces, behaves like a spring. Your floor distorts 1 centimeter before it exerts an upward restoring force equal to the weight of 10 guests. It will thus distort 2 centimeters before supporting 20 guests and 10 centimeters before supporting 100 guests. While this distortion should be within the elastic limit of the floor beams, it may cause the plaster and paint to crack. If the beams break, the floor will collapse.

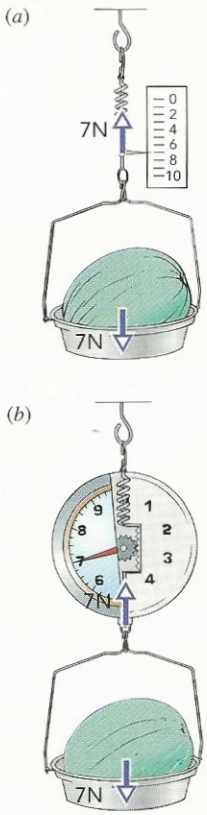


Fig. 3.1.3 Two spring scales weighing melons. Each scale balances the melon's downward weight with the upward force of a spring. The heavier the melon, the more the spring will stretch before it exerts enough upward force to balance the melon's weight. The top scale has a pointer to indicate how far the spring has stretched and thus how much the melon weighs. The bottom scale has a rack and pinion gear that turns a needle on a dial. As the comblike rack moves up and down, it turns the toothed pinion gear.

How a Hanging Grocery Scale Measures Weight

We're now ready to understand how spring scales work. Imagine a hanging spring scale of the kind used to weigh produce. Inside this scale is a coil spring, suspended from the ceiling by its upper end (Fig. 3.1.3). Hanging from its lower end is a basket. For the sake of simplicity, imagine that this basket has little or no weight. With no force pulling down on it, the scale's spring adopts its equilibrium length, and the basket, experiencing zero net force, is in a position of stable equilibrium. If you shift the basket up or down and then let go of it, the spring will push it back to this position.

When you place a melon in the basket, the melon's weight pushes it downward. The basket starts descending and, as it does, the spring stretches and begins to exert an upward force on the basket. The more the spring stretches, the greater this upward force, so that eventually the spring is stretched just enough so that its upward force exactly supports the melon's weight. The basket is now in a new stable equilibrium position—again experiencing zero net force.

How does the scale determine the melon's weight? It uses Hooke's law. Once the basket has adopted its new equilibrium position, where the melon's weight is exactly balanced by the upward force of the spring, the amount the spring has stretched is an accurate measure of the melon's weight.

The scales in Fig. 3.1.3 differ only in the way they measure how far the spring has stretched beyond its equilibrium length. In Fig. 3.1.3*a*, the scale uses a pointer attached to the end of the spring, while in Fig. 3.1.3*b*, the scale uses a rack and pinion gear

system that converts the small linear motion of the stretching spring into a much more visible rotary motion of the dial needle. The rack is the series of evenly spaced teeth attached to the lower end of the spring; the pinion is the toothed wheel attached to the dial needle. As the spring stretches, the rack moves downward, and its teeth cause the pinion to rotate. The farther the rack moves, the more the pinion turns, and the higher the weight reported by the needle.

Each of these spring scales reports a number for the weight of the melon you put in the basket. In order for that number to mean something, the scale has to be calibrated. **Calibration** is the process of comparing a local device or reference to a generally accepted standard to ensure accuracy. To calibrate a spring scale, the device or its reference components must be compared against standard weights. Someone must put a standard weight in the basket and measure just how far the spring stretches. Each spring is different, although spring manufacturers try to make all their springs as identical as possible.

Check Your Understanding #3: Scaling Down

If you pull the basket of a hanging grocery store scale downward 1 centimeter, it reports a weight of 5 N (about 1.1 lbf) for the contents of its basket. If you pull the basket downward 3 centimeters, what weight will it report?

Answer: The scale will read 15 N (about 3.3 lbf).

Why: The scale's dial is simply reporting the position of its basket. The dial is calibrated so that a 1-centimeter drop in the basket indicates that the spring is pulling up on it with a force of 5 N. Since the spring's restoring force is described by Hooke's law, a 3-centimeter drop in the basket means that the spring is exerting an upward force of 15 N on the basket.

Bouncing Bathroom Scales

As we noted earlier, the most common type of bathroom scale is also a spring scale (Fig. 3.1.4). When you step on this kind of scale, you depress its surface and levers inside it pull on a hidden spring. That spring stretches until it exerts, through the levers, an upward force on you that is equal to your weight. At the same time, a rack and pinion mechanism (see Fig. 3.1.3*b*) inside the scale turns a wheel with numbers printed on it. When the wheel stops moving, you can read one of these numbers through a window in the scale. Because which number you see depends on how far the spring has stretched, this number indicates your weight.

However, the wheel rocks briefly back and forth around your actual weight before it settles down. The wheel moves because you're bouncing up and down as the scale gradually gets rid of excess energy. When you first step on the scale's surface, its spring is not stretched and it isn't pushing up on you at all. You begin to fall. As you descend, the spring stretches and the scale begins to push up on your feet. By the time you reach the equilibrium height, where the scale is exactly supporting your weight, you are traveling downward quickly and coast right past that equilibrium. The scale begins to read more than your weight.

The scale now accelerates you upward. Your descent slows, and you soon begin to rise back toward equilibrium. Again you coast past the proper height, but now the scale begins to read less than your weight. You are bouncing up and down because you have excess energy that is shifting back and forth between gravitational potential energy,

Courtesy Lou Bloomfield

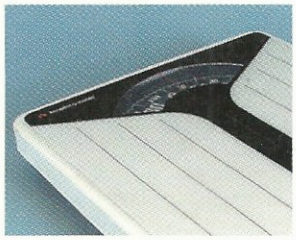


Fig. 3.1.4 When you step on this bathroom scale, its surface moves downward slightly and compresses a stiff spring. The extent of this compression is proportional to your weight, which is reported by the dial. Levers inside the scale make it insensitive to exactly where you stand.

kinetic energy, and elastic potential energy. This bouncing continues until sliding friction in the scale has converted it all into thermal energy. Only then does the bouncing stop and the scale read your correct weight.

The bouncing that you experience about this stable equilibrium is a remarkable motion, one that we'll study in detail when we examine clocks in Chapter 9. You are effectively a mass supported by a spring, and your rhythmic rise and fall is that of a *harmonic oscillator*. Harmonic oscillators are so common and important in nature that Chapter 9 is devoted to them. The details can wait, but there are two features of your present situation that I'll point out now.

First, your total potential energy is at its minimum when you're at the stable equilibrium. Even though both gravitational and elastic potentials are involved, their sum increases as you shift away from the equilibrium. Since an object always accelerates so as to reduce its total potential energy as quickly as possible, you always accelerate toward the stable equilibrium.

Second, your kinetic energy reaches its peak as you pass through the stable equilibrium. Having accelerated toward that equilibrium until the moment of arrival, you're moving fast and coast right through it. But once you leave it, you begin to accelerate toward it again. That acceleration is backward, opposite your velocity, so you are decelerating. Therefore, you reached your peak speed and kinetic energy at the moment you passed through equilibrium. As you bounce up and down, waiting for the scale to waste your excess energy, that excess transforms back and forth rhythmically between kinetic and potential forms.

Common Misconceptions: Equilibrium and Motionlessness

Misconception: An object at equilibrium is always motionless.

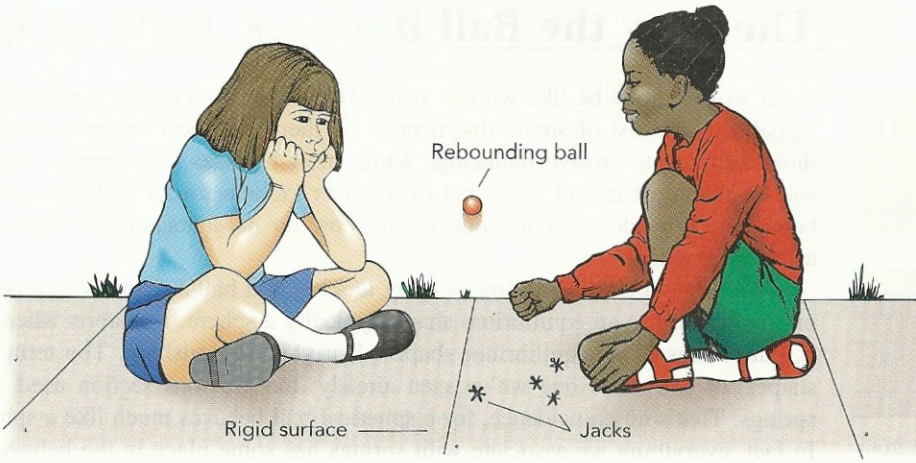
Resolution: An object at equilibrium is not accelerating, but its velocity may not be zero. If it was moving when it reached equilibrium, it will coast through that equilibrium at constant velocity.

Check Your Understanding #4: **Weighed Down**

When you step on the surface of a spring bathroom scale, you can feel it move downward slightly. How is the distance that the scale's surface moves downward when you step on it related to the weight it reports?

Answer: The distance the scale's surface moves downward is proportional to the weight it reports.

Why: The scale's spring is connected to its surface by levers so that as the surface moves downward, the spring distorts by a proportional amount. The spring's distortion is reported on the dial. Thus the dial's reading is proportional to the surface's downward movement.



SECTION 3.2 Ball Sports: Bouncing

If you visit a toy or sporting goods store, you'll find many different balls—almost a unique ball for every sport or ball game. These balls differ in more than just size and weight. Some are very hard, others very soft; some are smooth, others rough or ridged.

In this section we'll focus primarily on another difference: the ability to bounce. A superball, for example, bounces extraordinarily well, while a foam rubber ball hardly bounces at all. Even balls that appear identical can be very different; a new tennis ball bounces much better than an old one. We'll begin this section by exploring these differences.

Questions to Think About: *Is it possible for a ball to bounce higher than the height from which it was dropped? Where does a ball's kinetic energy go as it bounces, and what happens to the energy that doesn't reappear after the bounce? What happens when a ball bounces off a moving object, such as a baseball bat? What role does the baseball bat's structure have in the bouncing process? Does it matter which part of a baseball bat hits the ball?*

Experiments to Do: *Drop a ball on a hard surface and watch it bounce. What happens to the ball's shape during the bounce? Hold the ball in your hands and push its surface inward with your fingers. What is the relationship between the force it exerts on your fingers and how far inward you dent it? Denting the ball takes work. Why? How does the ball's energy change as it dents? What happens to the ball's energy as its shape returns to normal (to equilibrium)?*

Drop the ball from various heights and see whether you can find a simple relationship between the ball's initial height and the height to which it rebounds. Now drop the ball on a soft surface, such as a pillow, or on a lively surface, such as an inflated balloon. Why does the surface it hits change the way the ball bounces?

The Way the Ball Bounces: Balls as Springs

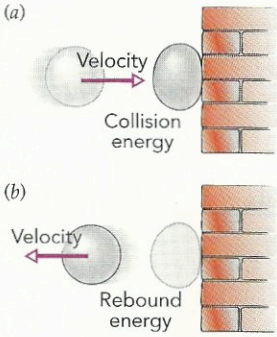


Fig. 3.2.1 A bounce from a wall has two halves: (*a*) the collision and (*b*) the rebound. During the collision between the ball and the wall, some of their kinetic energy is transformed into other forms—an amount called the collision energy. During the rebound, some stored energy is released as kinetic energy—an amount called the rebound energy. The rebound energy is always less than the collision energy because some energy is lost as thermal energy. However, a lively ball wastes less energy than a dead one.

What would sports be like without balls? Basketball, baseball, tennis, golf, soccer, volleyball . . . the list of sports that depend on them is almost endless—and nearly all of those ball sports involve bouncing. While most bounces are obvious, others are more subtle. When a baseball hits a bat or a player kicks a soccer ball, those balls truly are bouncing. Why does a ball bounce, and how do its characteristics and circumstances affect its bounce?

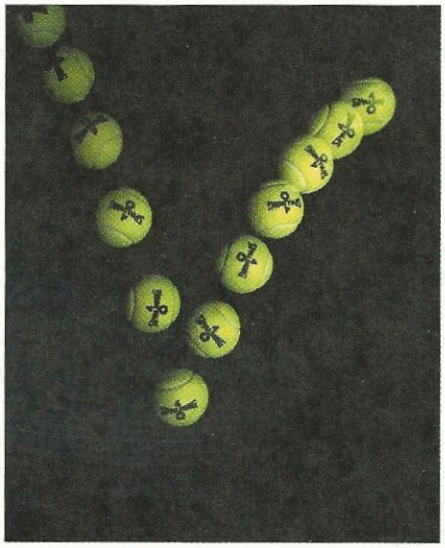
We'll begin to explain bouncing by looking at a ball's shape. When nothing pushes on the ball, it has an equilibrium shape, typically a sphere. It distorts when you push on it, but returns to its equilibrium shape when you stop pushing. The term "equilibrium shape," of course, is one we've seen already: the previous section used it to describe springs. That's no coincidence, for a spherical ball behaves much like a spherical spring. In fact, everything we associate with springs has some place in the behavior of balls.

This springlike behavior is evident when a ball bounces off the floor or a bat. As those two objects collide (Fig. 3.2.1*a*), the ball's surface distorts and its elastic potential energy increases. The energy responsible for that distortion is extracted from the kinetic energies of the colliding objects. As the two objects subsequently rebound (Fig. 3.2.1*b*), the ball's surface returns toward its equilibrium and its elastic potential energy decreases. That return to equilibrium releases energy that is added to the kinetic energies of the rebounding objects.

We'll call the kinetic energy absorbed during the collision the **collision energy** and the kinetic energy released during the rebound the **rebound energy**. How do those two energies compare? Since energy is conserved and the two objects appear unchanged by the bounce, shouldn't the rebound energy equal the collision energy?

In fact, the two energies would be equal except for one important detail: the two objects *have* changed. Their thermal energies have increased. As it distorts and then returns to equilibrium, the ball wastes some of the collision energy as thermal energy, so the rebound energy is always less than the collision energy (Fig. 3.2.2).

Some balls bounce better than others. A very bouncy ball is often called "lively," and a ball that doesn't bounce well is said to be "dead." A lively ball is extremely elastic—it



Courtesy Lou Bloomfield

Fig. 3.2.2 When a tennis ball hits the floor, it dents inward to store energy and then rebounds somewhat more slowly than it arrived. These images show the ball's position at twelve equally spaced times. Is the ball bouncing to the left or the right? How can you tell?

Table 3.2.1 Approximate Energy Ratios and Speed Ratios for a Variety of Balls

TYPE OF BALL	REBOUND ENERGY / COLLISION ENERGY	REBOUND SPEED† / COLLISION SPEED
Superball	0.81	0.90
Racquet ball	0.72	0.85
Golf ball	0.67	0.82
Basketball	0.64	0.80
Tennis ball	0.56	0.75
Steel ball bearing	0.42	0.65
Baseball	0.30	0.55
Foam rubber ball	0.09	0.30
"Unhappy" ball	0.01	0.10
Beanbag	0.002	0.04

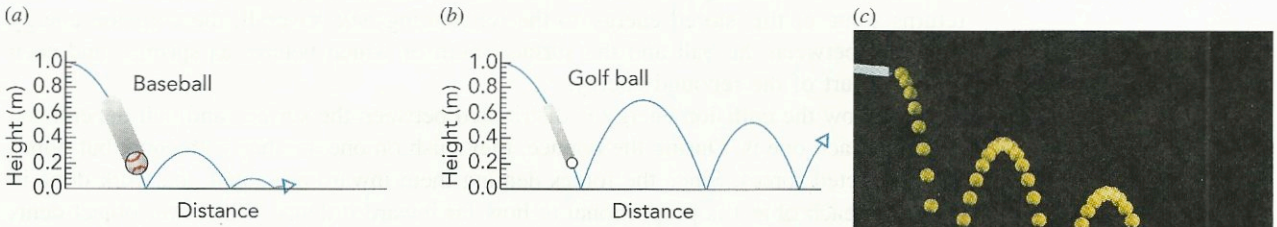
†Known as the *coefficient of restitution*, this speed ratio can be squared to obtain the energy ratio.

converts most of the collision energy into elastic potential energy during the collision and converts most of that elastic potential energy into rebound energy during the rebound. A dead ball, on the other hand, is barely elastic at all—it converts most of the collision energy into thermal energy during the collision and converts most of what's left into thermal energy during the rebound.

The ratio of rebound energy to collision energy (Table 3.2.1) determines how high a ball will bounce when you drop it from rest onto a hard floor (Fig. 3.2.3). An ideally elastic ball would have a ratio of 1.00 and would rebound to its initial height. A real ball, however, wastes some of the collision energy and rebounds to a lesser height. For example, a baseball's rebound energy is only 0.30 times its collision energy, so it will rebound to only 30% of its original height. Without that dramatic energy loss during a bounce, baseball pitchers would need to wear armor.

While that *energy* ratio is useful, a ball is traditionally characterized by a *speed* ratio: its rebound speed divided by its collision speed. Here, the collision speed is how fast the two objects approach one another before the bounce, and the rebound speed is how fast those objects separate after the bounce. Their ratio is known as the ball's **coefficient of restitution**:

$$\text{coefficient of restitution} = \frac{\text{rebound speed of ball}}{\text{collision speed of ball}} \tag{3.2.1}$$



Courtesy Lou Bloomfield

Fig. 3.2.3 (*a*) A baseball wastes 70% of the collision energy as thermal energy and bounces weakly. (*b*) In contrast, a golf ball wastes only 30% of the collision energy and bounces well. (*c*) The photo at right of a golf ball illustrates this in stop-motion.

(see Table 3.2.1). The larger a ball's coefficient of restitution, the faster it rebounds from a surface for a given collision speed. For example, a basketball's coefficient of restitution is 0.80, so when it bounces off the backboard during a foul shoot, its rebound speed is only 0.80 times its collision speed. That decrease in speed makes it easier for the ball to drop into the basket after it bounces than before it bounces.

Since a ball's kinetic energy is proportional to the square of its speed, its energy ratio is simply the square of its speed ratio. Measuring those ratios is more than an academic exercise because most of the organizations that govern ball sports specify their balls' coefficients of restitution. It's a matter of fairness and safety. For example, baseballs could easily be made so lively that every game would be a home-run derby. Just think of all the asterisks.

Balls bounce best when they store energy through compression rather than through surface bending. That's because most ball materials, such as leather or leather-like plastics, experience lots of wasteful internal friction during bending. Since solid balls involve compression, they usually bounce well, whether they're made of rubber, wood, plastic, or metal. Air-filled balls, however, bounce well only when properly inflated. A normal basketball, which stores most of its energy in its compressed air, has a high coefficient of restitution. In contrast, an underinflated basketball, which experiences lots of surface bending during a collision, barely bounces at all. Similarly, a tennis ball bounces best when new; after a while, the compressed air inside leaks out and the ball's coefficient of restitution drops.

Check Your Understanding #1: A Game of Marbles

As you head into the park to play a game of marbles with your friends, several of the glass marbles fall through a hole in your marble bag and bounce nicely on the granite walkway. How can a marble bounce?

Answer: When the marble collides with the hard granite surface, it dents inward and converts most of its kinetic energy into elastic potential energy. It then rebounds, converting this stored energy back into kinetic energy as it bounces from the surface.

Why: An elastic marble has a very high coefficient of restitution and bounces well from a hard surface.

How the Surface Affects the Bounce

Since the surface on which a ball bounces isn't perfectly hard, that surface also contributes to the bouncing process. It distorts and stores energy when the ball hits it and returns some of this stored energy to the rebounding ball. Overall, the collision energy is shared between the ball and the surface, both of which behave as springs, and each provides part of the rebound energy.

Just how the collision energy is distributed between the surface and ball depends on how stiff each one is. During the bounce, they push on one another with equal but oppositely directed forces. Since the forces denting them inward are equal, the work done in distorting each object is proportional to how far inward it dents. Whichever object dents the farthest receives the most collision energy.

Since the ball usually distorts more than the surface it hits, most of the collision energy normally goes into the ball. You might expect the ball to provide most of the

rebound energy, too. However, that's not always true. Some lively elastic surfaces store collision energy very efficiently and return almost all of it as rebound energy. Since a relatively dead ball wastes most of the collision energy it receives, a lively surface's contribution to the rebound energy can be very important to the bounce.

For example, a lively racket is critical to the game of tennis because the racket's strings provide much of the rebound energy as the ball bounces off the racket (Fig. 3.2.4). The strings are livelier than the ball, so increasing the fraction of collision energy that is invested in the strings actually speeds up the rebounding ball. That's why a player who is willing to sacrifice aiming accuracy for greater ball speed will string his racket relatively loosely. The looser strings will receive more of the collision energy and return almost all of it as rebound energy.

Courtesy Louis Bloomfield

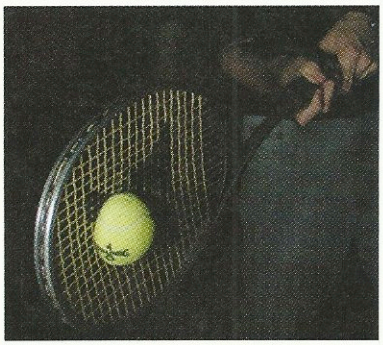


Fig. 3.2.4 When a tennis ball bounces from a moving racket, both the ball and racket dent inward. The ball and racket share the collision energy almost evenly.

Trampolines and springboards are even more extreme examples, with surfaces so lively that they can even make people bounce. People, like beanbags, have coefficients of restitution near zero; when you land on a trampoline, it receives and stores most of the collision energy and then provides most of the rebound energy.

The stiffnesses of the ball and surface also determine how much force each object exerts on the other and thus how quickly the collision proceeds. Hard objects resist denting more strongly than soft objects. When both objects are very hard, the forces involved are large and the acceleration is rapid. Thus a steel ball rebounds very quickly from a concrete floor because the two exert enormous forces on one another. If the ball and/or surface are relatively soft, the forces are weaker and the acceleration is slower.

What if the surface that a ball hits isn't very massive? In that case, the surface may do part or all of the "bouncing." During the bounce, the ball and the surface accelerate in opposite directions and share the rebound energy. Massive surfaces, such as floors and walls, accelerate little and receive almost none of the rebound energy. But when the surface a ball hits is not very massive, you may see it accelerate. When a ball hits a lamp on the coffee table, the ball will do most of the accelerating, but the lamp is likely to fall over, too.

Similarly, when a baseball strikes a baseball bat, the ball and bat accelerate in opposite directions. The more massive the bat, the less it accelerates. To ensure that most of the rebound energy went to the baseball, the legendary hitters of the early twentieth century used massive bats. Such bats are no longer in vogue because they're too difficult to swing. But in the early days of baseball, when pitchers were less skillful, massive bats drove many long home runs.

Check Your Understanding #2: The Game Begins

You are playing the game of marbles on a soft dirt field. The goal is to knock glass marbles out of a circle by hitting them with other marbles. You initially drop several marbles onto the ground inside the circle and they hardly bounce at all. What prevents them from bouncing well here?

Answer: The soft dirt distorts more than the hard marble and receives most of the collision energy. It converts most of that energy into thermal energy so the marble rebounds weakly.

Why: While a marble bounces nicely on a hard surface, the dirt is soft and receives virtually all of the collision energy when the hard marble hits it. The dirt distorts during the impact but stores little energy because it's not very elastic. The marble doesn't rebound much.

How a Moving Surface Affects the Bounce

The previous paragraph describes the act of hitting a baseball with a moving baseball bat as though it were a case of "bouncing." That might sound a little strange. When a baseball hits a stationary bat, the ball bounces. However, if a moving bat hits a stationary baseball, is it proper to say that the ball bounces?

The answer is yes. Any time the bat and ball approach one another and collide, it's a bounce, and everything we've discussed about bouncing applies. The ball's coefficient of restitution, for example, is still the ratio of the ball's rebound speed to its collision speed. But since the ball was stationary before the bounce and moving after it, we clearly have to be careful what we mean by collision speed and rebound speed.

Collision speed is neither the speed of the ball nor the speed of the bat; it's the speed at which those two objects approach one another before the bounce. Similarly, rebound speed is the speed at which the objects separate from one another after the bounce. Technically, both speeds stem from the difference between the bat's velocity and the ball's velocity. However, as long as each object is heading directly toward or away from the other object, collision and rebound speeds are relatively simple to calculate. When the bat and ball are heading in opposite directions, you add their speeds and when they're heading in the same direction, you subtract their speeds.

That simple approach should be familiar from watching cars on the highway. When two cars are moving 60 mph in opposite directions on a narrow road, they are approaching one another at a hair-raising 120 mph. Let's hope they don't collide. When a car traveling 60 mph comes up behind a second car traveling 55 mph in the same direction, however, they are approaching one another at a leisurely 5 mph. If they collide, it'll only be a fender-bender.

We can use these observations about speeds and bouncing to explain why the baseball you just hit is now traveling over the center fielder's head. Let's suppose that, right before the collision (Fig. 3.2.5*a*), the pitched baseball was approaching home plate at 100 km/h (62 mph) and that, as you swung to meet the ball, your bat was moving toward the pitcher at 100 km/h. Since each object is moving toward the other, their speed of approach is the sum of their individual speeds, or 200 km/h (124 mph).

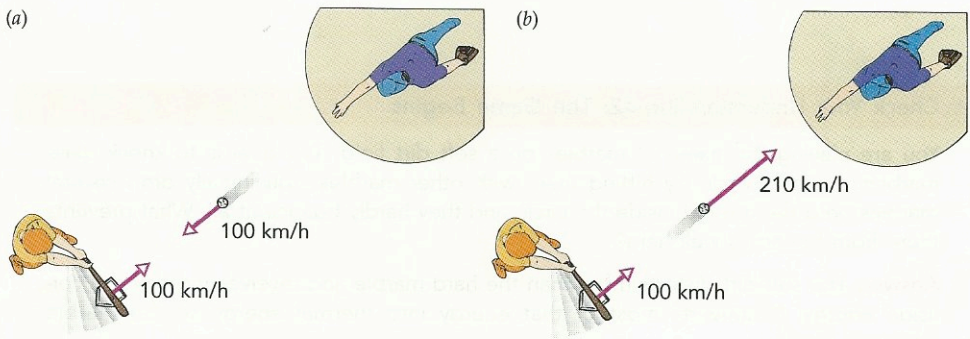


Fig. 3.2.5 (*a*) Before they collide, the bat and ball are approaching one another at an overall speed of 200 km/h. (*b*) After the collision, the two are separating from one another at a speed of 110 km/h. However, because the bat is moving toward the pitcher at 100 km/h, the outgoing ball is traveling at 210 km/h in that same direction.

The baseball's coefficient of restitution is 0.55, so after the collision (Fig. 3.2.5*b*) the speed of separation was only 0.55 times the speed of approach, or 110 km/h. The outgoing ball and the swinging bat separate from one another at 110 km/h. Since the bat is still moving toward the pitcher at 100 km/h, the ball must be traveling toward the pitcher even faster: at 100 km/h plus 110 km/h or a total speed of 210 km/h (130 mph)! That's why the baseball flies past everyone in the outfield and into the stands.

Check Your Understanding #3: Crashing Marbles

Two of you flick your marbles into the circle simultaneously from opposite sides of the circle and they collide head-on. Each marble was traveling forward at 1 m/s (3.3 ft/s). How quickly were the two marbles approaching one another just before they hit?

Answer: They were approaching at 2 m/s (6.6 ft/s).

Why: The velocities reported in the question are those observed by people sitting still with respect to the circle. Since the marbles are heading toward one another, you must add their speeds to obtain the collision speed.

Surfaces Also Bounce . . . and Twist and Bend

As you can see, a surface's motion has a large effect on a ball bouncing off it. A surface that moves toward an incoming ball will strengthen the rebound, while one that moves away from the ball will weaken it. But we're neglecting the ball's effect on the surface itself. Sometimes that surface bounces, too.

A baseball bat is a case in point. When you swing your bat into a pitched ball, the bat doesn't continue on exactly as before. The ball pushes on the bat during the collision and the bat responds in a number of interesting ways.

First, as we noted before, the bat rebounds from the ball. The bat decelerates slightly during the collision, so that its speed after the impact is a little less than before it. Since the ball's final speed depends on the bat's final speed, a slower bat means a slower ball. Thus we've slightly overestimated the ball's speed as it heads toward the bleachers.

Second, the ball's impact sets the bat spinning. When the ball pushes on the bat and makes it accelerate backward, it also exerts a torque on the bat about its center of mass and makes it undergo angular acceleration (Fig. 3.2.6). While these two types of acceleration might seem inconsequential, your hands notice their effects. The bat's acceleration tends to yank its handle toward the catcher, while its angular acceleration tends to twist its handle toward the pitcher. The extent of these two motions depends on just where the ball hits the bat. If the ball hits a point known as the **center of percussion**, the handle experiences no overall acceleration (Fig. 3.2.6*c*). The smooth feel of such a collision explains why the center of percussion, located about 7 inches from the end of the bat, is known as a "sweet spot."

Finally, the collision often causes the bat to vibrate. Like a xylophone bar struck by a mallet (Fig. 3.2.7*a*), the bat bends back and forth rapidly with its ends and center moving

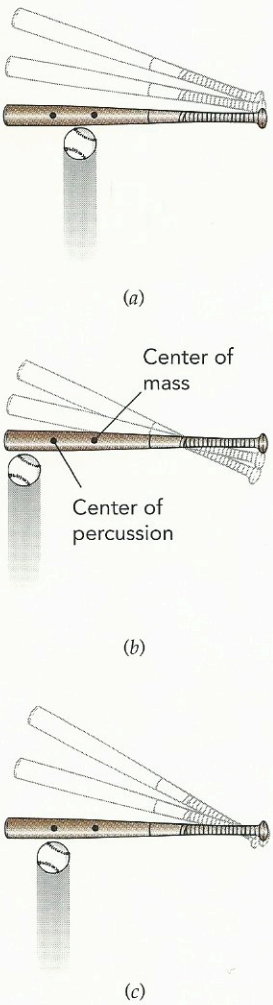


Fig. 3.2.6 When a ball hits a bat, the bat experiences both acceleration and angular acceleration. (*a*) If the ball hits near the bat's center, the angular acceleration is small and the bat's handle accelerates backward. (*b*) If the ball hits near the bat's end, the angular acceleration is large and the bat's handle accelerates forward. (*c*) But if the ball hits the bat's center of percussion, the angular acceleration is just right to keep the handle from accelerating.

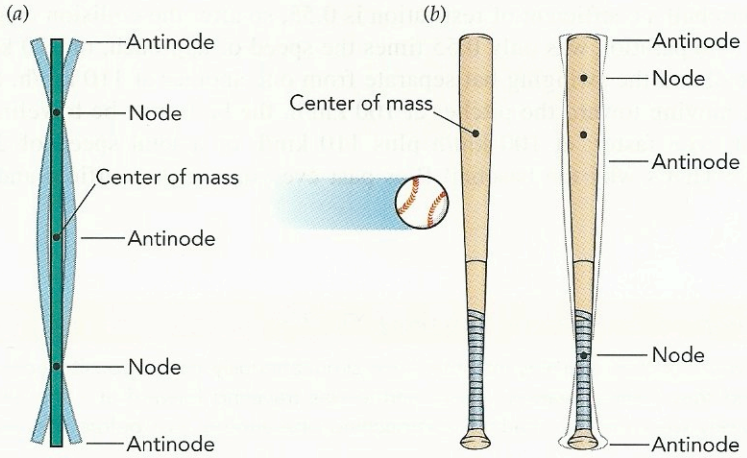


Fig. 3.2.7 (*a*) When struck by a mallet, a xylophone bar vibrates with its middle and ends moving back and forth in opposite directions. The parts that move farthest are antinodes, and the points that don't move at all are nodes. (*b*) When struck by a ball, a baseball bat vibrates in a similar fashion. However, an impact at one of the bat's nodes causes no vibration.

in opposite directions (Fig. 3.2.7*b*). These vibrations sting your hands and can even break a wooden bat. However, near each end of the bat, there's a point that doesn't move when the bat vibrates—a **vibrational node**. When the ball hits the bat at its node, no vibration occurs. Instead, the bat emits a crisp, clear "crack" and the ball travels farther. Fortunately, the bat's vibrational node and its center of percussion almost coincide, so you can hit the ball with both sweet spots at once.

As these handle motions and bending vibrations illustrate, the science and engineering of bats is surprisingly complicated. That's why bat manufacturers are forever developing better, more potent ones. Like the makers of golf clubs, tennis rackets, bowling equipment, and billiard tables, they dream of bounces so perfect that all of the collision energy is stored and returned as rebound energy. Known as **elastic collisions**, such perfect bounces are common among the tiny atoms in a gas, but unattainable for ordinary objects; there are just too many ways for any large item to divert or dissipate energy, including as thermal energy, sound, vibration, and light.

Although equipment manufacturers must resign themselves to **inelastic collisions**—collisions that fail to return some of the collision energy as rebound energy—they get closer to perfection every year. They also push right up to the limits of regulation, and occasionally beyond, in their quests for maximum performance.

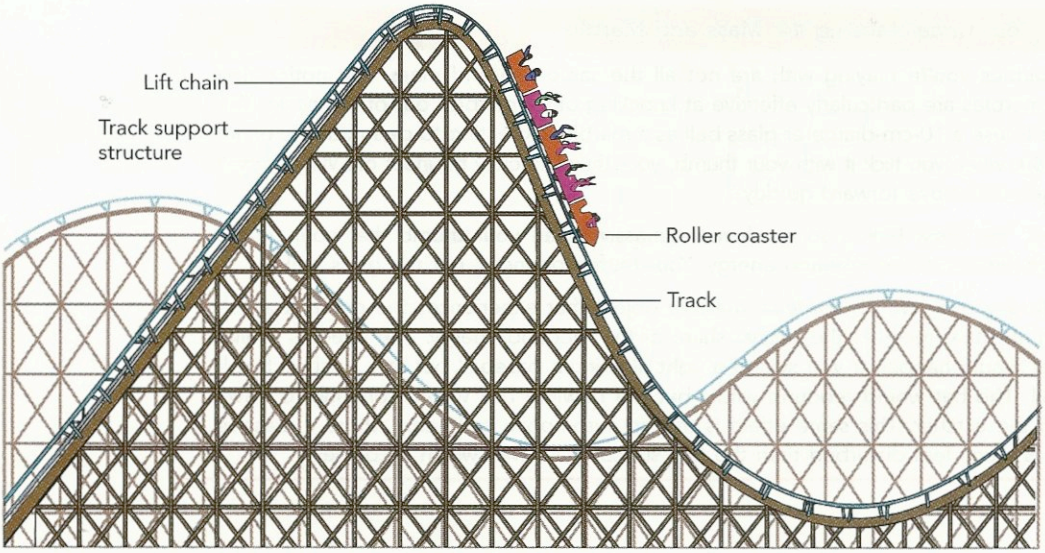
Multiwalled aluminum, titanium, and composite bats are a case in point. Each of these hollow bats is soft enough to dent considerably during its impact with the ball so that it receives much of the collision energy. Its circular barrel flattens into an oval, storing the collision energy beautifully, and then kicks back to circular over a time that is well matched to the timing of the bounce itself. And because the hi-tech bat's outer wall is thin and light, it retains only a tiny fraction of the rebound energy. Unlike the hard surface of a wooden bat, which barely dents and thus barely participates in the energy storage process, one of these hi-tech bats acts as a trampoline—it stores and returns so much of the collision energy that it substantially increases the outgoing speed of the batted ball. You can find equally hi-tech equipment at the golf shop or tennis store. We're in an era in which scientific analysis and design are radically altering sports.

Check Your Understanding #4: **Mass and Marbles**

The marbles you're playing with are not all the same size and mass. You notice that larger marbles are particularly effective at knocking other marbles out of the circle. You decide to use a 10-cm-diameter glass ball as a marble, expecting to clean out the entire circle. But when you flick it with your thumb, your thumb merely bounces off. Why doesn't the glass ball move forward quickly?

Answer: The glass ball is so much more massive than your thumb that your thumb receives almost all the rebound energy. Your thumb bounces, not the glass ball.

Why: In any collision, it's the least massive object that experiences the greatest acceleration and that receives the largest share of the rebound energy. The effect is similar to what would happen if you swung a light aluminum baseball bat at a pitched bowling ball. The bat would rebound wildly but the bowling ball would continue to travel toward the catcher. This same effect is true in automobile collisions, where a massive sedan is much less disturbed than the tiny subcompact with which it collides.



SECTION 3.3 Carousels and Roller Coasters

As your sports car leaps forward at a green light, you're pressed firmly back against your seat. It's as though gravity were somehow pulling you down and backward at the same time. It's not gravity that pulls back on you, though; it's your own inertia preventing you from accelerating forward with the car.

When this happens, you're experiencing the feeling of acceleration. We encounter this feeling many times each day, whether through turning in an automobile or riding up several floors in a fast elevator. Nowhere are the feelings of acceleration more acute than at the amusement park. We accelerate up, down, and around on the carousel, back and forth in the bumper cars, and left and right in the scrambler. The ultimate ride, of course, is the roller coaster, which is one big, wild experience of acceleration. When you close your eyes on a straight stretch of highway, you can hardly tell the automobile is moving. When you close your eyes on a roller coaster, however, you have no trouble feeling every last turn in the track. It's not the speed you feel, but the acceleration. What is often called motion sickness should really be called acceleration sickness.

Questions to Think About: *How does your body feel its own weight? When you swing a bucket full of water around in a circle, as we asked you to do in the chapter opening, why does the bucket pull outward on you? Why can you swing that bucket completely over your head without spilling the water inside it? What keeps you from falling out of a roller coaster as it goes over the top of a loop-the-loop? Which car of a roller coaster should you sit in to experience the best ride?*

Experiments to Do: *To begin associating the familiar sensations of motion with the physics of acceleration, travel as a passenger in a vehicle that makes lots of turns and stops. Close your eyes and see whether you can tell which way the vehicle is turning*

and when it's starting or stopping. Which way do you feel pulled when the vehicle turns left? Turns right? Starts? Stops? How is this sensation related to the direction of the vehicle's acceleration? Now find a time when the vehicle is traveling at constant velocity on a level path and see whether you feel any sensations that tell you which way it's heading. Try to convince yourself that it's heading backward or sideways rather than forward. Which is easier to feel: your acceleration or your velocity?

Carousels and Acceleration

While roller coasters offer interesting visual effects, such as narrowly missing obstacles, and strange orientations, such as upside down, the real thrill of roller coasters comes from their accelerations. Plenty of other amusement park rides suspend you sideways or upside down, so that you feel ordinary gravity pulling at you from unusual angles. But why pay for those when you can stand on your head for free? For a *real* thrill, you need acceleration to give you the weightless feeling you experience as a roller coaster dives over its first big hill or the intense heaviness you feel as it whips you around a sharp corner. Why do accelerations give rise to these wonderful sensations, and why are they most extreme when you're sitting in the last car of the roller coaster?

To answer those questions, we'll need to take another look at acceleration. Although you may start your day at an amusement park by riding its biggest roller coaster, some of us might benefit from a warm-up. Let's start with a simpler ride: a carousel.

When you ride on a carousel, you travel in a *circular path* around a central pivot. That's not the motion of an object that's simply coasting forward and exhibiting inertia. If you were experiencing zero net force, you would travel in a straight line at a steady pace in accordance with Newton's first law. However, since your path is circular instead of straight, your direction of travel is changing; you must be experiencing a nonzero net force and you must be accelerating.

Which way are you accelerating? Remarkably, you are always accelerating toward the center of the circle. To see why that's so, let's look down on a simple carousel that's turning counterclockwise at a steady pace (Fig. 3.3.1). At first, the boy riding the carousel is directly east of its central pivot and is moving northward (Fig. 3.3.1*a*). If nothing were pulling on the boy, he would continue northward and fly off the carousel. Instead, he follows a circular path by accelerating toward the pivot—that is, toward the west. As a result, his velocity turns toward the northwest and he heads in that direction. To keep from flying off the carousel, he must continue to accelerate toward the pivot, which is now southwest of him (Fig. 3.3.1*b*). His velocity turns toward the west, and he follows the circle in that direction. And so it goes (Fig. 3.3.1*c*).

The boy's body is always trying to go in a straight line, but the carousel keeps pulling him inward so that he accelerates toward the central pivot. The boy is experiencing **uniform circular motion**. "Uniform" means that the boy is always moving at the same speed, although his direction keeps changing. "Circular" describes the path the boy follows as he moves, his trajectory.

Like any object undergoing uniform circular motion, the boy is always accelerating toward the center of the circle. An acceleration of this type, toward the center of a circle, is called a **centripetal acceleration** and is caused by a centrally directed force, a **centripetal force**. A centripetal force is not a new, independent type of force like gravity, but the net result of whatever forces act on the object. Centripetal means "center-seeking," and a centripetal force pushes the object toward that center. The carousel uses support forces and friction to exert a centripetal force on the boy, and he experiences a centripetal acceleration. Amusement park rides often involve centripetal acceleration (Fig. 3.3.2).

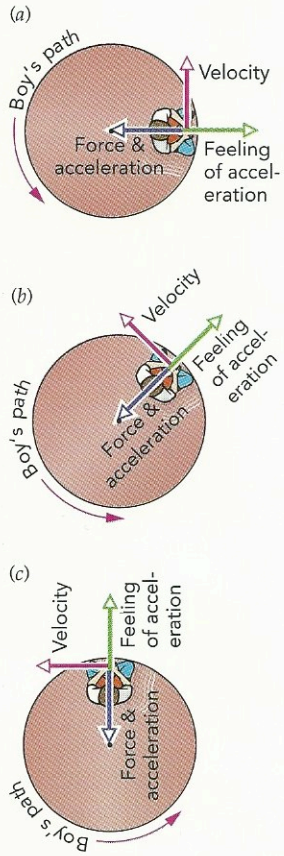


Fig. 3.3.1 A boy riding on a turning carousel is always accelerating toward the central pivot. His velocity vector shows that he is moving in a circle but his acceleration vector points toward the pivot. When he is heading north (*a*), he is accelerating toward the west. His velocity gradually changes direction until he is heading northwest (*b*), at which time he is accelerating toward the southwest. He turns further until he is heading west (*c*) and is then accelerating toward the south. (North is upward.)

Stuart Dee/The Image Bank/Getty Images

Fig. 3.3.2 The people on this ride travel in a circle, pulled inward by cords so that they accelerate toward the center of the circle.

The amount of acceleration the boy experiences depends on his speed and the radius of the carousel. The faster the boy is moving and the smaller the radius of his circular trajectory, the more he accelerates. His acceleration is equal to the square of his speed divided by the radius of his path.

We can also determine the boy's acceleration from the carousel's angular speed and its radius. The faster the carousel turns and the larger the radius of the boy's circular trajectory, the more he accelerates. His acceleration is equal to the square of the carousel's angular speed times the radius of his path. We can express these two relationships as word equations:

$$\text{acceleration} = \frac{\text{speed}^2}{\text{radius}} = \text{angular speed}^2 \cdot \text{radius}, \tag{3.3.1}$$

in symbols:

$$a = \frac{v^2}{r} = \omega^2 \cdot r,$$

and in everyday language:

Making a tight, high-speed turn involves lots of acceleration.

Common Misconceptions: Centrifugal Force

Misconception: As you swing an object in a circle, that object is pulled outward by "centrifugal force."

Resolution: If the object were free of forces, inertia would cause it to travel in a straight line. But because you are pulling the object inward, it accelerates inward and its path bends into a circle. Since you are exerting an inward force on the object, it is exerting an outward force on you, in accordance with Newton's third law. However, that outward force acts on you, not on the object. There is no outward "centrifugal force" acting on the object itself.

Check Your Understanding #1: **Banking on a Curve**

Your racing car comes to a banked, left-hand turn, which it completes easily. Why is it essential that a racetrack turn be banked so that it slopes downhill toward the center of the turn?

Answer: A banked turn is needed so that the support force exerted by the racetrack on the car's wheels can provide at least some of the centripetal force needed to accelerate the car around the turn.

Why: As a car and driver travel around a circular turn, they are accelerating toward the center of the track and require a huge centripetal force inward. On a level track, the only horizontal force available is static friction between the ground and the car's tires. If static friction is unable to provide enough inward force, the car will skid off the track, following a straight-line path. This type of accident is typical of a highway curve on an icy day and is why designers bank the curves. The banks are ramps sloping down toward the center so that the horizontal component of the support force exerted by the track on the car's wheels provides an additional, inward, centripetal force to help that car accelerate around the curve.

Check Your Figures #1: **Going for a Spin**

Some children are riding on a playground carousel with a radius of 1.5 m (4.9 ft). The carousel turns once every two seconds. How quickly are the children accelerating?

Answer: They are accelerating about 15 m/s^2 (50 ft/s^2).

Why: Because the children are in uniform circular motion, their acceleration is given by Eq. 3.3.1. The carousel turns once every 2 seconds, so its angular velocity is 2π radians divided by 2 seconds. Omitting "radians" because they're the natural unit of angle, the carousel's angular velocity is π 1/s. Since its radius is 1.5 meters, the children's acceleration is

$$\text{children's acceleration} = (\pi\ 1/\text{s})^2 \cdot 1.5\ \text{m} = 14.8\,\text{m/s}^2.$$

Since our measurements of the carousel's radius and its turning time are only accurate to about 10%, our calculation of the children's acceleration is only accurate to about 10%. We report it as 15 m/s^2 (50 ft/s^2).

The Experience of Acceleration

Nothing is more central to the laws of motion than the relationship between force and acceleration. Until now, we've looked at forces and noticed that they can cause accelerations; now let's take the opposite perspective, looking at accelerations and noticing that they require forces. For you to accelerate, something must push or pull on you. Just where and how that force is exerted on you determine what you feel when you accelerate.

The backward sensation you feel as your car accelerates forward is caused by your body's inertia, its tendency not to accelerate (Fig. 3.3.3). The car and your seat are accelerating forward, and since the seat acts to keep you from traveling through its surface, it exerts a forward support force on you that causes you to accelerate forward. But the seat can't exert a force uniformly throughout your body. Instead, it pushes only on your back, and your back then pushes on your bones, tissues, and internal organs to make them accelerate forward. Each piece of tissue or bone is responsible for the forward force

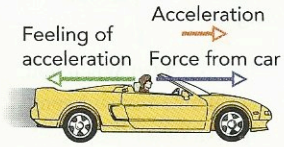


Fig. 3.3.3 As you accelerate forward in a car, you sense a gravity-like feeling of acceleration in the direction opposite to the acceleration. This feeling of acceleration is really the mass of your body resisting acceleration.

needed to accelerate forward the tissue in front of it. A whole chain of forces, starting from your back and working forward toward your front, causes your entire body to accelerate forward.

Let's compare this situation with what happens when you're standing motionless on the floor. Since gravity exerts a downward force on you that's distributed uniformly throughout your body, each part of your body has its own independent weight; these individual weights, taken together, add up to your total weight. The floor, for its part, is exerting an upward support force on you that keeps you from accelerating downward through its surface. But the floor can't exert a force uniformly throughout your body. Instead, it pushes only on your feet, and your feet then push on your bones, tissues, and internal organs to keep them from accelerating downward. Each piece of tissue or bone is responsible for the upward force needed to keep the tissue above it from accelerating downward. A whole chain of forces, starting from your feet and working upward toward your head, keeps your entire body from accelerating downward.

As you probably noticed, the two previous paragraphs are very similar—and so are the sensations of gravity and acceleration. When the ground is preventing you from falling, you feel "heavy"; your body senses all the internal forces needed to support its pieces so that they don't accelerate, and you interpret these sensations as weight. When the car seat is causing you to accelerate forward, you also feel "heavy"; your body senses all the internal forces needed to accelerate its pieces forward, and you interpret these sensations as weight. This time you experience the weightlike sensation toward the back of the car.

Try as you may, you can't distinguish the weightlike sensation that you experience as you accelerate from the true force of gravity. And you're not the only one fooled by acceleration. Even the most sophisticated laboratory instruments can't determine directly whether they are experiencing gravity or are accelerating. However, despite the convincing sensations, the backward heavy feeling in your gut as you accelerate forward is the result of inertia and is not due to a real backward force. We'll call this experience a **feeling of acceleration**. It always points in the direction opposite the acceleration that causes it, and its strength is proportional to that acceleration.

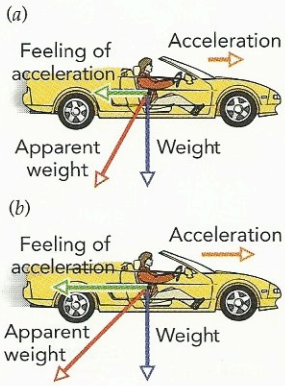


Fig. 3.3.4 (*a*) When you accelerate forward gently, the backward feeling of acceleration is small and your apparent weight is mostly downward. (*b*) When you accelerate forward quickly, you experience a strong backward feeling of acceleration and your apparent weight is backward and down.

If you accelerate forward quickly, the backward feeling of acceleration you experience can be quite large. However, you don't experience this feeling of acceleration all by itself; you also experience your downward weight, and together these effects feel like an especially strong weight at an angle somewhere between straight down and the back of the car. We'll call the combined experience of weight and feeling of acceleration your **apparent weight**. The faster you accelerate, the stronger the backward feeling of acceleration and the more your apparent weight points toward the back of the car (Fig. 3.3.4).

Feelings of acceleration don't have to point backward. They can also point forward or even to the side. When you turn your car to the left, you're accelerating leftward and experience a strong rightward feeling of acceleration. When you're not driving and can safely close your eyes, you should be able to feel acceleration in any direction.

So what does the boy on the spinning carousel feel? Since he is accelerating inward, toward the center of the circle, he experiences a feeling of acceleration outward, away from the center of the circle. The boy feels as though his weight is pulling him outward as well as down, and he clings tightly to the carousel to keep from falling off.

Weight and feeling of acceleration can differ significantly in strength. although your weight is the specific gravitational force you experience near the earth's surface, the feeling of acceleration that you experience can have any strength or direction. If you are moving very rapidly around a small circle, you can easily experience a feeling of acceleration that is stronger than your weight.

Your feeling of acceleration can be measured relative to your weight. When a feeling of acceleration matches the feeling of your weight, it is said to be 1 gravity or 1g, for short. To experience a 1g feeling of acceleration, you must accelerate in the opposite direction at 9.8 m/s^2 (32 ft/s^2), the acceleration due to gravity. That acceleration is easily achieved on a playground carousel. If you accelerate 5 times that quickly, on the scrambler or on an airplane maneuvering sharply, you'll experience a 5g feeling of acceleration.

Check Your Understanding #2: The Feel of a Tight Turn

You're sitting in the passenger seat of a racing car that is moving rapidly along a level track. The track takes a sharp turn to the left, and you find yourself thrown against the door to your right. What horizontal forces are acting on you, and what feelings of acceleration do you experience?

Answer: The car seat and door are exerting a leftward force on you, causing you to accelerate leftward with the car. You also experience a rightward feeling of acceleration, as your inertia acts to keep you from accelerating leftward.

Why: As the car turns left, it accelerates toward the left. The car seat and right door together exert a leftward force on you, to prevent the car from driving out from under you. Because it has mass, your body resists this leftward acceleration. You feel your body trying to go in a straight line, which would carry it out the right door of the car as the car accelerates toward the left.

Roller Coaster Acceleration

We're now prepared to look at a roller coaster and understand what you feel as you go over hills (Fig. 3.3.5) and loop-the-loops (Fig. 3.3.6).

Every time the roller coaster accelerates, you experience a feeling of acceleration in the direction opposite your acceleration. That feeling of acceleration gives you an apparent weight that's different from your real weight. As we saw with a car, rapid forward acceleration tips your apparent weight backward toward the rear of the vehicle, while rapid deceleration tips it toward the front. But a roller coaster can do something a car can't: it can accelerate downward rapidly! In that case, the feeling of acceleration you experience is upward and opposes your downward weight so that they partially cancel. As a result, your apparent weight is less than your real weight and points downward or perhaps, if the downward acceleration is fast enough, points upward.

Consider that last possibility: if you accelerate downward at just the right rate, the upward feeling of acceleration will exactly cancel your downward weight. You will feel perfectly weightless, as though gravity didn't exist at all. The rate of downward acceleration that causes this perfect cancellation is that of a freely falling object. Your weight won't have changed, but the roller coaster will no longer be supporting you and you will be accelerating downward at 9.8 m/s^2 (32 ft/s^2). You will experience the same sensations as a diver who has just stepped off the high dive.

Since freely falling objects are subject only to the forces of gravity, they don't have to push on one another

Harry DiOrio/The Image Works

Fig. 3.3.5 As this roller coaster plunges down the first hill, its last car is pulled over the edge by the cars in front of it and its riders feel almost weightless.

Bob Torrez/Stone/Getty Images

Fig. 3.3.6 As it goes over the loop-the-loop, this roller coaster is accelerating rapidly toward the center of the circle. When it reaches the top of the loop, the track pushes the roller coaster downward and the riders feel pressed into their seats. If they close their eyes, they won't even be able to tell that they're upside down.

to keep their relative positions. As you fall, your hat and sunglasses will fall with you and won't require any support forces from your head. Even if your sunglasses come off, they will hover in front of you as the two of you accelerate downward together. Similarly, your internal organs don't need to support one another, and the absence of internal support forces gives rise to the exhilarating sensation of free fall.

However, because a roller coaster is attached to a track, its rate of downward acceleration can actually exceed that of a freely falling object. In those special situations, the track will be assisting gravity in pushing the roller coaster downward. As a rider, you will feel less than weightless. The upward feeling of acceleration will be so large that your apparent weight will be in the upward direction, as though the world had turned upside down!

Check Your Understanding #3: Drop Tower Panic

A drop tower is a terrifying amusement park ride in which you are strapped into a seat, lifted high in the air, and then dropped. While you're in free fall, what is your apparent weight?

Answer: Your apparent weight is zero.

Why: As you fall freely, you are accelerating downward at the full acceleration due to gravity. The upward feeling of acceleration you experience exactly matches your downward weight, so that your apparent weight is zero. You feel perfectly weightless.

Roller Coaster Loop-the-Loops

Figure 3.3.7 shows a single-car roller coaster at various points along a simple track with one hill and one loop-the-loop. Weight, the feeling of acceleration, and apparent weight are all vector quantities, as are the car's velocity and acceleration. These quantities are indicated with arrows of varying lengths that show each vector's direction and magnitude. The longer the arrow, the greater the magnitude of the quantity it represents.

At the top of the first hill (Fig. 3.3.7*a*), the single-car roller coaster is almost stationary. You, the rider, feel only your weight, straight down—nothing exciting yet. However, as soon as the car begins its descent, accelerating down the track, a feeling of acceleration appears pointing up the track (Fig. 3.3.7*b*). The combination of your weight and the feeling of acceleration gives you an apparent weight that is very small and points down and into the track. Most people find this sudden reduction in apparent weight to be terrifying. Our bodies are very sensitive to partial weightlessness, and this falling sensation is half the fun of a roller coaster. An astronaut, falling freely in space, has this disquieting weightless feeling for days on end. No wonder astronauts have such frequent troubles with motion (or rather acceleration) sickness.

On the earth, the weightless feeling can't last. It occurs only during downward acceleration and disappears as your car levels off near the bottom of the hill. By the time the car begins its rise into the loop-the-loop, it is traveling at maximum speed and has begun to accelerate upward (Fig. 3.3.7*c*). This upward acceleration creates a downward feeling

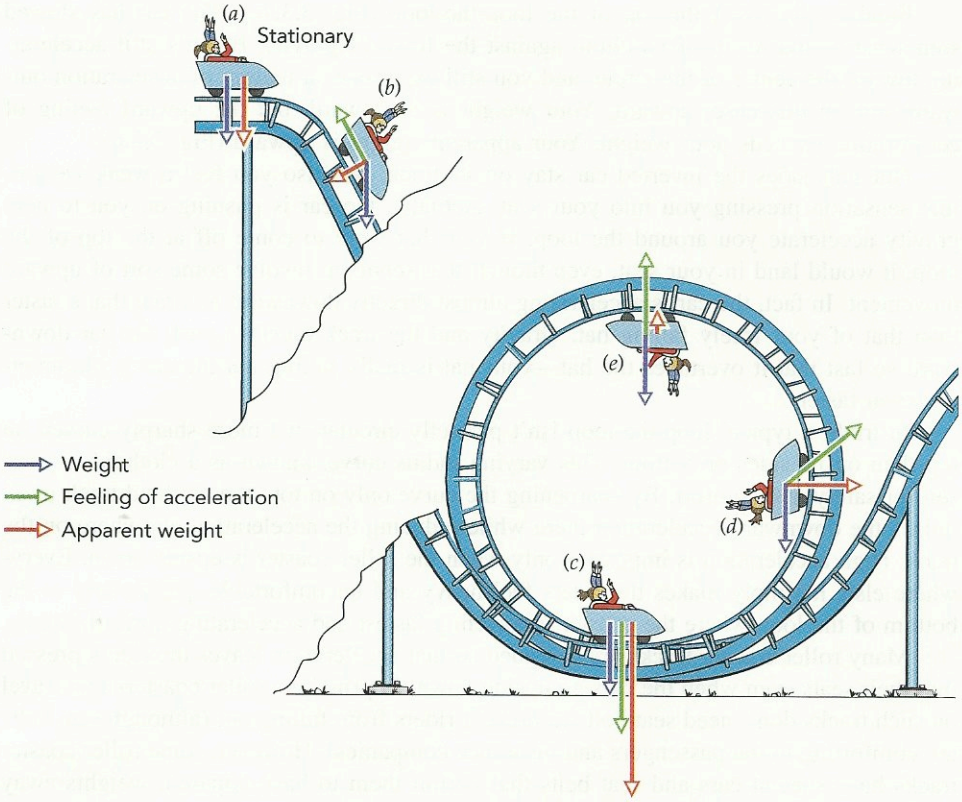


Fig. 3.3.7 A single-car roller coaster going over the first hill and a loop-the-loop. At each point along the track, the car experiences its weight, a feeling of acceleration due to its current acceleration, and an apparent weight that is the sum of those two. The apparent weight always points toward the track and the car doesn't fall off it.

of acceleration so that your apparent weight is huge and downward. You feel pressed into your seat as you experience 2 or 3g's.

The trip through the loop-the-loop resembles uniform circular motion. It's roughly like taking a single turn around a vertical carousel. However, as the car rises into the loop-the-loop, some of its kinetic energy becomes gravitational potential energy and the car slows down. As the car descends out of the loop-the-loop, this gravitational potential energy returns to kinetic form and the car speeds up. As a result of these speed changes, your acceleration is not exactly inward toward the center of the loop-the-loop, and the feeling of acceleration you experience is not exactly outward. Still, an inward acceleration and an outward feeling of acceleration are good approximations for what occurs.

Halfway up the loop-the-loop, your true acceleration is inward and downward, so the feeling of acceleration you experience is outward and upward (Fig. 3.3.7*d*). Your apparent weight is still much more than your weight and is directed outward. You feel pressed into your seat, and the car itself is pressed against the track (Fig. 3.3.8).

Chad Slattery/Stone/Getty Images

Fig. 3.3.8 The roller coaster pushes these riders inward as it travels around the loop-the-loop. The riders experience strong feelings of acceleration outward and can hardly tell that they're turning upside down.

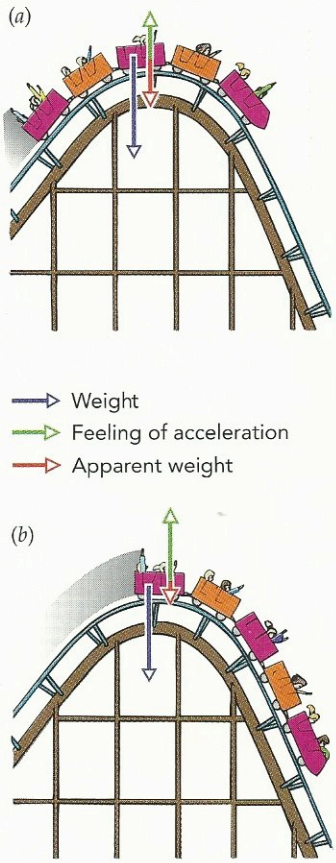


Fig. 3.3.9 When a multicar roller coaster descends the first hill, the ride experienced in the first cars is different from that in the last cars. (*a*) The first cars travel over the crest of the hill slowly and reach high speed only well down the hill. The cars behind them slow their descent. (*b*) The last cars are whipped over the top and are traveling very rapidly early on. The last cars accelerate downward dramatically as they go over the first hill and their riders experience a strong feeling of weightlessness.

Finally, you reach the top of the loop-the-loop (Fig. 3.3.7*e*). The car has slowed somewhat as the result of its climb against the force of gravity. But it's still accelerating toward the center of the circle, and you still experience a feeling of acceleration outward and, in this case, upward. Your weight is downward, but the upward feeling of acceleration exceeds your weight. Your apparent weight is upward (Fig. 3.3.6)!

Not only does the inverted car stay on its track, but also you feel a weak weight-like sensation pressing you into your seat. Actually, the car is pushing on you to help gravity accelerate you around the loop. If your hat were to come off at the top of the loop, it would land in your seat, even though that seems to involve some sort of upward movement. In fact, the car is accelerating almost directly downward at a rate that's faster than that of your freely falling hat. Gravity and the track together push the car downward so fast that it overtakes the hat—your hat is really falling but the car is plummeting even faster.

In truth, a typical loop-the-loop isn't perfectly circular; it's more sharply curved on top than on its sides or bottom. This varying radius curve, known as a clothoid, is chosen for safety and comfort. By sharpening the curve only on top, the clothoid track maximizes the downward acceleration there while reducing the acceleration elsewhere on the track. High acceleration is important only when the roller coaster is upside down. Everywhere else, it simply makes the riders feel heavy and uncomfortable, particularly at the bottom of the loop where the coaster is traveling fastest and accelerating upward rapidly.

Many roller coaster tracks are designed so that acceleration leaves the riders pressed into their seats even when the cars go upside down. In principle, roller coasters that travel on such tracks don't need seat belts to prevent riders from falling out (although seat belts are comforting to the passengers and insurance companies). However, some roller coaster tracks have special cars and seat belts that permit them to have apparent weights away from the track. These roller coasters can and do go upside down without enough downward acceleration to keep the riders in their seats. In such roller coasters, the riders feel like they are hanging and if one of them were to lose a hat, it would fall to the ground rather than into the car.

What about a roller coaster with more than one car? For the most part, the same rules apply. However, new forces now act on each car: forces exerted by the other cars in the train. The effects of these cars are most pronounced at the top of the first and biggest hill. As the train disconnects from the lift chain and approaches the descent it is rolling forward slowly, and the first cars are well over the crest of the hill before they pick up much speed (Fig. 3.3.9*a*). They're pulling hard on the cars behind them, and those cars are pulling back, slowing their descent. By the time the train is moving fast, the first car is well down the hill. By then, the track is beginning to turn upward and the first car's riders experience mostly upward acceleration and downward feeling of acceleration. That's why riders in the first few cars of a roller coaster don't feel much weightlessness.

In contrast, the last car is moving at high speed early in its descent. It undergoes a dramatic downward acceleration as it's yanked over the crest of the first hill by the cars in front of it (Fig. 3.3.9*b*). As a result, its riders feel large upward feelings of acceleration and quite extreme weightlessness. In fact, the designers of the track must be careful not to make the downward acceleration too rapid, or the roller coaster will flick the riders in the last car right out of their seats. Each time the last car crests a hill, it accelerates downhill in a way that no other car on the coaster can match.

Obviously, it does matter where you sit on a roller coaster. The first seat offers the most exciting view, but it provides less than spectacular weightless feelings. The last car almost always offers the best weightless feelings. Probably the dullest seat in the roller coaster is the second; it offers a relatively tame ride and an unchanging view of the people in the front seat.

Check Your Understanding #4: Taking to the Air

Your racing car travels over a bump in the track and suddenly becomes airborne. What keeps you in the air? Has gravity disappeared?

Answer: Gravity is still present, but your inertia prevents you from following a rapid downturn in the surface you are traveling along.

Why: If the road you are traveling along suddenly turns downward, you must accelerate downward to stay in contact with its surface. The steeper and more abrupt the descent, the more downward acceleration you need. The only downward force you experience is your weight, which can cause a downward acceleration of no more than 9.8 m/s^2 (32 ft/s^2). If the surface drops out from under you faster than that, you will become airborne. You will then be falling freely and accelerating downward as fast as gravity will permit. Eventually, you will fall to the surface. In many sports, including skiing, motorcycle racing, and skateboarding, a person traveling along an uneven surface becomes airborne after passing over a bump.

Epilogue for Chapter 3

In this chapter we looked at the physical concepts involved in four types of simple machines. In *spring scales*, we explored the relationship between the force acting on a spring and its distortion, and we examined how this distortion can be used to measure an object's weight. In *bouncing balls*, we examined the process of storing and releasing kinetic energy during a collision. As we saw, both the ball and the object it hits contribute to the bounce.

In *carousels and roller coasters*, we explored both the sensations we feel as we accelerate and why those sensations occur. We saw that circular motion involves a centrally directed acceleration that gives rise to an outwardly directed feeling of acceleration.

Explanation: Swinging Water Overhead

As you swing the bucket over your head, you are pulling downward on it and causing it to accelerate downward very rapidly. The water remains in the inverted bucket because the bucket is accelerating downward faster than gravity alone can accelerate the water. Although the water is free to fall, the bucket overtakes the falling water. As a result, the water is pressed into the bottom of the bucket. The same effect occurs when you push a book downward rapidly with your open palm. Although the book is free to fall, it remains pressed into your palm because your hand is accelerating it downward faster than gravity. Finally, if you stop swinging the bucket too abruptly, the bucket's contents will not decelerate with it. Instead, they will spill or smash.

Chapter Summary

How Spring Scales Work: A spring scale measures an object's weight by supporting that object with a spring. When the object is at rest, the spring's upward force exactly balances the object's downward weight; the scale then reports the upward restoring force its

spring is exerting on the object. As Hooke's law describes, that restoring force is proportional to the spring's distortion, so the scale can determine it by measuring how far the spring has bent. This measurement is often done mechanically and is reported with a needle or dial.

How Bouncing Balls Work: A ball behaves like a spherical or oblong spring. It stores elastic potential energy as it distorts away from its equilibrium shape and releases some of that energy as it returns to normal. When a ball strikes a surface, some kinetic energy is removed from the ball and the surface and is either stored within those objects as elastic potential energy or lost as thermal energy. As the objects rebound, some of the stored energy becomes kinetic energy again. The kinetic energy returned—the rebound energy—is always less than the kinetic energy initially removed from the objects—the collision energy. The missing energy has been converted into thermal energy.

How Carousels and Roller Coasters Work: A carousel uses centripetal acceleration to give each rider an outward feeling of acceleration. Combined with weight, this gravity-like sensation gives the rider an apparent weight that points downward and outward.

A roller coaster also uses rapid acceleration to create unusual apparent weights for its riders. Each time the coaster accelerates on a hill or turn, the rider experiences a feeling of acceleration in the direction opposite the acceleration. This feeling of acceleration, combined with the rider's weight, creates an apparent weight that varies dramatically in amount and direction throughout the ride. It's this fluctuating apparent weight, particularly its near approaches to zero, that make riding a roller coaster so exciting.

Important Laws and Equations

1. Hooke's Law: The restoring force exerted by an elastic object is proportional to how far it is from its equilibrium shape, or

$$\text{restoring force} = -\text{spring constant} \cdot \text{distortion}. \qquad (3.1.1)$$

2. Acceleration of an Object in Uniform Circular Motion: An object in uniform circular motion has a centripetal acceleration equal to the square of its speed divided by the radius of its circular trajectory, which is equal to the square of its angular speed times the radius of its circular trajectory, or

$$\text{acceleration} = \frac{\text{speed}^2}{\text{radius}} = \text{angular speed}^2 \cdot \text{radius}. \qquad (3.3.1)$$

Exercises

1. In what way does the string of a bow and arrow behave like a spring?

2. As you wind the mainspring of a mechanical watch or clock, why does the knob get harder and harder to turn?

3. Curly hair behaves like a weak spring that can stretch under its own weight. Why is a hanging curl straighter at the top than at the bottom?

4. When you lie on a spring mattress, it pushes most strongly on the parts of you that stick into it the farthest. Why doesn't it push up evenly on your entire body?

5. If you pull down on the basket of a hanging grocery store scale so that it reads 15 N, how much downward force are you exerting on the basket?

6. While you're weighing yourself on a bathroom scale, you reach out and push downward on a nearby table. Is the weight reported by the scale high, low, or correct?

7. There's a bathroom scale on your kitchen table and your friend climbs up to weigh himself on it. One of the table's legs is weak and you're afraid that he'll break it, so you hold up that corner of the table. The table remains level as you push upward on the corner with a force of 100 N. Is the weight reported by the scale high, low, or correct?

8. If you put your bathroom scale on a ramp and stand on it, will the weight it reports be high, low, or correct?

9. When you step on a scale, it reads your weight plus the weight of your clothes. Only your shoes are touching the scale, so how does the weight of the rest of your clothes contribute to the weight reported by the scale?

10. To weigh an infant you can step on a scale once with the infant and then again without the infant. Why is the difference between the scale's two readings equal to the weight of the infant?

11. An elastic ball that wastes 30% of the collision energy as heat when it bounces on a hard floor will rebound to 70% of the height from which it was dropped. Explain the 30% loss in height.

12. The best running tracks have firm but elastic rubber surfaces. How does a lively surface assist a runner?

13. Why is it so exhausting to run on soft sand?

14. Steep mountain roads often have emergency ramps for trucks with failed brakes. Why are these ramps most effective when they are covered with deep, soft sand?

15. There have been baseball seasons in which so many home runs were hit that people began to suspect that something was wrong with the baseballs. What change in the baseballs would account for them traveling farther than normal?

16. During rehabilitation after hand surgery, patients are often asked to squeeze and knead putty to strengthen their muscles. How does the energy transfer in squeezing putty differ from that in squeezing a rubber ball?

17. Your car is on a crowded highway with everyone heading south at about 100 km/h (62 mph). The car ahead of you slows down slightly and your car bumps into it gently. Why is the impact so gentle?

18. Bumper cars are an amusement park ride in which people drive small electric vehicles around a rink and intentionally bump them into one another. All of the cars travel at about the same speed. Why are head-on collisions more jarring than other types of collisions?

19. When two trains are traveling side by side at breakneck speed, it's still possible for people to jump from one train to the other. Explain why this can be done safely.

20. If you drop a steel marble on a wooden floor, why does the floor receive most of the collision energy and contribute most of the rebound energy?

21. A RIF (reduced injury factor) baseball has the same coefficient of restitution as a normal baseball except that it deforms more severely during a collision. Why does this increased deformability lessen the forces exerted by the ball during a bounce and reduce the chances of its causing injury?

22. Padded soles in running shoes soften the blow of hitting the pavement. Why does padding reduce the forces involved in bringing your foot to rest?

23. Some athletic shoes have inflatable air pockets inside them. These air pockets act like springs that become stiffer as you pump up the air pressure. High pressure also makes you bounce back up off the floor sooner. Why does high pressure shorten the bounce time?

24. Why does it hurt less to land on a soft foam pad than on bare concrete after completing a high jump?

25. Why must the surface of a hammer be very hard and stiff for it to drive a nail into wood?

26. Some amusement park rides move you back and forth in a horizontal direction. Why is this motion so much more disturbing to your body than cruising at a high speed in a jet airplane?

27. You are traveling in a subway along a straight, level track at a constant velocity. If you close your eyes, you can't tell which way you're heading. Why not?

28. Moving a can of spray paint rapidly in one direction will not mix it nearly as well as shaking it back and forth. Why is it so important to change directions as you mix the paint?

29. Why does a baby's rattle only make noise when the baby moves it back and forth and not when the baby moves it steadily in one direction?

30. In some roller coasters, the cars travel through a smooth tube that bends left and right in a series of complicated turns. Why does the car always roll up the right-hand wall of the tube during a sharp left-hand turn?

31. Railroad tracks must make only gradual curves to prevent trains from derailing at high speeds. Why is a train likely to derail if it encounters a sharp turn while it's traveling fast?

32. Police sometimes use metal battering rams to knock down doors. They hold the ram in their hands and swing it into a door from about 1 m away. How does the battering ram increase the amount of force the police can exert on the door?

33. When a moving hammer hits a nail, it exerts the enormous force needed to push the nail into wood. This force is far greater than the hammer's weight. How is it produced?

34. A hammer's weight is downward, so how can a hammer push a nail upward into the ceiling?

35. As you swing back and forth on a playground swing, your apparent weight changes. At what point do you feel the heaviest?

36. Some stores have coin-operated toy cars that jiggle back and forth on a fixed base. Why can't these cars give you the feeling of actually driving in a drag race?

37. A salad spinner is a rotating basket that dries salad after washing. How does the spinner extract the water?

38. People falling from a high diving board feel weightless. Has gravity stopped exerting a force on them? If not, why don't they feel it?

39. When your car travels rapidly over a bump in the road, you suddenly feel weightless. Explain.

40. Astronauts learn to tolerate weightlessness by riding in an airplane (nicknamed the "vomit comet") that follows an unusual trajectory. How does the pilot direct the plane in order to make its occupants feel weightless?

41. You board an elevator with a large briefcase in your hand. Why does that briefcase suddenly feel particularly heavy when the elevator begins to move upward?

42. As your car reaches the top in a smoothly turning Ferris wheel, which way are you accelerating?

Problems

1. Your new designer chair has an S-shaped tubular metal frame that behaves just like a spring. When your friend, who weighs 600 N, sits on the chair, it bends downward 4 cm. What is the spring constant for this chair?

2. You have another friend who weighs 1000 N. When this friend sits on the chair from Problem 1, how far does it bend?

3. You're squeezing a springy rubber ball in your hand. If you push inward on it with a force of 1 N, it dents inward 2 mm. How far must you dent it before it pushes outward with a force of 5 N?

4. When you stand on a particular trampoline, its springy surface shifts downward 0.12 m. If you bounce on it so that its surface shifts downward 0.30 m, how hard is it pushing up on you?

5. Engineers are trying to create artificial "gravity" in a ring-shaped space station by spinning it like a centrifuge. The ring is 100 m in radius. How quickly must the space station turn in order to give the astronauts inside it apparent weights equal to their real weights at the earth's surface?

6. A satellite is orbiting the earth just above its surface. The centripetal force making the satellite follow a circular trajectory is just its weight, so its centripetal acceleration is about 9.8 m/s^2 (the acceleration due to gravity near the earth's surface). If the earth's radius is about 6375 km, how fast must the satellite be moving? How long will it take for the satellite to complete one trip around the earth?

7. When you put water in a kitchen blender, it begins to travel in a 5-cm-radius circle at a speed of 1 m/s. How quickly is the water accelerating?

8. In Problem 7, how hard must the sides of the blender push inward on 0.001 kg of the spinning water?