4 Forces and Newton's Laws of Motion

These ice boats sail across the ice at great speeds. What gets the boats moving in the first place? What keeps them moving once they're going?

LOOKING AHEAD ➤➤

The goal of Chapter 4 is to establish a connection between force and motion.

What Causes Motion?

Galileo was the first to realize that objects in *uniform motion* require no "cause" for their motion. Only *changes* in motion—accelerations—require a cause: a *force*.

What is a Force?

We'll understand force by first examining the properties common to all forces, then by studying a number of forces we'll encounter often.

Forces are a *push* or a *pull*, act on an *object*, and have an identifiable *agent*. Forces are *vectors*.

Looking Back ◀◀
1.5 Vectors and motion

Newton's Third Law

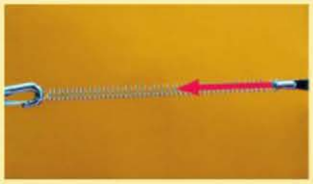
When two objects interact, each exerts a force on the other. Newton's third law tells us that these two forces point in *opposite* directions but have the *same* magnitudes.

The force of the hammer on the nail has the same magnitude as the force of the nail on the hammer.

Some Important Forces

It's important to understand the characteristics of a number of important forces. Some of the forces you'll learn about in this chapter are . . .

Weight
The force of gravity acting on an object.

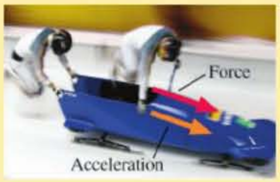


Spring force
The force exerted by a stretched or compressed spring.

Normal force
A force that a surface exerts on an object.

Newton's Second Law

Newton's second law tells us what forces *do* when applied to an object. We'll find that forces act to *accelerate* objects. We will use Newton's second law throughout this textbook to solve a wide variety of physics problems.



An object's acceleration vector is in the same direction as the net force acting on the object.

Looking Back ◀◀
2.4 Acceleration

Looking Back ◀◀
3.2–3.3 Vectors and coordinate systems

Identifying and Representing Forces

One of the most important skills you'll learn in this chapter is to properly identify the forces that act on an object. Then you'll learn to organize these forces in a *free-body diagram.*

Other than the weight force, all forces acting on an object come from other objects

We can represent all the forces acting on an object in a free-body

4.1 What Causes Motion?

The ice boats shown in the chapter-opening photo fly across the frozen lake at some 60 mph. We could use kinematics to describe the boats' motion with pictures, graphs, and equations. Kinematics provides a language to describe *how* something moves, but tells us nothing about *why* the boats accelerate briskly before reaching their top speed. For the more fundamental task of understanding the *cause* of motion, we turn our attention to **dynamics.** Dynamics joins with kinematics to form **mechanics,** the general science of motion. We study dynamics qualitatively in this chapter, then develop it quantitatively in the next four chapters.

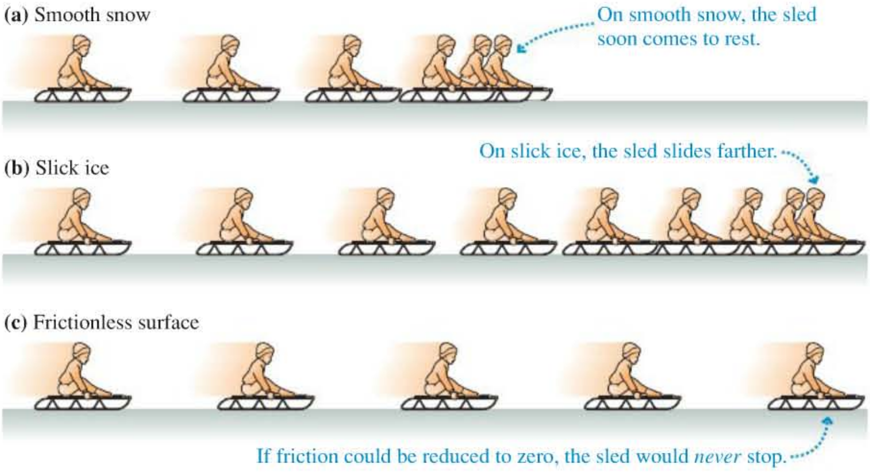
As we remarked in Chapter 1, Aristotle (384–322 BC) and his contemporaries in the world of ancient Greece were very interested in motion. One question they asked was: What is the "natural state" of an object if left to itself? It does not take an expensive research program to see that every moving object on earth, if left to itself, eventually comes to rest. You must push a shopping cart to keep it rolling, but when you stop pushing, the cart soon comes to rest; a boulder bounds downhill and then tumbles to a halt. Having observed many such examples himself, Aristotle concluded that the natural state of an earthly object is to be *at rest.* An object at rest requires no explanation; it is doing precisely what comes naturally to it. We'll soon see, however, that this simple viewpoint is *incomplete.*

Aristotle further pondered moving objects. A moving object is *not* in its natural state and thus requires an explanation: Why is this object moving? What keeps it going and prevents it from being in its natural state? When a puck is sliding across the ice, what keeps it going? Why does an arrow fly through the air once it is no longer being pushed by the bowstring? Although these questions seem like reasonable ones to pose, it was Galileo who first showed that the questions being asked were, in fact, the wrong ones.

Galileo reopened the question of the "natural state" of objects. He suggested focusing on the *idealized case* in which resistance to the motion (e.g., friction or air resistance) is zero. He performed many experiments to study motion. Let's imagine a modern experiment of this kind, as shown in FIGURE 4.1.

The rocks in this rockslide quickly came to rest. Is this the "natural state" of objects?

FIGURE 4.1 Sleds sliding on increasingly smooth surfaces.



▶ **Interstellar coasting** A nearly perfect example of Newton's first law is the pair of Voyager space probes launched in 1977. Both spacecraft long ago ran out of fuel and are now coasting through the frictionless vacuum of space. Although not entirely free of influence from the sun's gravity, they are now so far from the sun and other stars that gravitational influences are very nearly zero. Thus, according to the first law, they will continue at their current speed of about 40,000 miles per hour essentially forever. Billions of years from now, long after our solar system is dead, the Voyagers will still be drifting through the stars.

TRY IT YOURSELF

Getting the ketchup out The ketchup stuck at the bottom of the bottle is initially at rest. If you hit the bottom of the bottle, the bottle suddenly moves down, taking the ketchup on the bottom of the bottle with it, so that the ketchup just stays stuck to the bottom. But if instead you hit *up* on the bottle, as shown, you force the bottle rapidly upward. By the first law, the ketchup that was stuck to the bottom stays at rest, so it separates from the upward-moving bottle: The ketchup has moved forward with respect to the bottle!

Tyler slides down a hill on his sled, then out onto a horizontal patch of smooth snow, which is shown in Figure 4.1a. Even if the snow is quite smooth, the friction between the sled and the snow will soon cause the sled to come to rest. What if Tyler slides down the hill onto some very slick ice, as in Figure 4.1b? This gives very low friction, and the sled could slide for quite a distance before stopping. Galileo's genius was to imagine the case where *all* sources of friction, air resistance, and other retarding influences were removed, as for the sled in Figure 4.1c sliding on idealized *frictionless* ice. We can imagine in that case that the sled, once started in its motion, would continue in its motion *forever,* moving in a straight line with no loss of speed. In other words, **the natural state of an object—its behavior if free of external influences—is *uniform motion* with constant velocity!** Further, "at rest" has no special significance in Galileo's view of motion; it is simply uniform motion that happens to have a velocity of zero. This implies that an object at rest, in the absence of external influences, will remain at rest forever.

Galileo's ideas were completely counter to those of the ancient Greeks. We no longer need to explain why a sled continues to slide across the ice; that motion is its "natural" state. What needs explanation, in this new viewpoint, is why objects *don't* continue in uniform motion. Why does a sliding puck eventually slow to a stop? Why does a stone, thrown upward, slow and eventually fall back down? Galileo's new viewpoint was that the stone and the puck are *not* free of "influences": The stone is somehow pulled toward the earth, and some sort of retarding influence acted to slow the sled down. Today, we call such influences that lead to deviations from uniform motion **forces.**

Galileo's experiments were limited to motion along horizontal surfaces. It was left to Newton to generalize Galileo's conclusions, and today we call this generalization Newton's first law of motion.

Newton's first law Consider an object with no force acting on it. If it is at rest, it will remain at rest; if it is moving, it will continue to move in a straight line at a constant speed.

FIGURE 4.2 Newton's first law tells us: Wear your seatbelts!

At the instant of impact, the car and driver are moving at the same speed.

The car slows as it hits, but the driver continues at the same speed . . .

. . . until he hits the now-stationary dashboard. Ouch!

As an important application of Newton's first law, consider the crash test of FIGURE 4.2. As the car contacts the wall, the wall exerts a force on the car and it begins to slow. But the wall is a force on the *car,* not on the dummy. In accordance with Newton's first law, the unbelted dummy continues to move straight ahead at his original speed. Only when he collides violently with the dashboard of the stopped car is there a force acting to halt the dummy's uniform motion. If he had been wearing a seatbelt, the influence (i.e., the force) of the seatbelt would have slowed the dummy at the much lower rate at which the car slows down. We'll study the forces of collisions in detail in Chapter 10.

4.2 Force

Newton's first law tells us that an object in motion subject to no forces will continue to move in a straight line forever. But this law does not explain in any detail exactly what a force *is.* Unfortunately, there is no simple one-sentence definition of force. The concept of force is best introduced by looking at examples of some common forces and considering the basic properties shared by all forces. This will be our task in the next two sections. Let's begin by examining the properties that all forces have in common, as presented in the table on the next page.

What is a force?

A force is a push or a pull.

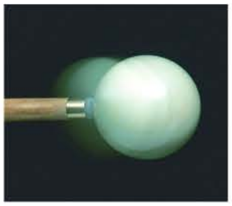
Our commonsense idea of a **force** is that it is a *push* or a *pull*. We will refine this idea as we go along, but it is an adequate starting point. Notice our careful choice of words: We refer to "*a* force" rather than simply "force." We want to think of a force as a very specific *action*, so that we can talk about a single force or perhaps about two or three individual forces that we can clearly distinguish—hence the concrete idea of "a force" acting on an object.

A force acts on an object.

Implicit in our concept of force is that **a force acts on an object.** In other words, pushes and pulls are applied *to* something—an object. From the object's perspective, it has a force *exerted* on it. Forces do not exist in isolation from the object that experiences them.

A force requires an agent.

Every force has an **agent,** something that acts or pushes or pulls; that is, a force has a specific, identifiable *cause*. As you throw a ball, it is your hand, while in contact with the ball, that is the agent or the cause of the force exerted on the ball. *If* a force is being exerted on an object, you must be able to identify a specific cause (i.e., the agent) of that force. Conversely, a force is not exerted on an object *unless* you can identify a specific cause or agent. Note that an agent can be an inert object such as a tabletop or a wall. Such agents are the cause of many common forces.



A force is a vector.

If you push an object, you can push either gently or very hard. Similarly, you can push either left or right, up or down. To quantify a push, we need to specify both a magnitude *and* a direction. It should thus come as no surprise that a force is a vector quantity. The general symbol for a force is the vector symbol $\vec{F}$. The size or strength of such a force is its magnitude F.

A force can be either a contact force . . .

There are two basic classes of forces, depending on whether the agent touches the object or not. **Contact forces** are forces that act on an object by touching it at a point of contact. The bat must touch the ball to hit it. A string must be tied to an object to pull it. The majority of forces that we will examine are contact forces.

. . . or a long-range force.

Long-range forces are forces that act on an object without physical contact. Magnetism is an example of a long-range force. You have undoubtedly held a magnet over a paper clip and seen the paper clip leap up to the magnet. A coffee cup released from your hand is pulled to the earth by the long-range force of gravity.

Let's summarize these ideas as our definition of force:

- A force is a push or a pull on an object.
- A force is a vector. It has both a magnitude and a direction.
- A force requires an agent. Something does the pushing or pulling. The agent can be an inert object such as a tabletop or a wall.
- A force is either a contact force or a long-range force. Gravity is the only long-range force we will deal with until much later in the book.

There's one more important aspect of forces. If you push against a door (the object) to close it, the door pushes back against your hand (the agent). If a tow rope pulls on a car (the object), the car pulls back on the rope (the agent). In general, if an agent exerts a force on an object, the object exerts a force on the agent. We really need to think of a force as an *interaction* between two objects. Although the interaction perspective is a more exact way to view forces, it adds complications that we would like to avoid for now. Our approach will be to start by focusing on how a single object responds to forces exerted on it. Later in this chapter, we'll return to the larger issue of how two or more objects interact with each other.

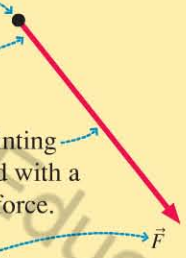
Force Vectors

We can use a simple diagram to visualize how forces are exerted on objects. Because we are using the particle model, in which objects are treated as points, the process of drawing a force vector is straightforward. Here is how it goes:

TACTICS BOX 4.1 Drawing force vectors

MP™

1. Represent the object as a particle.
2. Place the *tail* of the force vector on the particle.
3. Draw the force vector as an arrow pointing in the direction that the force acts, and with a length proportional to the size of the force.
4. Give the vector an appropriate label.

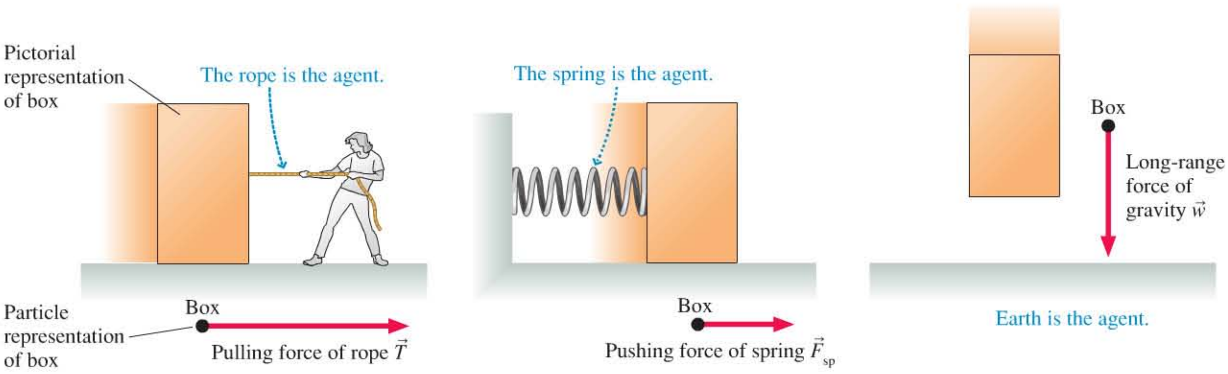


Exercise 1

Step 2 may seem contrary to what a "push" should do (it may look as if the force arrow is *pulling* the object rather than *pushing* it), but recall that moving a vector does not change it as long as the length and angle do not change. The vector $\vec{F}$ is the same regardless of whether the tail or the tip is placed on the particle. Our reason for using the tail will become clear when we consider how to combine several forces.

FIGURE 4.3 shows three examples of force vectors. One is a pull, one a push, and one a long-range force, but in all three the *tail* of the force vector is placed on the particle representing the object.

FIGURE 4.3 Three force vectors.



Combining Forces

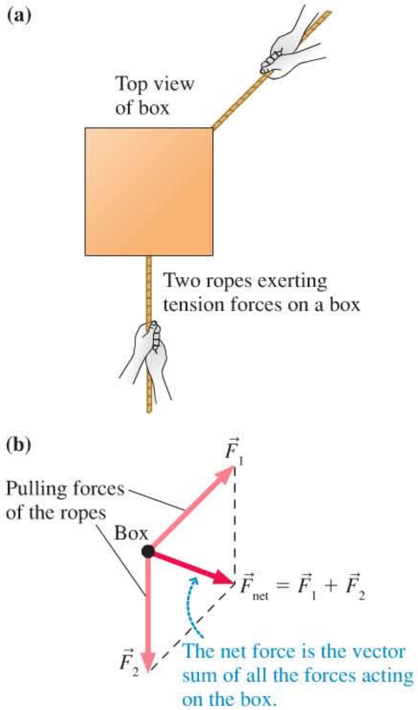
FIGURE 4.4a shows a top view of a box being pulled by two ropes, each exerting a force on the box. How will the box respond? Experimentally, we find that when several forces $\vec{F}_1, \vec{F}_2, \vec{F}_3, \ldots$ are exerted on an object, they combine to form a **net force** that is the *vector* sum of all the forces:

$$\vec{F}_{net} = \vec{F}_1 + \vec{F}_2 + \vec{F}_3 + \cdots \tag{4.1}$$

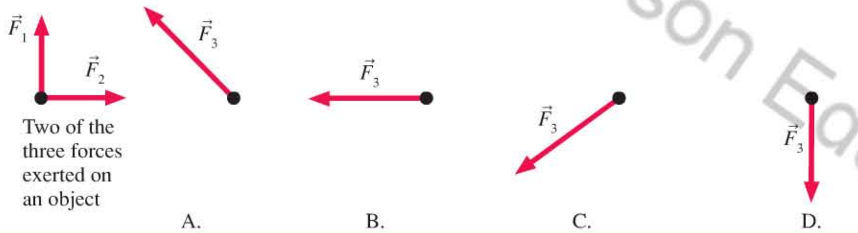
That is, the single force $\vec{F}_{net}$ causes the exact same motion of the object as the combination of original forces $\vec{F}_1, \vec{F}_2, \vec{F}_3, \ldots$. Mathematically, this summation is called a *superposition* of forces. The net force is sometimes called the *resultant force*. **FIGURE 4.4b** shows the net force on the box.

NOTE ► It is important to realize that the net force $\vec{F}_{net}$ is not a new force acting *in addition* to the original forces $\vec{F}_1, \vec{F}_2, \vec{F}_3, \ldots$. Instead, we should think of the original forces being *replaced* by $\vec{F}_{net}$. ◄

FIGURE 4.4 Two forces applied to a box.



STOP TO THINK 4.1 Two of the three forces exerted on an object are shown. The net force points directly to the left. Which is the missing third force?



4.3 A Short Catalog of Forces

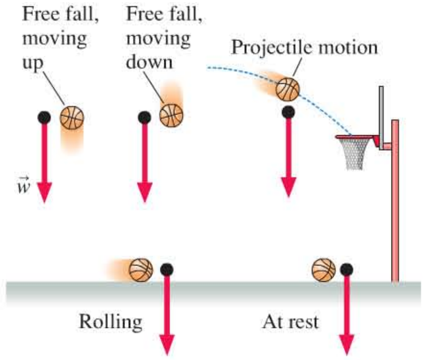
There are many forces we will deal with over and over. This section will introduce you to some of them and to the symbols we use to represent them.

Weight

A falling rock is pulled toward the earth by the long-range force of gravity. Gravity is what keeps you in your chair, keeps the planets in their orbits around the sun, and shapes the large-scale structure of the universe. We'll have a thorough look at gravity in Chapter 6. For now we'll concentrate on objects on or near the surface of the earth (or other planet).

The gravitational pull of the earth on an object on or near the surface of the earth is called **weight.** The symbol for weight is $\vec{w}$. Weight is the only long-range force we will encounter in the next few chapters. The agent for the weight force is the *entire earth* pulling on an object. The weight force is in some ways the simplest force we'll study. As **FIGURE 4.5** shows, **an object's weight vector always points vertically downward,** no matter how the object is moving.

FIGURE 4.5 Weight always points vertically downward.



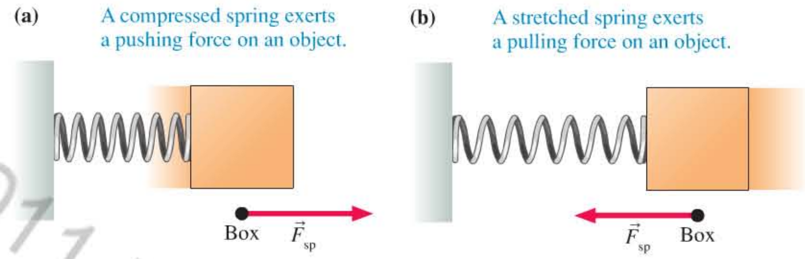
NOTE ► We often refer to "the weight" of an object. This is an informal expression for w, the magnitude of the weight force exerted on the object. Note that **weight is not the same thing as mass.** We will briefly examine mass later in the chapter and explore the connection between weight and mass in Chapter 5. ◄

Springs come in many forms. When deflected, they push or pull with a spring force.

Spring Force

Springs exert one of the most basic contact forces. A spring can either push (when compressed) or pull (when stretched). FIGURE 4.6 shows the **spring force.** In both cases, pushing and pulling, the tail of the force vector is placed on the particle in the force diagram. There is no special symbol for a spring force, so we simply use a subscript label: $\vec{F}_{sp}$.

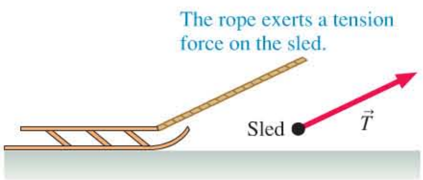
FIGURE 4.6 The spring force is parallel to the spring.



Although you may think of a spring as a metal coil that can be stretched or compressed, this is only one type of spring. Hold a ruler, or any other thin piece of wood or metal, by the ends and bend it slightly. It flexes. When you let go, it "springs" back to its original shape. This is just as much a spring as is a metal coil.

Tension Force

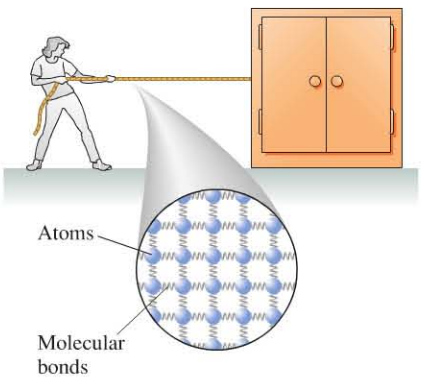
FIGURE 4.7 Tension is parallel to the rope.



When a string or rope or wire pulls on an object, it exerts a contact force that we call the **tension force,** represented by $\vec{T}$. **The direction of the tension force is always in the direction of the string or rope,** as you can see in FIGURE 4.7. When we speak of "the tension" in a string, this is an informal expression for T, the size or magnitude of the tension force. Note that the tension force can only *pull* in the direction of the string; if you try to *push* with a string, it will go slack and be unable to exert a force.

We can think about the tension force using a microscopic picture. If you were to use a very powerful microscope to look inside a rope, you would "see" that it is made of *atoms* joined together by *molecular bonds.* Molecular bonds are not rigid connections between the atoms. They are more accurately thought of as tiny *springs* holding the atoms together, as in FIGURE 4.8. Pulling on the ends of a string or rope stretches the molecular springs ever so slightly. The tension within a rope and the tension force experienced by an object at the end of the rope are really the net spring force exerted by billions and billions of microscopic springs.

FIGURE 4.8 An atomic model of tension.



This atomic-level view of tension introduces a new idea: a microscopic **atomic model** for understanding the behavior and properties of **macroscopic** (i.e., containing many atoms) objects. We will frequently use atomic models to obtain a deeper understanding of our observations.

The atomic model of tension also helps to explain one of the basic properties of ropes and strings. When you pull on a rope tied to a heavy box, the rope in turn exerts a tension force on the box. If you pull harder, the tension force on the box becomes greater. How does the box "know" that you are pulling harder on the other end of the rope? According to our atomic model, when you pull harder on the rope, its microscopic springs stretch a bit more, increasing the spring force they exert on each other—and on the box they're attached to.

Normal Force

If you sit on a bed, the springs in the mattress compress and, as a consequence of the compression, exert an upward force on you. Stiffer springs would show less compression but would still exert an upward force. The compression of extremely stiff springs might be measurable only by sensitive instruments. Nonetheless, the springs would compress ever so slightly and exert an upward spring force on you.

FIGURE 4.9 shows a book resting on top of a sturdy table. The table may not visibly flex or sag, but—just as you do to the bed—the book compresses the molecular springs in the table. The compression is very small, but it is not zero. As a consequence, the compressed molecular springs *push upward* on the book. We say that "the table" exerts the upward force, but it is important to understand that the pushing is *really* done by molecular springs. Similarly, an object resting on the ground compresses the molecular springs holding the ground together and, as a consequence, the ground pushes up on the object.

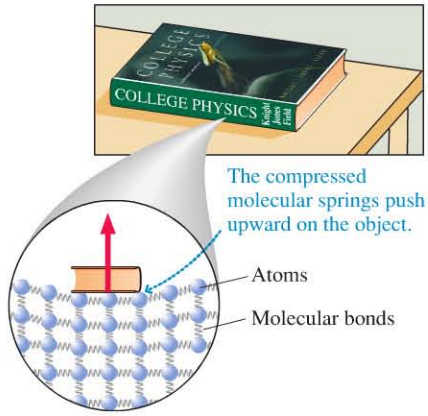


FIGURE 4.9 An atomic model of the force exerted by a table.

We can extend this idea. Suppose you place your hand on a wall and lean against it, as shown in FIGURE 4.10. Does the wall exert a force on your hand? As you lean, you compress the molecular springs in the wall and, as a consequence, they push outward *against* your hand. So the answer is Yes, the wall does exert a force on you. It's not hard to see this if you examine your hand as you lean: You can see that your hand is slightly deformed, and becomes more so the harder you lean. This deformation is direct evidence of the force that the wall exerts on your hand. Consider also what would happen if the wall suddenly vanished. Without the wall there to push against you, you would topple forward.

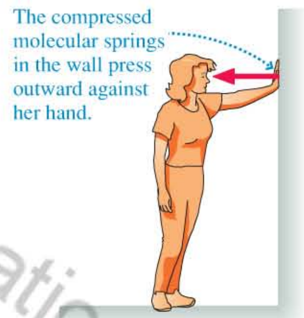


FIGURE 4.10 The wall pushes outward against your hand.

The force the table surface exerts is vertical, while the force the wall exerts is horizontal. In all cases, the force exerted on an object that is pressing against a surface is in a direction *perpendicular* to the surface. Mathematicians refer to a line that is perpendicular to a surface as being *normal* to the surface. In keeping with this terminology, we define the **normal force** as the force exerted by a surface (the agent) against an object that is pressing against the surface. The symbol for the normal force is $\vec{n}$.

We're not using the word "normal" to imply that the force is an "ordinary" force or to distinguish it from an "abnormal force." A surface exerts a force *perpendicular* (i.e., normal) to itself as the molecular springs press *outward.* FIGURE 4.11 shows an object on an inclined surface, a common situation. Notice how the normal force $\vec{n}$ is perpendicular to the surface.

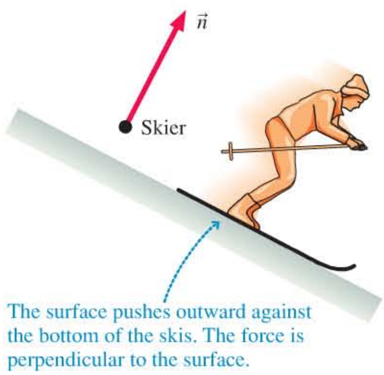


FIGURE 4.11 The normal force is perpendicular to the surface.

The normal force is a very real force arising from the very real compression of molecular bonds. It is in essence just a spring force, but one exerted by a vast number of microscopic springs acting at once. The normal force is responsible for the "solidness" of solids. It is what prevents you from passing right through the chair you are sitting in and what causes the pain and the lump if you bang your head into a door. Your head can then tell you that the force exerted on it by the door was very real!

Friction

You've certainly observed that a rolling or sliding object, if not pushed or propelled, slows down and eventually stops. You've probably discovered that you can slide better across a sheet of ice than across asphalt. And you also know that most objects stay in place on a table without sliding off even if the table is tilted a bit. The force responsible for these sorts of behavior is **friction.** The symbol for friction is $\vec{f}$.

Friction, like the normal force, is exerted by a surface. Unlike the normal force, however, **the frictional force is always *parallel* to the surface,** not perpendicular to it. (In many cases, a surface will exert *both* a normal and a frictional force.) On a microscopic level, friction arises as atoms from the object and atoms on the surface run into each other. The rougher the surface is, the more these atoms are forced into close proximity and, as a result, the larger the friction force. We will develop a simple model of friction in the next chapter that will be sufficient for our needs. For now, it is useful to distinguish between two kinds of friction:

- *Kinetic friction,* denoted $\vec{f}_k$, acts as an object slides across a surface. Kinetic friction is a force that always "opposes the motion," meaning that the friction force $\vec{f}_k$ on a sliding object points in the direction opposite the direction of the object's motion.
- *Static friction,* denoted $\vec{f}_s$, is the force that keeps an object "stuck" on a surface and prevents its motion relative to the surface. Finding the direction of $\vec{f}_s$ is a little trickier than finding it for $\vec{f}_k$. Static friction points opposite the direction in which the object *would* move if there were no friction. That is, it points in the direction necessary to *prevent* motion.

FIGURE 4.12 shows examples of kinetic and static friction.

FIGURE 4.12 Kinetic and static friction are parallel to the surface.

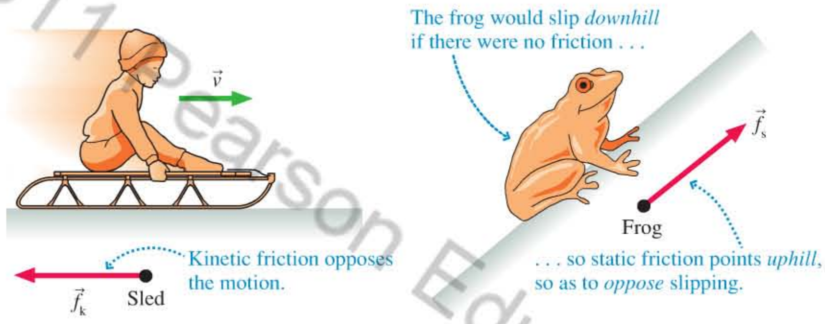
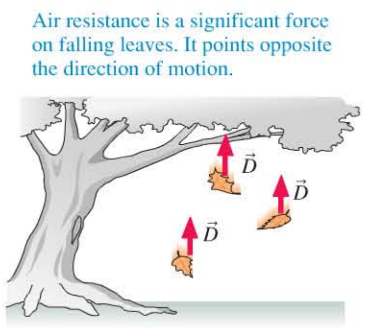


FIGURE 4.13 Air resistance is an example of drag.



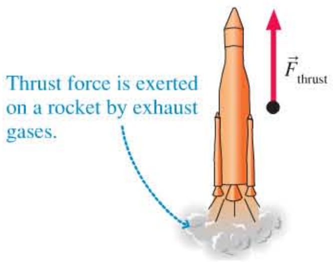
Drag

Friction at a surface is one example of a *resistive force,* a force that opposes or resists motion. Resistive forces are also experienced by objects moving through *fluids*—gases (like air) and liquids (like water). This kind of resistive force—the force of a fluid on a moving object—is called **drag** and is symbolized as $\vec{D}$. Like kinetic friction, **drag points opposite the direction of motion.** FIGURE 4.13 shows an example of drag.

Drag can be a large force for objects moving at high speeds or in dense fluids. Hold your arm out the window as you ride in a car and feel how hard the air pushes against your arm; note also how the air resistance against your arm increases rapidly as the car's speed increases. Drop a lightweight bead into a beaker of water and watch how slowly it settles to the bottom. The drag force of the water on the bead is significant.

On the other hand, for objects that are heavy and compact, moving in air, and with a speed that is not too great, the drag force of air resistance is fairly small. To keep things as simple as possible, **you can neglect air resistance in all problems unless a problem explicitly asks you to include it.** The error introduced into calculations by this approximation is generally pretty small.

FIGURE 4.14 The thrust force on a rocket is opposite the direction of the expelled gases.



Thrust

A jet airplane obviously has a force that propels it forward; likewise for the rocket in FIGURE 4.14. This force, called **thrust,** occurs when a jet or rocket engine expels gas molecules at high speed. Thrust is a contact force, with the exhaust gas being the agent that pushes on the engine. The process by which thrust is generated is rather subtle and requires an appreciation of Newton's third law, introduced later in this chapter. For now, we need only consider that **thrust is a force opposite the direction in which the exhaust gas is expelled.** There's no special symbol for thrust, so we will call it $\vec{F}_{\text{thrust}}$.

It's a drag At the high speeds attained by racing cyclists, air drag can become very significant. The world record for the longest distance traveled in one hour on an ordinary bicycle is 56.38 km, set by Chris Boardman in 1996. But a bicycle with an aerodynamic shell has a much lower drag force, allowing it to attain significantly higher speeds. The bike shown here was pedaled 84.22 km in one hour by Sam Whittingham in 2004, for an amazing average speed of 52.3 mph!

Electric and Magnetic Forces

Electricity and magnetism, like gravity, exert long-range forces. The forces of electricity and magnetism act on charged particles. We will study electric and magnetic forces in detail in Part VI of this book. For now, it is worth noting that the forces holding molecules together—the molecular bonds—are not actually tiny springs. Atoms and molecules are made of charged particles—electrons and protons—and what we call a molecular bond is really an electric force between these particles. So when we say that the normal force and the tension force are due to "molecular springs," or that friction is due to atoms running into each other, what we're really saying is that these forces, at the most fundamental level, are actually electric forces between the charged particles in the atoms.

4.4 Identifying Forces

Force and motion problems generally have two basic steps:

1. Identify all of the forces acting on an object.
2. Use Newton's laws and kinematics to determine the motion.

Understanding the first step is the primary goal of this chapter. We'll turn our attention to step 2 in the next chapter.

A typical physics problem describes an object that is being pushed and pulled in various directions. Some forces are given explicitly, while others are only implied. In order to proceed, it is necessary to determine all the forces that act on the object. It is also necessary to avoid including forces that do not really exist. Now that you have learned the properties of forces and seen a catalog of typical forces, we can develop a step-by-step method for identifying each force in a problem. A list of the most common forces we'll come across in the next few chapters is given in Table 4.1.

TABLE 4.1 Common forces and their notation

Force	Notation
General force	$\vec{F}$
Weight	$\vec{w}$
Spring force	$\vec{F}_{\text{sp}}$
Tension	$\vec{T}$
Normal force	$\vec{n}$
Static friction	$\vec{f}_{\text{s}}$
Kinetic friction	$\vec{f}_{\text{k}}$
Drag	$\vec{D}$
Thrust	$\vec{F}_{\text{thrust}}$

TACTICS BOX 4.2 Identifying forces

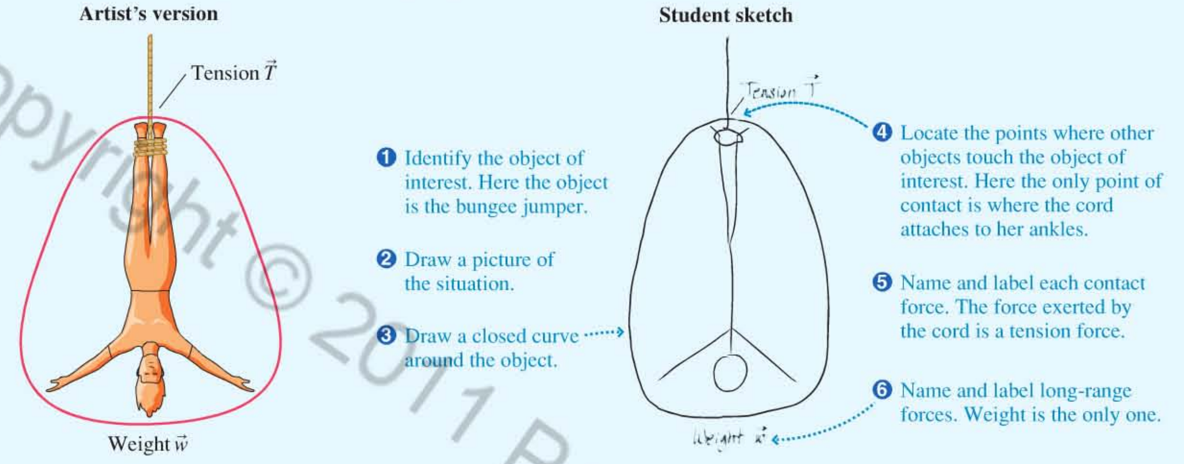
1. **Identify the object of interest.** This is the object whose motion you wish to study.
2. **Draw a picture of the situation.** Show the object of interest and all other objects—such as ropes, springs, and surfaces—that touch it.
3. **Draw a closed curve around the object.** Only the object of interest is inside the curve; everything else is outside.
4. **Locate every point on the boundary of this curve where other objects touch the object of interest.** These are the points where *contact forces* are exerted on the object.
5. **Name and label each contact force acting on the object.** There is at least one force at each point of contact; there may be more than one. When necessary, use subscripts to distinguish forces of the same type.
6. **Name and label each long-range force acting on the object.** For now, the only long-range force is weight.

Exercises 4–8

CONCEPTUAL EXAMPLE 4.1 Identifying forces on a bungee jumper

A bungee jumper has leapt off a bridge and is nearing the bottom of her fall. What forces are being exerted on the bungee jumper?

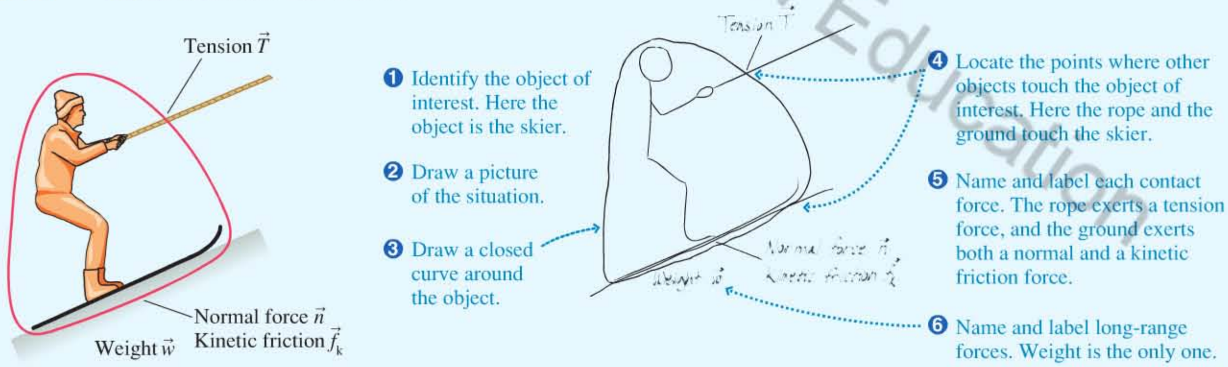
REASON FIGURE 4.15 Forces on a bungee jumper.



CONCEPTUAL EXAMPLE 4.2 Identifying forces on a skier

A skier is being towed up a snow-covered hill by a tow rope. What forces are being exerted on the skier?

REASON FIGURE 4.16 Forces on a skier.



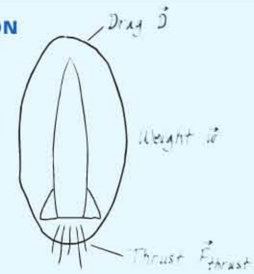
NOTE ► You might have expected two friction forces and two normal forces in Example 4.2, one on each ski. Keep in mind, however, that we're working within the particle model, which represents the skier by a single point. A particle has only one contact with the ground, so there is a single normal force and a single friction force. The particle model is valid if we want to analyze the motion of the skier as a whole, but we would have to go beyond the particle model to find out what happens to each ski. ◄

CONCEPTUAL EXAMPLE 4.3 Identifying forces on a rocket

A rocket is being launched to place a new satellite in orbit. Air resistance is not negligible. What forces are being exerted on the rocket?

REASON

FIGURE 4.17 Forces on a rocket.



STOP TO THINK 4.2 You've just kicked a rock, and it is now sliding across the ground about 2 meters in front of you. Which of these are forces acting on the rock? List all that apply.

A. Gravity, acting downward
B. The normal force, acting upward
C. The force of the kick, acting in the direction of motion
D. Friction, acting opposite the direction of motion
E. Air resistance, acting opposite the direction of motion

4.5 What Do Forces Do?

The fundamental question is: How does an object move when a force is exerted on it? The only way to answer this question is to do experiments. To do experiments, however, we need a way to reproduce the same force again and again, and we need a standard object so that our experiments are repeatable.

FIGURE 4.18 shows how you can use your fingers to stretch a rubber band to a certain length—say, 10 centimeters—that you can measure with a ruler. We'll call this the *standard length.* You know that a stretched rubber band exerts a force because your fingers *feel* the pull. Furthermore, this is a reproducible force. The rubber band exerts the same force every time you stretch it to the standard length. We'll call the magnitude of this force the *standard force* F. Not surprisingly, two identical rubber bands, each stretched to the standard length, exert twice the force of one rubber band; three rubber bands exert three times the force; and so on.

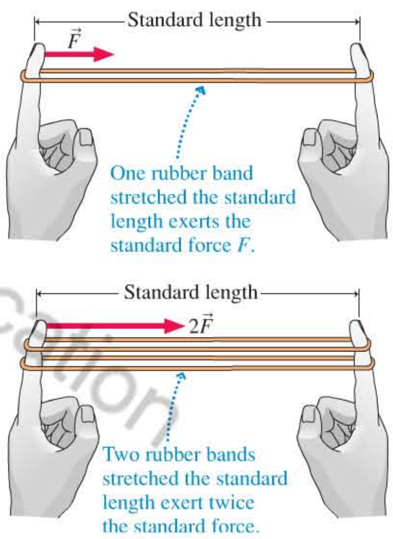
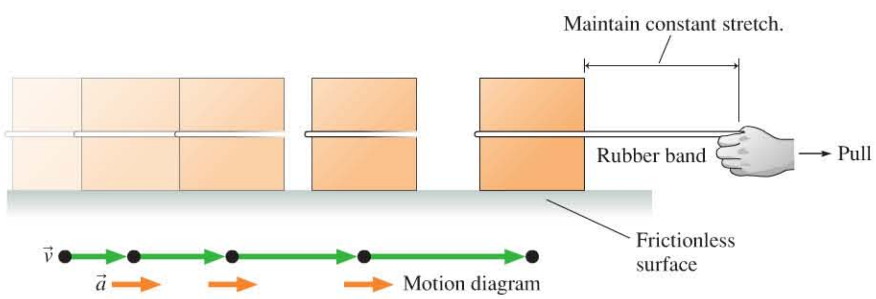


FIGURE 4.18 A reproducible force.

We'll also need several identical standard objects to which the force will be applied. As we learned in Chapter 1, the SI unit of mass is the kilogram (kg). The kilogram is defined in terms of a particular metal block kept in a vault in Paris. For our standard objects, we will make ourselves several identical copies, each with, by definition, a mass of 1 kg. At this point, you can think of mass as the "quantity of matter" in an object. This idea will suffice for now, but by the end of this section, we'll be able to give a more precise meaning to the concept of mass.

Now we're ready to start the virtual experiment. First, place one of the 1 kg blocks on a frictionless surface. (In a real experiment, we can nearly eliminate friction by floating the block on a cushion of air.) Second, attach a rubber band to the block and stretch the band to the standard length. Then the block experiences the same force F as your finger did. As the block starts to move, in order to keep the pulling force constant you must *move your hand* in just the right way to keep the length of the rubber band—and thus the force—*constant*. **FIGURE 4.19** shows the experiment being carried out. Once the motion is complete, you can use motion diagrams and kinematics to analyze the block's motion.

FIGURE 4.19 Measuring the motion of a 1 kg block that is pulled with a constant force.



The motion diagram in Figure 4.19 shows that the velocity vectors are getting longer, so the velocity is increasing: The block is *accelerating*. Furthermore, a close inspection of the motion diagram shows that the acceleration vectors are all the same length. This is the first important finding of this experiment: **An object pulled with**

FIGURE 4.20 Graph of acceleration versus force.

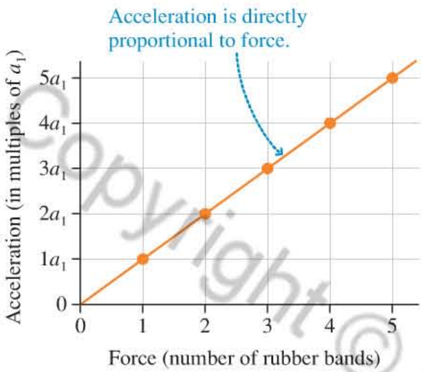
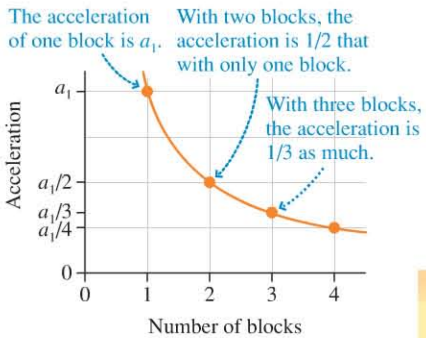


FIGURE 4.21 Graph of acceleration versus number of blocks.



a constant force moves with a constant acceleration. This finding could not have been anticipated in advance. It's conceivable that the object would speed up for a while and then move with a steady speed. Or that it would continue to speed up, but that the *rate* of increase, the acceleration, would steadily decline. But these descriptions do not match what happens. Instead, the object continues *with a constant acceleration* for as long as you pull it with a constant force. We'll call this constant acceleration of *one* block pulled by *one* band a_1.

What happens if you increase the force by using several rubber bands? To find out, use two rubber bands. Stretch both to the standard length to double the force to $2F$, then measure the acceleration. Measure the acceleration due to three rubber bands, then four, and so on. FIGURE 4.20 is a graph of the results. Force is the independent variable, the one you can control, so we've placed force on the horizontal axis to make an acceleration-versus-force graph. The graph reveals our second important finding: **Acceleration is directly proportional to force.**

The final question for our virtual experiment is: How does the acceleration of an object depend on the mass of the object, the "quantity of matter" that it contains? To find out, we'll glue two of our 1 kg blocks together, so that we have a block with twice as much matter as a 1 kg block—that is, a 2 kg block. Now apply the same force—a single rubber band—as you applied to the single 1 kg block. FIGURE 4.21 shows that the acceleration is *one-half* as great as that of the single block. If we glue three blocks together, making a 3 kg object, we find that the acceleration is only *one-third* of the 1 kg block's acceleration. In general, we find that the acceleration is proportional to the *inverse* of the mass of the object. So our third important result is: **Acceleration is *inversely proportional* to an object's mass.**

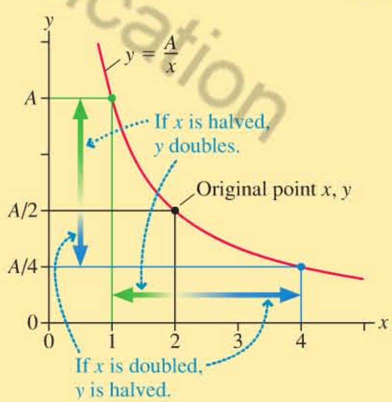
Inversely proportional relationships

Two quantities are said to be **inversely proportional** to each other if one quantity is proportional to the *inverse* of the other. Mathematically, this means that

$$y = \frac{A}{x}$$

y is inversely proportional to x

Here, A is a proportionality constant. This relationship is sometimes written as $y \propto 1/x$.



SCALING
- If you double x, you halve y.
- If you triple x, y is reduced by a factor of 3.
- If you halve x, y doubles.
- If you reduce x by a factor of 3, y becomes 3 times as large.

RATIOS For any two values of x—say, x_1 and x_2—we have

$$y_1 = \frac{A}{x_1} \quad \text{and} \quad y_2 = \frac{A}{x_2}$$

Dividing the y_1 equation by the y_2 equation, we find

$$\frac{y_1}{y_2} = \frac{A/x_1}{A/x_2} = \frac{A}{x_1}\frac{x_2}{A} = \frac{x_2}{x_1}$$

That is, the ratio of y-values is the inverse of the ratio of the corresponding values of x.

LIMITS
- As x gets very large, y approaches zero.
- As x approaches zero, y gets very large.

Exercise 10

Our original idea of mass was that it was a measure of the "quantity of matter" that an object contains. Now we see that a more precise way of defining the mass of an object is in terms of its *acceleration*. You're familiar with this idea: It's much harder to get your car rolling by pushing it than to get your bicycle rolling; it's harder to stop a heavily loaded grocery cart than to stop a skateboard. This tendency to resist a change in velocity (i.e., to resist speeding up or slowing down) is called **inertia.** Thus we can say that more massive objects have more inertia.

These considerations allow us to unambiguously determine the mass of an object by measuring its acceleration, as the next example shows.

EXAMPLE 4.4 Finding the mass of an unknown block

When a rubber band is stretched to pull on a 1.0 kg block with a constant force, the acceleration of the block is measured to be 3.0 m/s^2. When a block with an unknown mass is pulled with the same rubber band, using the same force, its acceleration is 5.0 m/s^2. What is the mass of the unknown block?

PREPARE Each block's acceleration is inversely proportional to its mass.

SOLVE We can use the result of the Inversely Proportional Relationships box to write

$$\frac{3.0\ \text{m/s}^2}{5.0\ \text{m/s}^2} = \frac{m}{1.0\ \text{kg}}$$

or

$$m = \frac{3.0\ \text{m/s}^2}{5.0\ \text{m/s}^2}(1.0\ \text{kg}) = 0.60\ \text{kg}$$

ASSESS With the same force applied, the unknown block had a *larger* acceleration than the 1.0 kg block. It makes sense, then, that its mass—its resistance to acceleration—is *less* than 1.0 kg.

STOP TO THINK 4.3 Two rubber bands stretched to the standard length cause an object to accelerate at 2 m/s^2. Suppose another object with twice the mass is pulled by four rubber bands stretched to the standard length. What is the acceleration of this second object?

A. 1 m/s^2 B. 2 m/s^2 C. 4 m/s^2 D. 8 m/s^2 E. 16 m/s^2

TRY IT YOURSELF

Feel the difference Because of its high sugar content, a can of regular soda has a mass about 4% greater than that of a can of diet soda. If you try to judge which can is more massive by simply holding one in each hand, this small difference is almost impossible to detect. If you *move* the cans up and down, however, the difference becomes subtly but noticeably apparent: People evidently are more sensitive to how the mass of each can resists acceleration than they are to the cans' weights alone.

4.6 Newton's Second Law

We can now summarize the results of our experiments. We've seen that **a force causes an object to accelerate. The acceleration *a* is directly proportional to the force *F* and inversely proportional to the mass *m*.** We can express both these relationships in equation form as

$$a = \frac{F}{m} \tag{4.2}$$

Note that if we double the size of the force F, the acceleration a will double, as we found experimentally. And if we triple the mass m, the acceleration will be only one-third as great, again agreeing with experiment.

Equation 4.2 tells us the magnitude of an object's acceleration in terms of its mass and the force applied. But our experiments also had another important finding: The *direction* of the acceleration was the same as the direction of the force. We can express this fact by writing Equation 4.2 in *vector* form as

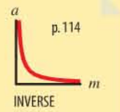
$$\vec{a} = \frac{\vec{F}}{m} \tag{4.3}$$

Finally, our experiment was limited to looking at an object's response to a *single* applied force acting in a single direction. Realistically, an object is likely to be subjected to several distinct forces $\vec{F}_1, \vec{F}_2, \vec{F}_3, \ldots$ that may point in different directions. What happens then? Experiments show that the acceleration of the object is determined by the *net force* acting on it. Recall from Figure 4.4 and Equation 4.1 that the net force is the *vector sum* of all forces acting on the object. So if several forces are acting, we use the *net* force in Equation 4.4.

Newton was the first to recognize these connections between force and motion. This relationship is known today as Newton's second law.

Newton's second law An object of mass m subjected to forces $\vec{F}_1, \vec{F}_2, \vec{F}_3, \ldots$ will undergo an acceleration $\vec{a}$ given by

$$\vec{a} = \frac{\vec{F}_{\text{net}}}{m} \tag{4.4}$$



where the net force $\vec{F}_{\text{net}} = \vec{F}_1 + \vec{F}_2 + \vec{F}_3 + \cdots$ is the vector sum of all forces acting on the object. **The acceleration vector $\vec{a}$ points in the same direction as the net force vector $\vec{F}_{\text{net}}$.**

An unfair advantage? Race car driver Danica Patrick was the subject of controversial comments by other drivers who thought her small mass of 45 kg gave her an advantage over heavier drivers; the next-lightest driver's mass was 61 kg. Because every driver's car must have the same mass, Patrick's overall racing mass was lower than any other driver's. Because a car's acceleration is inversely proportional to its mass, her car could be expected to have a slightly greater acceleration.

We'll use Newton's second law in Chapter 5 to solve many kinds of motion problems; for the moment, however, the critical idea is that an object accelerates in the direction of the net force acting on it.

The significance of Newton's second law cannot be overstated. There was no reason to suspect that there should be any simple relationship between force and acceleration. Yet a simple but exceedingly powerful equation relates the two. Newton's work, preceded to some extent by Galileo's, marks the beginning of a highly successful period in the history of science during which it was learned that the behavior of physical objects can often be described and predicted by mathematical relationships. While some relationships are found to apply only in special circumstances, others seem to have universal applicability. Those equations that appear to apply at all times and under all conditions have come to be called "laws of nature." Newton's second law is a law of nature; you will meet others as we go through this book.

We can rewrite Newton's second law in the form

$$\vec{F}_{\text{net}} = m\vec{a} \tag{4.5}$$

which is how you'll see it presented in many textbooks and how, in practice, we'll often use the second law. Equations 4.4 and 4.5 are mathematically equivalent, but Equation 4.4 better describes the central idea of Newtonian mechanics: A force applied to an object causes the object to accelerate.

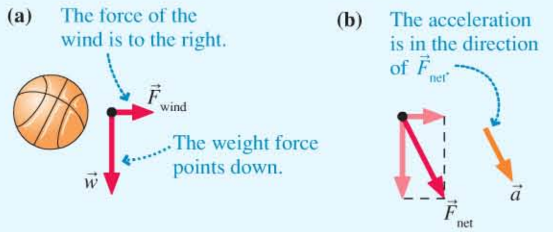
NOTE ► When several forces act on an object, be careful not to think that the strongest force "overcomes" the others to determine the motion on its own. It is $\vec{F}_{\text{net}}$, the sum of *all* the forces, that determines the acceleration $\vec{a}$. ◄

CONCEPTUAL EXAMPLE 4.5 Acceleration of a wind-blown basketball

A basketball is released from rest in a stiff breeze directed to the right. In what direction does the ball accelerate?

REASON As shown in FIGURE 4.22a, two forces are acting on the ball: its weight $\vec{w}$ directed downward and a wind force $\vec{F}_{\text{wind}}$ pushing the ball to the right. Newton's second law tells us that the direction of the acceleration is the same as the direction of the net force $\vec{F}_{\text{net}}$. In FIGURE 4.22b we find $\vec{F}_{\text{net}}$ by graphical vector addition of $\vec{w}$ and $\vec{F}_{\text{wind}}$. We see that $\vec{F}_{\text{net}}$ and therefore $\vec{a}$ point down and to the right.

FIGURE 4.22 A basketball falling in a strong breeze.



Units of Force

Because $\vec{F}_{net} = m\vec{a}$, the unit of force must be mass units multiplied by acceleration units. We've previously specified the SI unit of mass as the kilogram. We can now define the basic unit of force as "the force that causes a 1 kg mass to accelerate at 1 m/s^2." From Newton's second law, this force is

$$1 \text{ basic unit of force} = (1 \text{ kg}) \times (1 \text{ m/s}^2) = 1 \frac{\text{kg} \cdot \text{m}}{\text{s}^2}$$

This basic unit of force is called a *newton:* One **newton** is the force that causes a 1 kg mass to accelerate at 1 m/s^2. The abbreviation for newton is N. Mathematically, 1 N = 1 kg · m/s^2.

The newton is a *secondary unit,* meaning that it is defined in terms of the *primary units* of kilograms, meters, and seconds. We will introduce other secondary units as needed.

It is important to develop a feeling for what the size of forces should be. Table 4.2 lists some typical forces. As you can see, "typical" forces on "typical" objects are likely to be in the range 0.01–10,000 N. Forces less than 0.01 N are too small to consider unless you are dealing with very small objects. Forces greater than 10,000 N would make sense only if applied to very massive objects.

The unit of force in the English system is the *pound* (abbreviated lb). Although the definition of the pound has varied throughout history, it is now defined in terms of the newton:

$$1 \text{ pound} = 1 \text{ lb} = 4.45 \text{ N}$$

You very likely associate pounds with kilograms rather than with newtons. Everyday language often confuses the ideas of mass and weight, but we're going to need to make a clear distinction between them. We'll have more to say about this in the next chapter.

TABLE 4.2 Approximate magnitude of some typical forces

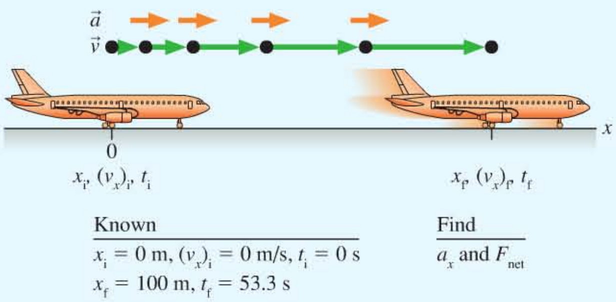
Force	Approximate magnitude (newtons)
Weight of a U.S. nickel	0.05
Weight of a 1-pound object	5
Weight of a 110-pound person	500
Propulsion force of a car	5000
Thrust force of a rocket motor	5,000,000

EXAMPLE 4.6 **Pulling an airplane**

In 2000, a team of 60 British police officers set a world record by pulling a Boeing 747, with a mass of 205,000 kg, a distance of 100 m in 53.3 s. Estimate the force with which each officer pulled on the plane.

PREPARE If we assume that the plane undergoes a constant acceleration, we can use kinematics to find the magnitude of that acceleration. Then we can use Newton's second law to find the force applied to the airplane. **FIGURE 4.23** shows the visual overview of the airplane.

FIGURE 4.23 Visual overview of the airplane accelerating.



SOLVE Because we know the net displacement of the plane and the time it took to move, we can use the kinematic equation

$$x_f = x_i + (v_x)_i \,\Delta t + \tfrac{1}{2} a_x (\Delta t)^2$$

to find the airplane's acceleration a_x. Using the known values $x_i = 0$ m and $(v_x)_i = 0$ m/s, we can solve for the acceleration:

$$a_x = \frac{2x_f}{(\Delta t)^2} = \frac{2(100 \text{ m})}{(53.3 \text{ s})^2} = 0.0704 \text{ m/s}^2$$

Now we apply Newton's second law. The net force is

$$F_{net} = ma_x = (205{,}000 \text{ kg})(0.0704 \text{ m/s}^2) = 1.44 \times 10^4 \text{ N}$$

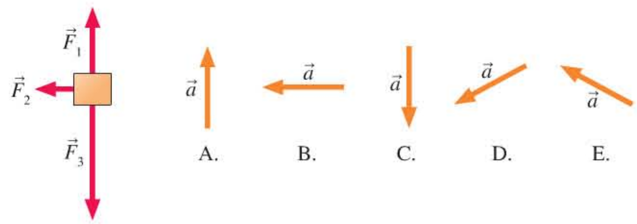
This is the force applied by all 60 men. Each man thus applies about 1/60th of this force, or around 240 N.

ASSESS Converting this force to pounds, we have

$$F = 240 \text{ N} \times \frac{1 \text{ lb}}{4.45 \text{ N}} = 54 \text{ lb}$$

Our answer is suspiciously low. Burly policemen can certainly apply a force greater than 54 lb. The fact that our calculation ended with a force that appears too small suggests we've overlooked something. In fact, we have. We've neglected the rolling friction of the plane's tires. We'll learn how to deal with friction in the next chapter, where we'll find that, because of the opposing friction force, the men have to pull harder than our estimate, in which we've ignored friction.

STOP TO THINK 4.4 Three forces act on an object. In which direction does the object accelerate?



4.7 Free-Body Diagrams

Having discussed at length what is and is not a force, and what forces do to an object, we are ready to assemble our knowledge about force and motion into a single diagram called a **free-body diagram.** A free-body diagram represents the object as a particle and shows *all* of the forces acting on the object. Learning how to draw a correct free-body diagram is a very important skill, one that in the next chapter will become a critical part of our strategy for solving motion problems. For now, let's concentrate on the basic skill of constructing a correct free-body diagram.

TACTICS BOX 4.3 Drawing a free-body diagram

1. **Identify all forces acting on the object.** This step was described in Tactics Box 4.2.
2. **Draw a coordinate system.** Use the axes defined in your pictorial representation (Tactics Box 2.2). If those axes are tilted, for motion along an incline, then the axes of the free-body diagram should be similarly tilted.
3. **Represent the object as a dot at the origin of the coordinate axes.** This is the particle model.
4. **Draw vectors representing each of the identified forces.** This was described in Tactics Box 4.1. Be sure to label each force vector.
5. **Draw and label the *net force* vector $\vec{F}_{\text{net}}$.** Draw this vector beside the diagram, not on the particle. Then check that $\vec{F}_{\text{net}}$ points in the same direction as the acceleration vector $\vec{a}$ on your motion diagram. Or, if appropriate, write $\vec{F}_{\text{net}} = \vec{0}$.

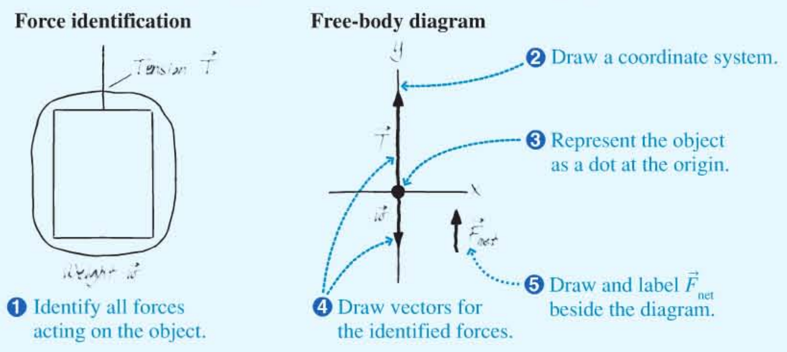
Exercises 17–22

EXAMPLE 4.7 Forces on an upward-accelerating elevator

An elevator, suspended by a cable, speeds up as it moves upward from the ground floor. Draw a free-body diagram of the elevator.

PREPARE FIGURE 4.24 illustrates the steps listed in Tactics Box 4.3.

FIGURE 4.24 Free-body diagram of an elevator accelerating upward.



ASSESS The coordinate axes, with a vertical y-axis, are the ones we use in a pictorial representation of the motion. The elevator is accelerating upward, so $\vec{F}_{net}$ must point upward. For this to be true, the magnitude of $\vec{T}$ must be greater than the magnitude of $\vec{w}$. The diagram has been drawn accordingly.

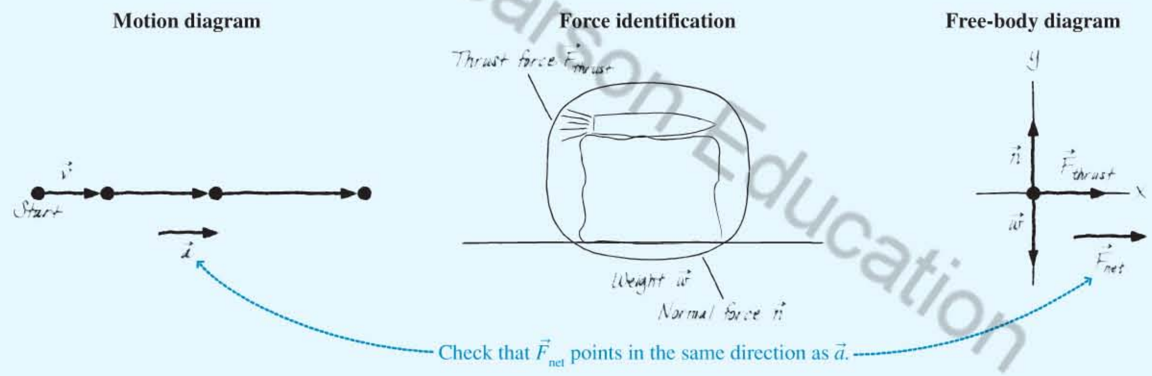
EXAMPLE 4.8 Forces on a rocket-propelled ice block

Bobby straps a small model rocket to a block of ice and shoots it across the smooth surface of a frozen lake. Friction is negligible. Draw a visual overview—a motion diagram, force identification diagram, and free-body diagram—of the block of ice.

PREPARE We treat the block of ice as a particle. The visual overview consists of a motion diagram to determine $\vec{a}$, a force identification picture, and a free-body diagram. The statement of the situation tells us that friction is negligible. We can draw these three pictures using Problem-Solving Strategy 1.1 for the motion diagram, Tactics Box 4.2 to identify the forces, and Tactics Box 4.3 to draw the free-body diagrams. These pictures are shown in **FIGURE 4.25**.

ASSESS The motion diagram tells us that the acceleration is in the positive x-direction. According to the rules of vector addition, this can be true only if the upward-pointing $\vec{n}$ and the downward-pointing $\vec{w}$ are equal in magnitude and thus cancel each other. The vectors have been drawn accordingly, and this leaves the net force vector pointing toward the right, in agreement with $\vec{a}$ from the motion diagram.

FIGURE 4.25 Visual overview for a block of ice shooting across a frictionless frozen lake.

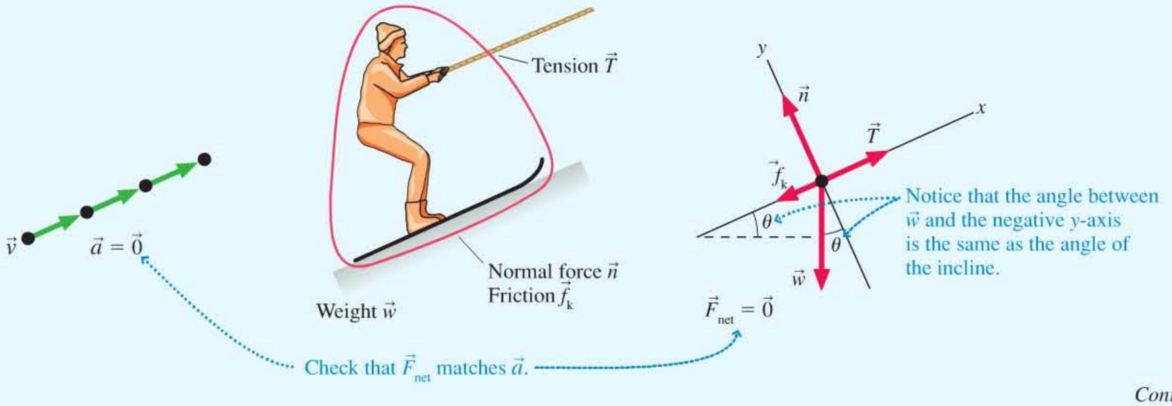


EXAMPLE 4.9 Forces on a towed skier

A tow rope pulls a skier up a snow-covered hill at a constant speed. Draw a full visual overview of the skier.

PREPARE This is Example 4.2 again with the additional information that the skier is moving at a constant speed. If we were doing a kinematics problem, the pictorial representation would use a tilted coordinate system with the x-axis parallel to the slope, so we use these same tilted coordinate axes for the free-body diagram. The motion diagram, force identification diagram, and free-body diagram are shown in **FIGURE 4.26**.

FIGURE 4.26 Visual overview for a skier being towed at a constant speed.



Continued

ASSESS We have shown $\vec{T}$ pulling parallel to the slope and $\vec{f}_k$, which opposes the direction of motion, pointing down the slope. The normal force $\vec{n}$ is perpendicular to the surface and thus along the y-axis. Finally, and this is important, the weight $\vec{w}$ is *vertically* downward, *not* along the negative y-axis.

The skier moves in a straight line with constant speed, so $\vec{a} = \vec{0}$. Newton's second law then tells us that $\vec{F}_{net} = m\vec{a} = \vec{0}$. Thus we have drawn the vectors such that the forces add to zero. We'll learn more about how to do this in Chapter 5.

Free-body diagrams will be our major tool for the next several chapters. Careful practice with the workbook exercises and homework in this chapter will pay immediate benefits in the next chapter. Indeed, it is not too much to assert that a problem is more than half solved when you correctly complete the free-body diagram.

STOP TO THINK 4.5 An elevator suspended by a cable is moving upward and slowing to a stop. Which free-body diagram is correct?

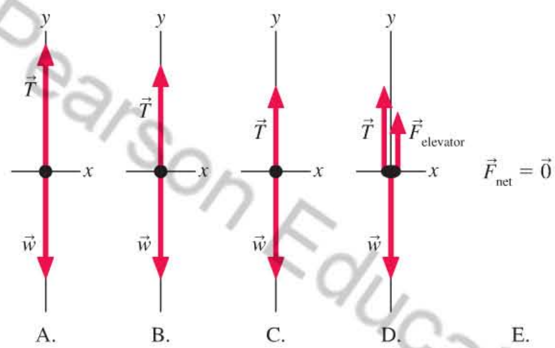


FIGURE 4.27 The hammer and the nail are a system of interacting objects.

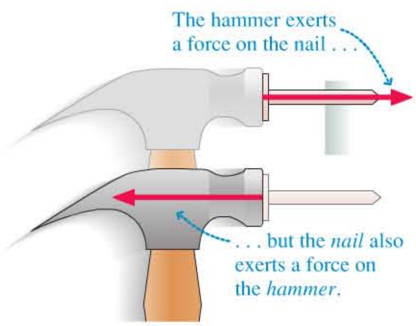
4.8 Newton's Third Law

Thus far, we've focused on the motion of a single particle responding to well-defined forces exerted by other objects, or to long-range forces. A skier sliding downhill, for instance, is subject to frictional and normal forces from the slope, and the pull of gravity on his body. Once we have identified these forces, we can use Newton's second law to calculate the acceleration, and hence the overall motion, of the skier.

But motion in the real world often involves two or more objects *interacting* with each other. Consider the hammer and nail in FIGURE 4.27. As the hammer hits the nail, the nail pushes back on the hammer. A bat and a ball, your foot and a soccer ball, and the earth–moon system are other examples of interacting objects.

Newton's second law is not sufficient to explain what happens when two or more objects interact. It does not explain how the force of the hammer on the nail is related to the force of the nail on the hammer. In this section we will introduce another law of physics, Newton's *third* law, that describes how two objects interact with each other.

FIGURE 4.28 The hammer and nail each exert a force on the other.



Interacting Objects

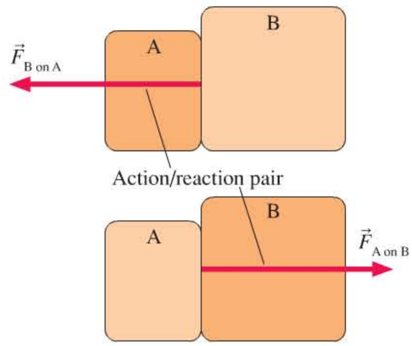
Think about the hammer and nail in Figure 4.27. As FIGURE 4.28 shows, the hammer certainly exerts a force on the nail as it drives the nail forward. At the same time, the nail exerts a force on the hammer. If you are not sure that it does, imagine hitting the nail with a glass hammer. It's the force of the nail on the hammer that would cause the glass to shatter.

Indeed, if you stop to think about it, any time that object A pushes or pulls on object B, object B pushes or pulls back on object A. As you push on a filing cabinet to move it, the cabinet pushes back on you. (If you pushed forward without the cabinet pushing back, you would fall forward in the same way you do if someone suddenly opens a door you're leaning against.) Your chair pushes upward on you (the normal force that keeps you from falling) while, at the same time, you push down on the chair, compressing the cushion. These are examples of what we call an *interaction*. An **interaction** is the mutual influence of two objects on each other.

These examples illustrate a key aspect of interactions: The forces involved in an interaction between two objects always occur as a *pair.* To be more specific, if object A exerts a force $\vec{F}_{\text{A on B}}$ on object B, then object B exerts a force $\vec{F}_{\text{B on A}}$ on object A. This pair of forces, shown in **FIGURE 4.29**, is called an **action/reaction pair.** Two objects interact by exerting an action/reaction pair of forces on each other. Notice the very explicit subscripts on the force vectors. The first letter is the *agent*—the source of the force—and the second letter is the *object* on which the force acts. $\vec{F}_{\text{A on B}}$ is thus the force exerted *by* A *on* B.

NOTE ► The name "action/reaction pair" is somewhat misleading. The forces occur simultaneously, and we cannot say which is the "action" and which the "reaction." Neither is there any implication about cause and effect; the action does not cause the reaction. **An action/reaction pair of forces exists as a pair, or not at all.** For action/reaction pairs, the labels are the key: Force $\vec{F}_{\text{A on B}}$ is paired with force $\vec{F}_{\text{B on A}}$. ◄

FIGURE 4.29 An action/reaction pair of forces.



Reasoning with Newton's Third Law

We've discovered that two objects always interact via an action/reaction pair of forces. Newton was the first to recognize how the two members of an action/reaction pair of forces are related to each other. Today we know this as Newton's third law:

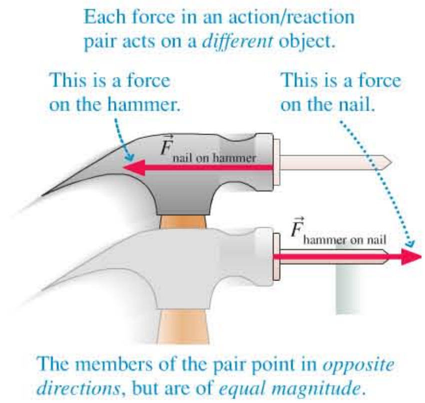
> **Newton's third law** Every force occurs as one member of an action/reaction pair of forces.
>
> - The two members of an action/reaction pair act on two *different* objects.
> - The two members of an action/reaction pair point in *opposite* directions and are *equal in magnitude.*

Newton's third law is often stated: "For every action there is an equal but opposite reaction." While this is a catchy phrase, it lacks the preciseness of our preferred version. In particular, it fails to capture an essential feature of the two members of an action/reaction pair—that each acts on a *different* object. This is shown in **FIGURE 4.30**, where a hammer hitting a nail exerts a force $\vec{F}_{\text{hammer on nail}}$ on the nail; by the third law, the nail must exert a force $\vec{F}_{\text{nail on hammer}}$ to complete the action/reaction pair.

Figure 4.30 also illustrates that these two forces point in *opposite directions.* This feature of the third law is also in accord with our experience. If the hammer hits the nail with a force directed to the right, the force of the nail on the hammer is directed to the left; if the force of my chair on me pushes up, the force of me on the chair pushes down.

Finally, Figure 4.30 shows that, according to Newton's third law, the two members of an action/reaction pair have *equal* magnitudes, so that $F_{\text{hammer on nail}} = F_{\text{nail on hammer}}$. This is something new, and it is by no means obvious. Indeed, this statement causes students the most trouble when applying the third law because it seems so counter to our intuition, as the following example shows.

FIGURE 4.30 Newton's third law.



Revenge of the target We normally think of the damage that the force of a bullet inflicts on its target. But according to Newton's third law, the target exerts an equal force on the bullet. The photo shows the damage sustained by bullets fired at 1600, 1800, and 2000 ft/s, after impacting a test target. The appearance of the bullet before firing is shown at the left.

CONCEPTUAL EXAMPLE 4.10 The bug versus the windshield

During the collision between a bug and the windshield of a fast-moving truck, which force has greater magnitude: the force of the windshield on the bug or the force of the bug on the windshield?

REASON The third law tells us that the magnitude of the force of the windshield on the bug must be *equal* to that of the bug on the windshield! How can this be, when the bug is so small compared to the truck? The source of puzzlement in problems like this is that Newton's third law equates the size of the *forces* acting on the two objects, not their *accelerations*. The acceleration of each object depends not only on the force applied to it, but also, according to Newton's second law, on its mass. The bug and the truck do in fact feel forces of equal strength from the other, but the bug, with its very small mass, undergoes an extreme acceleration from this force while the acceleration of the heavy truck is negligible.

ASSESS It is important to separate the *effects* of the forces (the accelerations) from the causes (the forces themselves). Because two interacting objects can have very different masses, their accelerations can be very different even though the interaction forces are of the same strength.

FIGURE 4.31 Examples of propulsion.

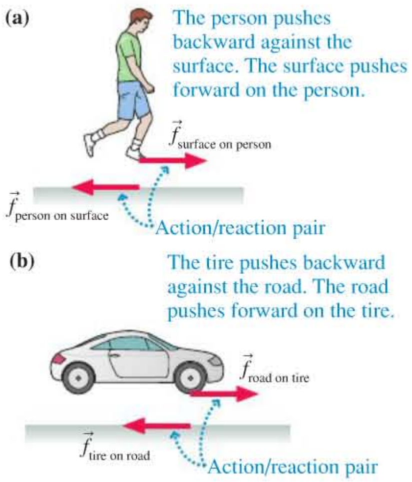


FIGURE 4.32 When the driver hits the gas, the force of the track on the tire is so great that the tire deforms.

You can *see* that the force of the road on the tire points forward by the way it twists the rubber of the tire.

We'll return to Newton's third law in Chapter 5, where we'll use it to solve problems involving two or more interacting objects.

Propulsion

A sprinter accelerates out of the blocks. Because he's accelerating, there must be a force on him in the forward direction. For a system with an internal source of energy, a force that drives the system is a force of **propulsion**. Propulsion is an important feature not only of walking or running but also of the forward motion of cars, jets, and rockets. Propulsion is somewhat counterintuitive, so it is worth a closer look.

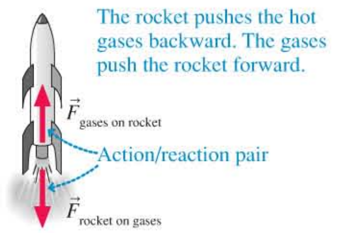
If you tried to walk across a frictionless floor, your foot would slip and slide *backward*. In order for you to walk, the floor needs to have friction so that your foot *sticks* to the floor as you straighten your leg, moving your body forward. The friction that prevents slipping is *static* friction. Static friction, you will recall, acts in the direction that prevents slipping, so the static friction force $\vec{f}_{\text{SonP}}$ (for Surface on Person) has to point in the *forward* direction to prevent your foot from slipping backward. As shown in **FIGURE 4.31a**, it is this forward-directed static friction force that propels you forward! The force of your foot on the floor, $\vec{f}_{\text{PonS}}$, is the other half of the action/reaction pair, and it points in the opposite direction as you push backward against the floor.

Similarly, the car in **FIGURE 4.31b** uses static friction to propel itself. The car uses its motor to turn the tires, causing the tires to push backward against the road ($\vec{f}_{\text{tire on road}}$). The road surface responds by pushing the car forward ($\vec{f}_{\text{road on tire}}$). This force of the road on the tire can be seen in photos of drag racers, where the forces are very great (**FIGURE 4.32**). Again, the forces involved are *static* friction forces. The tire is rolling, but the bottom of the tire, where it contacts the road, is instantaneously at rest. If it weren't, you would leave one giant skid mark as you drove and would burn off the tread within a few miles.

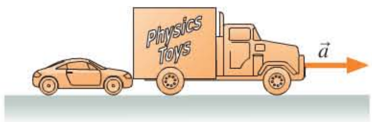
Rocket motors are somewhat different because they are not pushing *against* anything external. That's why rocket propulsion works in the vacuum of space. Instead, the rocket engine pushes hot, expanding gases out of the back of the rocket, as shown in **FIGURE 4.33**. In response, the exhaust gases push the rocket forward with the force we've called *thrust*.

Now we've assembled all the pieces we need in order to start solving problems in dynamics. We have seen what forces are and how to identify them, and we've learned how forces cause objects to accelerate according to Newton's second law. We've also found how Newton's third law governs the interaction forces between two objects. Our goal in the next several chapters is to apply Newton's laws to a variety of problems involving straight-line and circular motion.

FIGURE 4.33 Rocket propulsion.



STOP TO THINK 4.6 A small car is pushing a larger truck that has a dead battery. The mass of the truck is greater than the mass of the car. Which of the following statements is true?



A. The car exerts a force on the truck, but the truck doesn't exert a force on the car.
B. The car exerts a larger force on the truck than the truck exerts on the car.
C. The car exerts the same amount of force on the truck as the truck exerts on the car.
D. The truck exerts a larger force on the car than the car exerts on the truck.
E. The truck exerts a force on the car, but the car doesn't exert a force on the truck.

INTEGRATED EXAMPLE 4.11 Pulling an excursion train

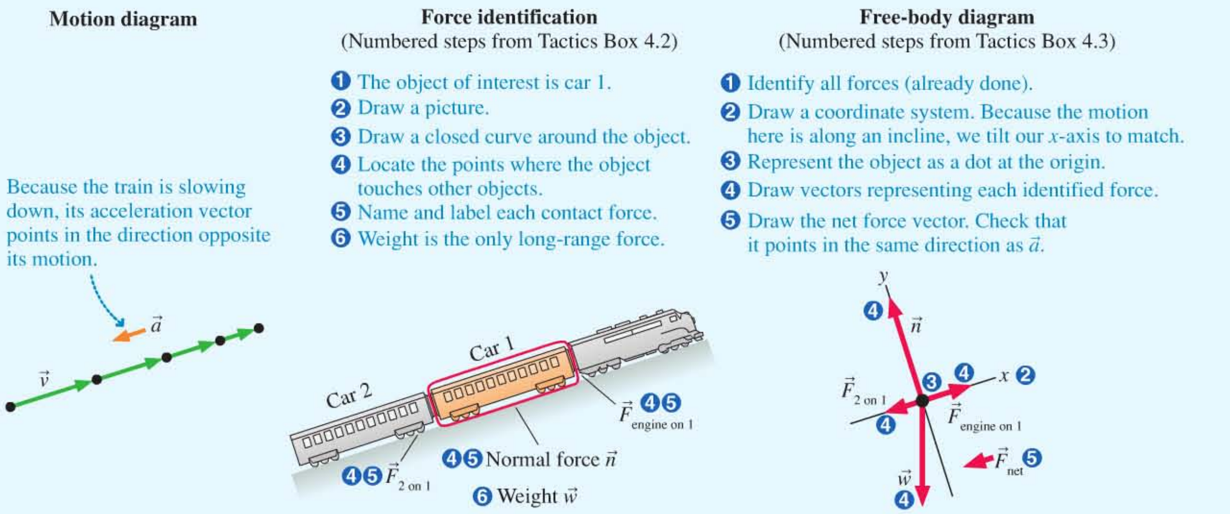
An engine slows as it pulls two cars of an excursion train up a mountain. Draw a visual overview (motion diagram, a force identification diagram, and free-body diagram) for the car just behind the engine. Ignore friction.

PREPARE Because the train is slowing down, the motion diagram consists of a series of particle positions that become closer together at successive times; the corresponding velocity vectors become shorter and shorter. To identify the forces acting on the car we use the steps of Tactics Box 4.2. Finally, we can draw a free-body diagram using Tactics Box 4.3.

SOLVE Finding the forces acting on car 1 can be tricky. The engine exerts a forward force $\vec{F}_{\text{engine on 1}}$ on car 1 where the engine touches the front of car 1. At its back, car 1 touches car 2, so car 2 must also exert a force on car 1. The direction of this force can be understood from Newton's third law. Car 1 exerts an uphill force on car 2 in order to pull it up the mountain. Thus, by Newton's third law, car 2 must exert an oppositely directed *downhill* force on car 1. This is the force we label $\vec{F}_{\text{2 on 1}}$. The three diagrams that make up the full visual overview are shown in **FIGURE 4.34**.

ASSESS Correctly preparing the three diagrams illustrated in this example is critical for solving problems using Newton's laws. The motion diagram allows you to determine the direction of the acceleration and hence of $\vec{F}_{\text{net}}$. Using the force identification diagram, you will correctly identify all the forces acting on the object and, just as important, not add any extraneous forces. And by properly drawing these force vectors in a free-body diagram, you'll be ready for the quantitative application of Newton's laws that is the focus of Chapter 5.

FIGURE 4.34 Visual overview for a slowing train car being pulled up a mountain.



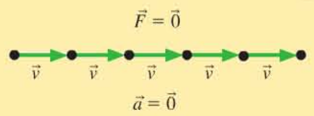
SUMMARY

The goal of Chapter 4 has been to establish a connection between force and motion.

GENERAL PRINCIPLES

Newton's First Law

Consider an object with no force acting on it. If it is at rest, it will remain at rest. If it is in motion, then it will continue to move in a straight line at a constant speed.



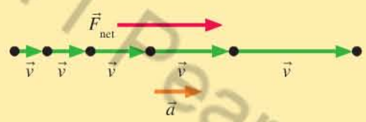
The first law tells us that no "cause" is needed for motion. Uniform motion is the "natural state" of an object.

Newton's Second Law

An object with mass m will undergo acceleration

$$\vec{a} = \frac{\vec{F}_{\text{net}}}{m}$$

where the net force $\vec{F}_{\text{net}} = \vec{F}_1 + \vec{F}_2 + \vec{F}_3 + \cdots$ is the vector sum of all the individual forces acting on the object.



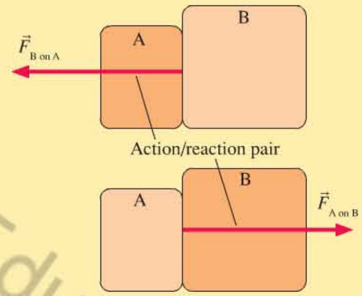
The second law tells us that a net force causes an object to accelerate. This is the connection between force and motion. The acceleration points in the direction of $\vec{F}_{\text{net}}$.

Newton's Third Law

Every force occurs as one member of an **action/reaction** pair of forces. The two members of an action/reaction pair:

- act on two *different* objects.
- point in opposite directions and are equal in magnitude:

$$\vec{F}_{\text{A on B}} = -\vec{F}_{\text{B on A}}$$



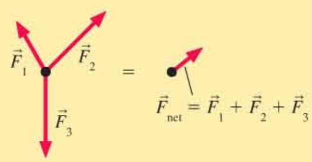
IMPORTANT CONCEPTS

Force is a push or pull on an object.

- Force is a vector, with a magnitude and a direction.
- A force requires an agent.
- A force is either a contact force or a long-range force.

The SI unit of force is the **newton** (N). A 1 N force will cause a 1 kg mass to accelerate at 1 m/s^2.

Net force is the vector sum of all the forces acting on an object.



Mass is the property of an object that determines its resistance to acceleration.

If the same force is applied to objects A and B, then the ratio of their accelerations is related to the ratio of their masses as

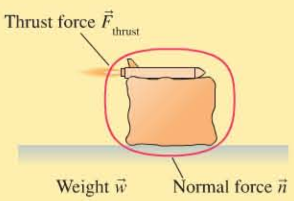
$$\frac{a_{\text{A}}}{a_{\text{B}}} = \frac{m_{\text{B}}}{m_{\text{A}}}$$

The mass of objects can be determined in terms of their accelerations.

APPLICATIONS

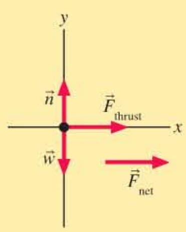
Identifying Forces

Forces are identified by locating the points where other objects touch the object of interest. These are points where contact forces are exerted. In addition, objects feel a long-range weight force.



Free-Body Diagrams

A free-body diagram represents the object as a particle at the origin of a coordinate system. Force vectors are drawn with their tails on the particle. The net force vector is drawn beside the diagram.



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Problems labeled INT integrate significant material from earlier chapters; BIO are of biological or medical interest.

Problem difficulty is labeled as | (straightforward) to ||||| (challenging).

VIEW ALL SOLUTIONS

QUESTIONS

Conceptual Questions

1. A hockey puck slides along the surface of the ice. If friction and air resistance are negligible, what force is required to keep the puck moving?
2. If an object is not moving, does that mean that there are no forces acting on it? Explain.
3. An object moves in a straight line at a constant speed. Is it true that there must be no forces of any kind acting on this object? Explain.
4. A ball sits near the front of a child's wagon. As she pulls on the wagon and it begins to move forward, the ball rolls toward the back of the wagon. Explain why the ball rolls in this direction.
5. If you know all of the forces acting on a moving object, can you tell in which direction the object is moving? If the answer is Yes, explain how. If the answer is No, give an example.
6. Three arrows are shot horizontally. They have left the bow and are traveling parallel to the ground as shown in Figure Q4.6. Air resistance is negligible. Rank in order, from largest to smallest, the magnitudes of the *horizontal* forces F_1, F_2, and F_3 acting on the arrows. Some may be equal. State your reasoning.

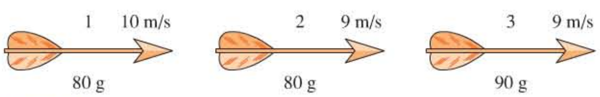


FIGURE Q4.6

7. A carpenter wishes to tighten the heavy head of his hammer onto its light handle. Which method shown in Figure Q4.7 will better tighten the head? Explain.

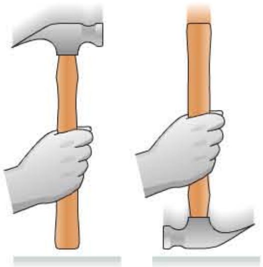


FIGURE Q4.7

8. BIO Internal injuries in vehicular accidents may be due to what is called the "third collision." The first collision is the vehicle hitting the external object. The second collision is the person hitting something on the inside of the car, such as the dashboard or windshield. This may cause external lacerations. The third collision, possibly the most damaging to the body, is when organs, such as the heart or brain, hit the ribcage, skull, or other confines of the body, bruising the tissues on the leading edge and tearing the organ from its supporting structures on the trailing edge.
   a. Why is there a third collision? In other words, why are the organs still moving after the second collision?
   b. If the vehicle was traveling at 60 mph before the first collision, would the organs be traveling more than, equal to, or less than 60 mph just before the third collision?
9. a. Give an example of the motion of an object in which the frictional force on the object is directed opposite to the motion.
   b. Give an example of the motion of an object in which the frictional force on the object is in the same direction as the motion.
10. Suppose you are an astronaut in deep space, far from any source of gravity. You have two objects that look identical, but one has a large mass and the other a small mass. How can you tell the difference between the two?
11. Jonathan accelerates away from a stop sign. His eight-year-old daughter sits in the passenger seat. On whom does the back of the seat exert a greater force?
12. The weight of a box sitting on the floor points directly down. The normal force of the floor on the box points directly up. Need these two forces have the same magnitude? Explain.
13. A ball weighs 2.0 N when placed on a scale. It is then thrown straight up. What is its weight at the very top of its motion? Explain.
14. Josh and Taylor, standing face-to-face on frictionless ice, push off each other, causing each to slide backward. Josh is much bigger than Taylor. After the push, which of the two is moving faster?
15. A person sits on a sloped hillside. Is it ever possible to have the static friction force on this person point down the hill? Explain.
16. BIO Walking without slipping requires a static friction force between your feet (or footwear) and the floor. As described in this chapter, the force on your foot as you push off the floor is forward while the force exerted by your foot on the floor is backward. But what about your *other* foot, the one moved during a stride? What is the direction of the force on that foot as it comes into contact with the floor? Explain.
17. Figure 4.31b showed a situation in which the force of the road on the car's tire points forward. In other situations, the force points backward. Give an example of such a situation.
18. Alyssa pushes to the right on a filing cabinet; the friction force from the floor pushes on it to the left. Because the cabinet doesn't move, these forces have the same magnitude. Do they form an action/reaction pair? Explain.
19. A very smart three-year-old child is given a wagon for her birthday. She refuses to use it. "After all," she says, "Newton's third law says that no matter how hard I pull, the wagon will exert an equal but opposite force on me. So I will never be able to get it to move forward." What would you say to her in reply?
20. Will hanging a magnet in front of an iron cart, as shown in Figure Q4.20, make it go? Explain why or why not.

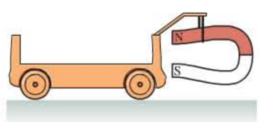


FIGURE Q4.20

Multiple-Choice Questions

21. | Figure Q4.21 shows the view looking down onto a frictionless sheet of ice. A puck, tied with a string to point P, slides on the surface of the ice in the circular path shown. If the string suddenly snaps when the puck is in the position shown, which path best represents the puck's subsequent motion?

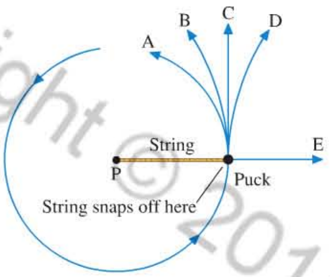


FIGURE Q4.21

22. | A block has acceleration a when pulled by a string. If two identical blocks are glued together and pulled with twice the original force, their acceleration will be
   A. $(1/4)a$
   B. $(1/2)a$
   C. a
   D. $2a$
   E. $4a$
23. | A 5.0 kg block has an acceleration of 0.20 m/s^2 when a force is exerted on it. A second block has an acceleration of 0.10 m/s^2 when subject to the same force. What is the mass of the second block?
   A. 10 kg
   B. 5.0 kg
   C. 2.5 kg
   D. 7.5 kg
24. | Tennis balls experience a large drag force. A tennis ball is hit so that it goes straight up and then comes back down. The direction of the drag force is
   A. Always up.
   B. Up and then down.
   C. Always down.
   D. Down and then up.
25. | A person gives a box a shove so that it slides up a ramp, then reverses its motion and slides down. The direction of the force of friction is
   A. Always down the ramp.
   B. Up the ramp and then down the ramp.
   C. Always down the ramp.
   D. Down the ramp and then up the ramp.
26. | A person is pushing horizontally on a box with a constant force, causing it to slide across the floor with a constant speed. If the person suddenly stops pushing on the box, the box will
   A. Immediately come to a stop.
   B. Continue moving at a constant speed for a while, then gradually slow down to a stop.
   C. Immediately change to a slower but constant speed.
   D. Immediately begin slowing down and eventually stop.
27. | Rachel is pushing a box across the floor while Jon, at the same time, is hoping to stop the box by pushing in the opposite direction. There is friction between the box and floor. If the box is moving at constant speed, then the magnitude of Rachel's pushing force is
   A. Greater than the magnitude of Jon's force.
   B. Equal to the magnitude of Jon's force.
   C. Less than the magnitude of Jon's force.
   D. The question can't be answered without knowing how large the friction force is.
28. || Dave pushes his four-year-old son Thomas across the snow on a sled. As Dave pushes, Thomas speeds up. Which statement is true?
   A. The force of Dave on Thomas is larger than the force of Thomas on Dave.
   B. The force of Thomas on Dave is larger than the force of Dave on Thomas.
   C. Both forces have the same magnitude.
   D. It depends on how hard Dave pushes on Thomas.
29. | Figure Q4.29 shows block A sitting on top of block B. A constant force $\vec{F}$ is exerted on block B, causing block B to accelerate to the right. Block A rides on block B without slipping. Which statement is true?
   A. Block B exerts a friction force on block A, directed to the left.
   B. Block B exerts a friction force on block A, directed to the right.
   C. Block B does not exert a friction force on block A.

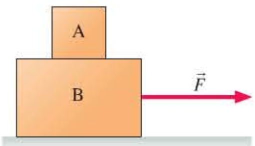


FIGURE Q4.29

VIEW ALL SOLUTIONS

PROBLEMS

Section 4.1 What Causes Motion?

1. | Whiplash injuries during an automobile accident are caused
BIO by the inertia of the head. If someone is wearing a seatbelt, her body will tend to move with the car seat. However, her head is free to move until the neck restrains it, causing damage to the neck. Brain damage can also occur.

   Figure P4.1 shows two sequences of head and neck motion for a passenger in an auto accident. One corresponds to a head-on collision, the other to a rear-end collision. Which is which? Explain.

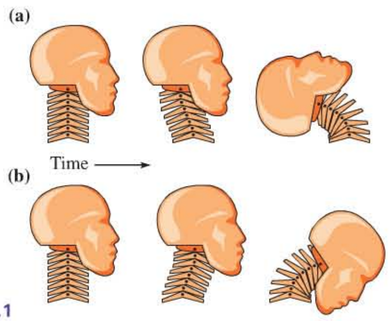


FIGURE P4.1

2. An automobile has a head-on collision. A passenger in the car experiences a compression injury to the brain. Is this injury most likely to be in the front or rear portion of the brain? Explain.
BIO

3. In a head-on collision, an infant is much safer in a child safety seat when the seat is installed facing the rear of the car. Explain.

Section 4.2 Force

Problems 4 through 6 show two forces acting on an object at rest. Redraw the diagram, then add a third force that will allow the object to remain at rest. Label the new force $\vec{F}_3$.

4.

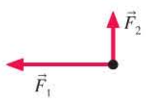


FIGURE P4.4

5.

FIGURE P4.5

6.

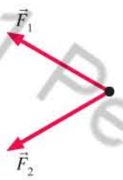


FIGURE P4.6

Section 4.3 A Short Catalog of Forces

Section 4.4 Identifying Forces

7. A mountain climber is hanging from a rope in the middle of a crevasse. The rope is vertical. Identify the forces on the mountain climber.
8. A circus clown hangs from one end of a large spring. The other end is anchored to the ceiling. Identify the forces on the clown.
9. A baseball player is sliding into second base. Identify the forces on the baseball player.
10. A jet plane is speeding down the runway during takeoff. Air resistance is not negligible. Identify the forces on the jet.
11. A skier is sliding down a 15° slope. Friction is not negligible. Identify the forces on the skier.
12. A tennis ball is flying horizontally across the net. Air resistance is not negligible. Identify the forces on the ball.

Section 4.5 What Do Forces Do?

13. Figure P4.13 shows an acceleration-versus-force graph for three objects pulled by rubber bands. The mass of object 2 is 0.20 kg. What are the masses of objects 1 and 3? Explain your reasoning.

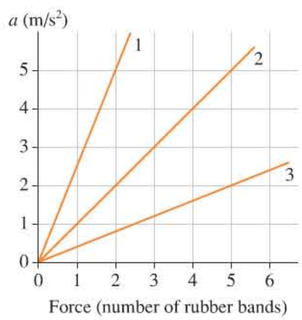


FIGURE P4.13

14. A constant force applied to object A causes it to accelerate at 5 m/s^2. The same force applied to object B causes an acceleration of 3 m/s^2. Applied to object C, it causes an acceleration of 8 m/s^2.
    a. Which object has the largest mass?
    b. Which object has the smallest mass?
    c. What is the ratio of mass A to mass B (m_A/m_B)?
15. Two rubber bands pulling on an object cause it to accelerate at 1.2 m/s^2.
    a. What will be the object's acceleration if it is pulled by four rubber bands?
    b. What will be the acceleration of two of these objects glued together if they are pulled by two rubber bands?
16. A constant force is applied to an object, causing the object to accelerate at 10 m/s^2. What will the acceleration be if
    a. The force is halved?
    b. The object's mass is halved?
    c. The force and the object's mass are both halved?
    d. The force is halved and the object's mass is doubled?
17. A constant force is applied to an object, causing the object to accelerate at 8.0 m/s^2. What will the acceleration be if
    a. The force is doubled?
    b. The object's mass is doubled?
    c. The force and the object's mass are both doubled?
    d. The force is doubled and the object's mass is halved?
18. A man pulling an empty wagon causes it to accelerate at 1.4 m/s^2. What will the acceleration be if he pulls with the same force when the wagon contains a child whose mass is three times that of the wagon?
19. A car has a maximum acceleration of 5.0 m/s^2. What will the maximum acceleration be if the car is towing another car of the same mass?

Section 4.6 Newton's Second Law

20. Figure P4.20 shows an acceleration-versus-force graph for a 500 g object. Redraw this graph and add appropriate acceleration values on the vertical scale.

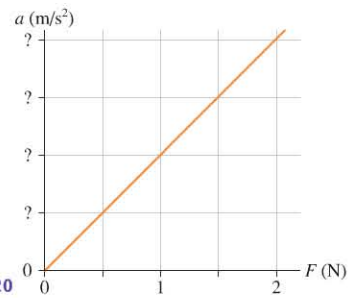


FIGURE P4.20

21. Figure P4.21 shows an object's acceleration-versus-force graph. What is the object's mass?

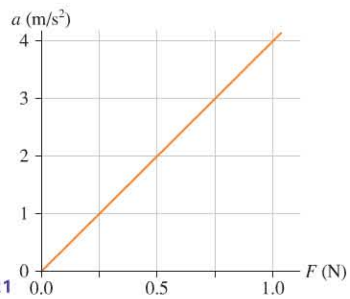


FIGURE P4.21

22. ‖ Two children fight over a 200 g stuffed bear. The 25 kg boy pulls to the right with a 15 N force and the 20 kg girl pulls to the left with a 17 N force. Ignore all other forces on the bear (such as its weight).
   a. At this instant, can you say what the velocity of the bear is? If so, what are the magnitude and direction of the velocity?
   b. At this instant, can you say what the acceleration of the bear is? If so, what are the magnitude and direction of the acceleration?

23. ‖ A 1500 kg car is traveling along a straight road at 20 m/s. INT Two seconds later its speed is 21 m/s. What is the magnitude of the net force acting on the car during this time?

24. ‖ Very small forces can have tremendous effects on the motion of very small objects. Consider a single electron, with a mass of 9.1×10^{-31} kg, subject to a single force equal to the weight of a penny, 2.5×10^{-2} N. What is the acceleration of the electron?

25. ‖ The motion of a very massive object is hardly affected by what would seem to be a substantial force. Consider a supertanker, with a mass of 3.0×10^{8} kg. If it is pushed by a rocket motor (see Table 4.2) and is subject to no other forces, what will be the magnitude of its acceleration?

Section 4.7 Free-Body Diagrams

Problems 26 through 28 show a free-body diagram. For each, (a) Redraw the free-body diagram and (b) Write a short description of a real object for which this is the correct free-body diagram. Use Examples 4.3, 4.4, and 4.5 as models of what a description should be like.

26. |

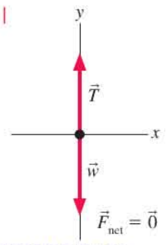


FIGURE P4.26

27. |

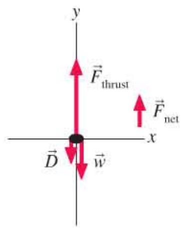


FIGURE P4.27

28. |

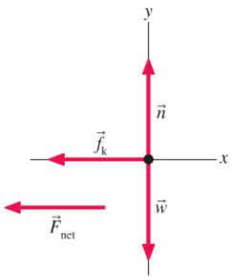


FIGURE P4.28

Problems 29 through 35 describe a situation. For each, identify all forces acting on the object and draw a free-body diagram of the object.

29. ‖ Your car is sitting in the parking lot.
30. ‖ Your car is accelerating from a stop.
31. ‖ Your car is slowing to a stop from a high speed.
32. ‖ Your physics textbook is sliding across the table.
33. ‖ An ascending elevator, hanging from a cable, is coming to a stop.
34. ‖ A skier slides down a slope at a constant speed.
35. ‖| You hold a picture motionless against a wall by pressing on it, as shown in Figure P4.35.

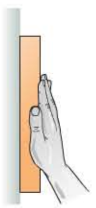


FIGURE P4.35

Section 4.8 Newton's Third Law

36. ‖ A weightlifter stands up from a squatting position while holding a heavy barbell across his shoulders. Identify all the action/reaction pairs of forces between the weight lifter and the barbell.

37. ‖ Three ice skaters, numbered 1, 2, and 3, stand in a line, each with her hands on the shoulders of the skater in front. Skater 3, at the rear, pushes on skater 2. Identify all the action/reaction pairs of forces between the three skaters. Draw a free-body diagram for skater 2, in the middle. Assume the ice is frictionless.

38. | A girl stands on a sofa. Identify all the action/reaction pairs of forces between the girl and the sofa.

General Problems

39. | Redraw the motion diagram INT shown in Figure P4.39, then draw a vector beside it to show the direction of the net force acting on the object. Explain your reasoning.

40. | Redraw the motion diagram INT shown in Figure P4.40, then draw a vector beside it to show the direction of the net force acting on the object. Explain your reasoning.

FIGURE P4.39

FIGURE P4.40

41. | Redraw the motion diagram INT shown in Figure P4.41, then draw a vector beside it to show the direction of the net force acting on the object. Explain your reasoning.

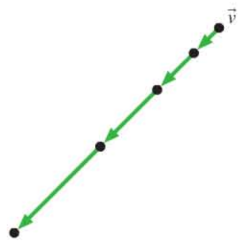


FIGURE P4.41

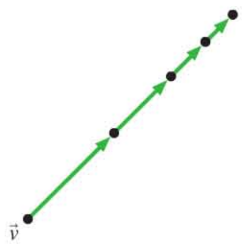


FIGURE P4.42

42. | Redraw the motion diagram shown in Figure P4.42, then INT draw a vector beside it to show the direction of the net force acting on the object. Explain your reasoning.

Problems 43 through 49 show a free-body diagram. For each:

a. Redraw the diagram.
b. Identify the direction of the acceleration vector $\vec{a}$ and show it as a vector next to your diagram. Or, if appropriate, write $\vec{a} = \vec{0}$.
c. Write a short description of a real object for which this is the correct free-body diagram. Use Examples 4.7, 4.8, and 4.9 as models of what a description should be like.

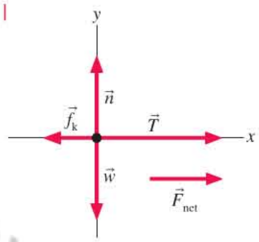
43. | 

FIGURE P4.43

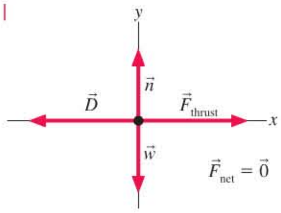
44. | 

FIGURE P4.44

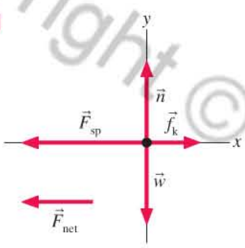
45. | 

FIGURE P4.45

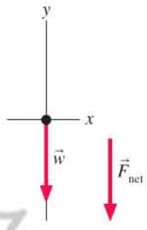
46. | 

FIGURE P4.46

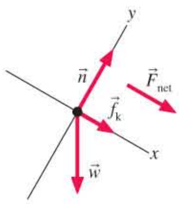
47. | 

FIGURE P4.47

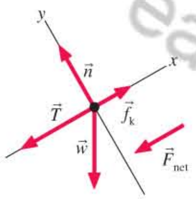
48. | 

FIGURE P4.48

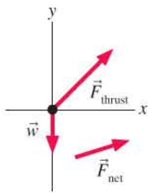
49. | 

FIGURE P4.49

50. |||| A student draws the flawed free-body diagram shown in Figure P4.50 to represent the forces acting on a car traveling at constant speed on a level road. Identify the errors in the diagram, then draw a correct free-body diagram for this situation.

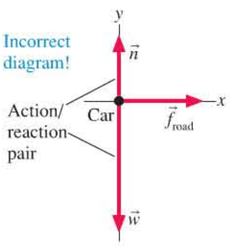


FIGURE P4.50

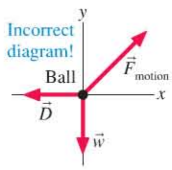


FIGURE P4.51

51. ||| A student draws the flawed free-body diagram shown in Figure P4.51 to represent the forces acting on a golf ball that is traveling upward and to the right a very short time after being hit off the tee. Air resistance is assumed to be relevant. Identify the errors in the diagram, then draw a correct free-body diagram for this situation.

Problems 52 through 63 describe a situation. For each, draw a motion diagram, a force identification diagram, and a free-body diagram.

52. || An elevator, suspended by a single cable, has just left the tenth floor and is speeding up as it descends toward the ground floor.
53. ||| A rocket is being launched straight up. Air resistance is not negligible.
54. ||| A jet plane is speeding down the runway during takeoff. Air resistance is not negligible.
55. || You've slammed on the brakes and your car is skidding to a stop while going down a 20° hill.
56. || A skier is going down a 20° slope. A *horizontal* headwind is blowing in the skier's face. Friction is small, but not zero.
57. || A bale of hay sits on the bed of a trailer. The trailer is starting to accelerate forward, and the bale is slipping toward the back of the trailer.
58. || A Styrofoam ball has just been shot straight up. Air resistance is not negligible.
59. ||| A spring-loaded gun shoots a plastic ball. The trigger has just been pulled and the ball is starting to move down the barrel. The barrel is horizontal.
60. || A person on a bridge throws a rock straight down toward the water. The rock has just been released.
61. ||| A gymnast has just landed on a trampoline. She's still moving downward as the trampoline stretches.
62. ||| A heavy box is in the back of a truck. The truck is accelerating to the right. Apply your analysis to the box.
63. || A bag of groceries is on the back seat of your car as you stop for a stop light. The bag does not slide. Apply your analysis to the bag.
64. || A rubber ball bounces. We'd like to understand *how* the ball bounces.
    a. A rubber ball has been dropped and is bouncing off the floor. Draw a motion diagram of the ball during the brief time interval that it is in contact with the floor. Show 4 or 5 frames as the ball compresses, then another 4 or 5 frames as it expands. What is the direction of $\vec{a}$ during each of these parts of the motion?
    b. Draw a picture of the ball in contact with the floor and identify all forces acting on the ball.
    c. Draw a free-body diagram of the ball during its contact with the ground. Is there a net force acting on the ball? If so, in which direction?
    d. During contact, is the force of the ground on the ball larger, smaller, or equal to the weight of the ball? Use your answers to parts a–c to explain your reasoning.
65. || If a car stops suddenly, you feel "thrown forward." We'd like to understand what happens to the passengers as a car stops. Imagine yourself sitting on a *very* slippery bench inside a car. This bench has no friction, no seat back, and there's nothing for you to hold on to.
    a. Draw a picture and identify all of the forces acting on you as the car travels in a straight line at a perfectly steady speed on level ground.
    b. Draw your free-body diagram. Is there a net force on you? If so, in which direction?
    c. Repeat parts a and b with the car slowing down.
    d. Describe what happens to you as the car slows down.
    e. Use Newton's laws to explain why you seem to be "thrown forward" as the car stops. Is there really a force pushing you forward?

66. BIO The fastest pitched baseball was clocked at 46 m/s. If the pitcher exerted his force (assumed to be horizontal and constant) over a distance of 1.0 m, and a baseball has a mass of 145 g,
   a. Draw a free-body diagram of the ball during the pitch.
   b. What force did the pitcher exert on the ball during this record-setting pitch?
   c. Estimate the force in part b as a fraction of the pitcher's weight.

67. BIO The froghopper, champion leaper of the insect world, can jump straight up at 4.0 m/s. The jump itself lasts a mere 1.0 ms before the insect is clear of the ground.
   a. Draw a free-body diagram of this mighty leaper while the jump is taking place.
   b. While the jump is taking place, is the force that the ground exerts on the froghopper greater than, less than, or equal to the insect's weight? Explain.

68. A beach ball is thrown straight up, and some time later it lands on the sand. Is the magnitude of the net force on the ball greatest when it is going up or when it is on the way down? Or is it the same in both cases? Explain. Air resistance should not be neglected for a large, light object.

Passage Problems

A Simple Solution for a Stuck Car

If your car is stuck in the mud and you don't have a winch to pull it out, you can use a piece of rope and a tree to do the trick. First, you tie one end of the rope to your car and the other to a tree, then pull as hard as you can on the middle of the rope, as shown in Figure P4.69a. This technique applies a force to the car much larger than the force that you can apply directly. To see why the car experiences such a large force, look at the forces acting on the center point of the rope, as shown in Figure P4.69b. The sum of the forces is zero, thus the tension is much greater than the force you apply. It is this tension force that acts on the car and, with luck, pulls it free.

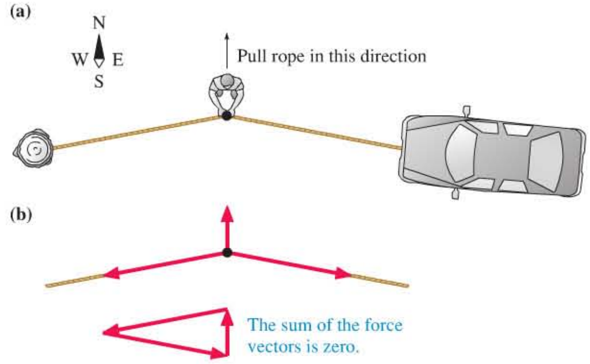


FIGURE P4.69

69. The sum of the three forces acting on the center point of the rope is assumed to be zero because
   A. This point has a very small mass.
   B. Tension forces in a rope always cancel.
   C. This point is not accelerating.
   D. The angle of deflection is very small.

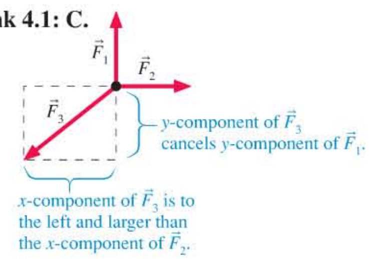
70. When you are pulling on the rope as shown, what is the approximate direction of the tension force on the tree?
   A. North B. South C. East D. West

71. Assume that you are pulling on the rope but the car is not moving. What is the approximate direction of the force of the mud on the car?
   A. North B. South C. East D. West

72. Suppose your efforts work, and the car begins to move forward out of the mud. As it does so, the force of the car on the rope is
   A. Zero.
   B. Less than the force of the rope on the car.
   C. Equal to the force of the rope on the car.
   D. Greater than the force of the rope on the car.

STOP TO THINK ANSWERS

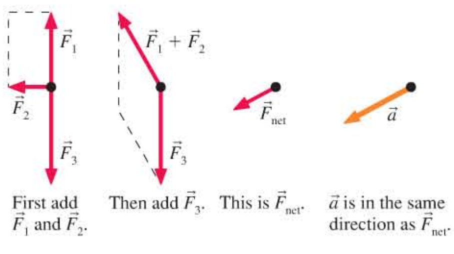
Stop to Think 4.1: C.



Stop to Think 4.2: A, B, and D. Friction and the normal force are the only contact forces. Nothing is touching the rock to provide a "force of the kick." We've agreed to ignore air resistance unless a problem specifically calls for it.

Stop to Think 4.3: B. Acceleration is proportional to force, so doubling the number of rubber bands doubles the acceleration of the original object from 2 m/s^2 to 4 m/s^2. But acceleration is also inversely proportional to mass. Doubling the mass cuts the acceleration in half, back to 2 m/s^2.

Stop to Think 4.4: D



Stop to Think 4.5: C. The acceleration vector points downward as the elevator slows. $\vec{F}_{net}$ points in the same direction as $\vec{a}$, so $\vec{F}_{net}$ also points downward. This will be true if the tension is less than the weight: $T < w$.

Stop to Think 4.6: C. Newton's third law says that the force of A on B is *equal* and opposite to the force of B on A. This is always true. The mass of the objects isn't relevant.