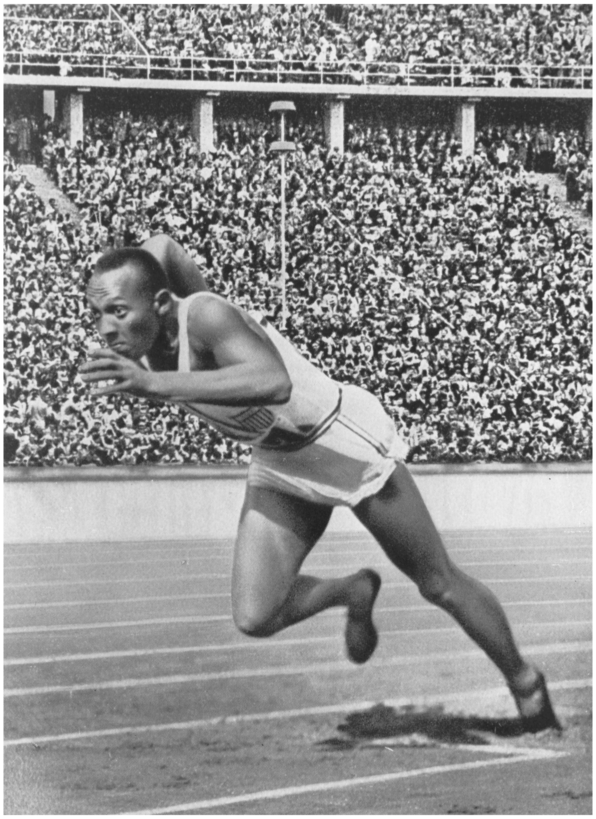

A 100-meter sprint is a good example of one-dimensional motion, but what is it that gets a sprinter moving in the first place? That's what we'll investigate in this chapter.

Photo credit: a photo of the American runner Jesse Owens at the Berlin Olympic Games in 1936, from Wikimedia Commons.

# Chapter 3 – Forces and Newton's Laws

**CHAPTER CONTENTS**



In Chapter 2, we talked about how things move, at least in one dimension. In this chapter, we'll begin talking about why things move. The explanation for why an object moves (or why it doesn't move, if it remains at rest) revolves around the force or forces that the object experiences, so we will spend some time discussing what forces are.

Sir Isaac Newton made several key contributions to our understanding of forces. For instance, some of the basic rules about forces are summarized by Newton's laws of motion, so we will devote some time to understanding what these laws are all about and how they are applied in various situations. A key contribution of Newton's, however, is the understanding that the same laws that govern how soccer balls and cars move here on Earth also determine how planets move around the Sun and how stars interact with one another within galaxies. Prior to Newton, most people thought of the heavens and the Earth as being completely separate – we now know that the laws of physics apply to objects in the heavens just as well as they apply here on Earth. Thus, although our discussions in this chapter concern everyday objects, remember that the conclusions can be applied much more generally.

## *3-1 Making Things Move*

Let's say a pen is lying on the desk in front of you, at rest. How could you make the pen move? There are many things you could do, such as:

- Pushing the pen with your hand.
- Picking the pen up and then dropping it.
- Tilting the desk, or the desktop, so the pen slides.

In all these cases, you are either directly applying a force to the pen or you are setting up a situation where something else applies an unbalanced force to the pen. What is a force?

> ***A force is simply a push or a pull.*** A force is a vector, so it has a direction. The SI unit of force is the newton (N). 1 N = 1 kg m/s$^2$.
>
> In addition, ***a force represents an interaction between objects***. For instance, the Earth exerts a force on the pen and the pen exerts a force on the Earth. Each object involved in an interaction experiences a force.

***Question***: Can an inanimate object like a pen or a desk exert a force? If so, describe how it is possible for inanimate objects to exert forces.

***Answer***: Yes, inanimate objects can exert forces. For instance, if you stand on a trampoline, the trampoline deforms under your weight (see Figure 3.1), and the trampoline exerts an upward force on you to prevent you from falling through it. The forces between atoms and molecules are much like the springs and stretchy material that make up a trampoline, so when a pen is on a desk both the pen and the desk are deformed a little (see Figure 3.2). The deformation is too small for you to observe easily, but the forces associated with it prevent the pen from falling through the desk.

**Figure 3.1**: Note how the surface of the trampoline deforms when the man exerts a force down on the trampoline, in the top picture, but it is not deformed when the man is in mid-air, in the bottom picture. Photo credit: public-domain image from Wikimedia Commons.

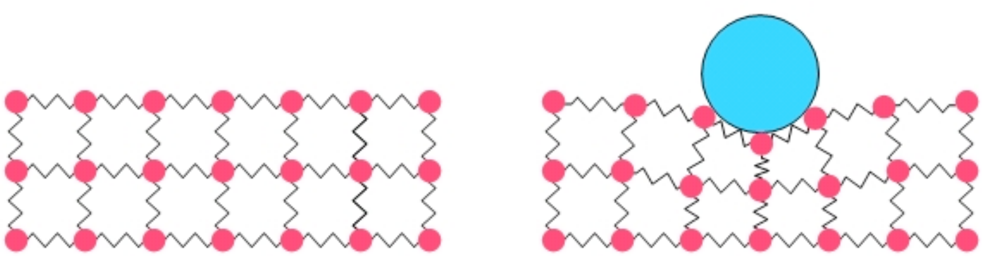

**Figure 3.2**: A diagram of an array of balls and springs, a model of a solid. A solid deforms when it is supporting an object. In this case, we'll use a model in which the object on top is considerably harder than the solid, so the object on top does not deform. In reality, both the object and the supporting solid would deform.

Some of the forces we'll make use of in the first part of the book include:

**The Force of Tension ($F_T$)**

Tension is the force exerted on an object by a string or rope. Remember that you can't push with a string or rope! The force of tension, $F_T$, on an object always points away from the object along the string or rope.

**The Contact Force ($F_C$)**

A contact force, $F_C$, arises when objects are in contact with one another. We often divide the contact force into its components, which we call the normal force and the force of friction.

**The Normal Force ($F_N$)**

The normal force is associated with objects in contact with one another, the normal force being the component of the contact force that is perpendicular to the surface of contact. When a book lies on a horizontal desktop, for instance, the desktop exerts an upward normal force on the book while the book exerts a downward normal force on the desktop. The symbol we will use to represent the normal force is $F_N$. In physics, "normal" generally means "perpendicular."

**The Force of Friction ($F_K$ or $F_S$)**

The force of friction is also associated with objects being in contact with one another, being the component of the contact force that is parallel to the surface of contact. The force of kinetic friction, $F_K$ , applies to situations where one object is sliding over another, while the force of static friction, $F_S$ , applies to situations where the objects do not move relative to one another. We'll get into much more detail about the force of friction in Chapter 5.

**The Force of Gravity ($F_G$)**

Unlike the other forces above, which require contact, the force of gravity acts at a distance. The Sun and the Earth, or a book and the Earth, exert a force of gravity on one another without the objects having to be in direct contact. We will explore gravity in more detail later, but let's begin by saying that the force of gravity that one object exerts on another is $F_G$, and points toward the object exerting the force.

**Four Fundamental Forces**

As we do above, we often list several forces. When we classify them, it turns out that there are only four fundamental forces (although there is excitement these days about a possible fifth force, associated with an increase in the expansion rate of the universe). The four forces are:

1. The force of gravity – an attractive force between objects that have mass.
2. The electromagnetic force – a force between charged objects, which we'll discuss in the second half of the book). The contact force, and its components the normal force and the force of friction, arise from interactions between tiny objects (e.g., electrons) that have charge – these forces are all manifestations of the electromagnetic force.
3. The nuclear force – the force that holds nuclei together (a nucleus is the collection of protons and neutrons at the center of every atom).
4. The weak nuclear force – associated with radioactive decay (such as when an atom of americium-241 in a smoke detector emits an alpha particle to ionize air molecules, a process that is explained in more detail toward the end of the book).

The electromagnetic force, the nuclear force, and the weak nuclear force, are actually all associated with a single force called the electroweak force. Physicists are currently working on a grand unified theory, attempting to unify gravity and the electroweak force into a single force.

***Essential Question 3.1***: Jump up into the air. While you are in mid-air, not in contact with the ground, do any of the forces listed above act on you? If so, which?

***Answer to Essential Question 3.1***: The primary force acting on you once you have left the ground is the force of gravity. You are attracted toward the Earth by the force of gravity even though you are not in contact with the Earth.

## *3-2 Free-Body Diagrams*

When analyzing a particular physical situation, it can be helpful to draw what is called a **free-body diagram**. This is a diagram in which arrows are attached to an object to represent the various forces applied to that object by external influences. The direction of an arrow is the same as the direction of the force the arrow represents, and the length of the arrow is proportional to the magnitude of that force. Each arrow is labeled with an appropriate symbol denoting the force the arrow represents.

When drawing a free-body diagram, it is helpful to keep two questions in mind:

1. For each force shown on the free-body diagram, what exerts the force?
2. Is the motion that would result from the set of forces acting on the object consistent with the actual motion of the object?

The following Explorations should help us learn how to answer those questions.

**EXPLORATION 3.2A – Drawing a free-body diagram for an object at rest**

**Figure 3.3**: Free-body diagram for an object that is not interacting with anything.

**Step 1 –** ***Sketch a free-body diagram for an object that is at rest in outer space, billions of kilometers away from anything.*** The free-body diagram in Figure 3.3 shows no forces, because the object does not interact with anything.

**Step 2 -** ***Sketch a free-body diagram for a book is at rest on a horizontal tabletop.*** The free-body diagram for this very common situation is shown in Figure 3.4. The Earth applies a downward force of gravity to the book, but the book remains at rest because there is an upward normal force applied to the book by the table. How do you think the magnitudes of these two forces compare? For the book to remain at rest, these two forces must cancel one another exactly, so the two forces have the same magnitude.

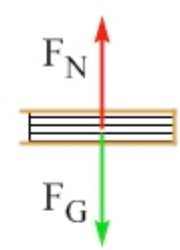


**Figure 3.4**: Free-body diagram for a book sitting at rest on a table.

**Step 3 -** ***Sketch a free-body diagram for a box that remains at rest on a horizontal tabletop even though you exert a horizontal force by pulling on a string tied to the box.*** The force you exert is transferred to the box by the string, so it is shown as a force of tension in Figure 3.5. When drawing the free-body diagram consider this question: Why doesn't the box move? If you pull hard enough, the box will move. In this case, though, the force you exert on the box is small enough that it can be balanced by another force in the opposite direction. This balancing force is the force of static friction, which we discuss in detail in chapter 5. Because the box does not move horizontally these two forces must cancel one another, so their magnitudes are equal.

As in step 2, the Earth applies a downward force of gravity to the box that is exactly balanced by the upward normal force applied to the box by the table.

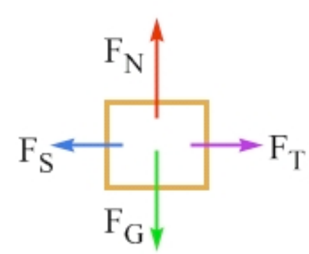


**Figure 3.5**: Free-body diagram for a box at rest on a table while you pull on a string to the right.

**Step 4** – ***What, if anything, is common to the three situations discussed above?*** First, in each case, the object remains at rest – its motion does not change. Second, although the three free-body diagrams clearly are different, in each case there is no net force acting on the object. ***The net force is the sum of all the forces acting on an object.*** Because forces are vectors, we must account for both the directions and magnitudes of forces when we add them. There is no net force in any of the cases above because either there is no force acting at all or all the forces cancel out. Based on this, let's theorize that when no net force acts on an object that is at rest, the object remains at rest.

**Key ideas for an object at rest**: The net force is the vector sum of all the forces acting on an object. When no net force acts on an object that is at rest, the object remains at rest.
**Related End-of-Chapter Exercises: 1, 15.**

**EXPLORATION 3.2B – The motion diagram and the free-body diagram**

Let's now start connecting forces to the motion ideas from chapter 2.

**Step 1** - ***Sketch a motion diagram for a ball you release from rest from some distance above the floor, showing its position at regular time intervals as it falls.*** The motion diagram in Figure 3.6 shows images of the ball that are close together near the top, where the ball moves slowly. As the ball speeds up, these images gradually get farther apart as the ball covers progressively larger distances in equal time intervals.

**Step 2** - ***Sketch the ball's free-body diagram, showing the forces acting on the ball as it falls. Neglect air resistance.*** If we can neglect air resistance, the Earth is the only object applying a force to the ball, and that force is a downward force of gravity. The free-body diagram is shown near the bottom right of in Figure 3.6.

**Step 3** - ***Does the free-body diagram show a net force acting on the ball as it falls? Does this net force increase substantially, decrease substantially, or stay reasonably constant as the ball falls?*** A downward net force acts on the ball because there is nothing to balance the force of gravity. This force is associated with the interaction between the ball and the Earth, and the strength of that interaction depends on the distance between the ball and the center of the Earth. If we drop a ball from a typical height of 1-2 meters, the distance between the ball and the center of the Earth changes by a very small fraction, so we can assume that the net force acting on the ball is constant.

**Step 4** - ***What is the connection between the motion diagram and the free-body diagram?*** The motion diagram shows that the ball's motion changes, because the successive images of the ball are not drawn equally spaced. When a net force acts on an object, the motion of the object changes.

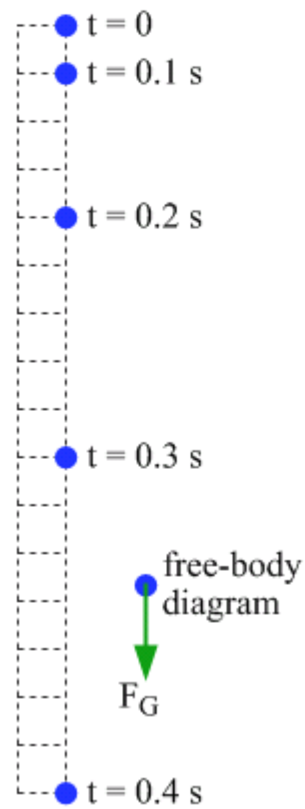


**Figure 3.6**: Motion diagram and free-body diagram for a ball dropped from rest.

**Key idea for motion and force**: When a net force acts on an object, the object's motion changes. **Related End-of-Chapter Exercises: 29, 30, 49.**

***Essential Question 3.2***: What if the ball in Exploration 3.2B had been thrown straight up, so it came to rest for an instant 0.4 s after leaving your hand? What would its motion diagram, and free-body diagram, look like?

***Answer to Essential Question 3.2***: After the ball leaves your hand, the only force acting on the ball is the force of gravity, so the free-body diagram would be the same as in Figure 3.6. The successive locations of the ball on the motion diagram would also be the same, with the times increasing from bottom to top instead of from top to bottom.

## *3-3 Constant Velocity, Acceleration, and Force*

If an object is moving at constant velocity, is there a net force acting in the direction of motion? Let's explore that idea.

**EXPLORATION 3.3A – Forces in a constant-velocity situation**

**Step 1 -** ***Sketch a motion diagram for an object that is drifting through space with a constant velocity to the right, billions of kilometers from anything.*** The motion diagram in Figure 3.7 shows images of the object that are equally spaced along a straight line.

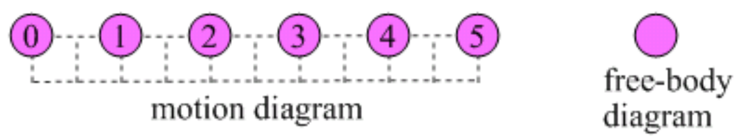


**Figure 3.7**: Motion diagram and free-body diagram for an object drifting to the right through space.

**Step 2 -** ***Sketch the object's free-body diagram, showing all the forces acting on the object as it drifts through space.*** Many people think that the free-body diagram should show a force acting to the right. Here is where you ask yourself, though, "What would apply that force?" The object is not interacting with anything, so there are no forces to show on the free-body diagram in Figure 3.7.

**Step 3 -** ***Repeat steps 1 and 2 for a box you drag with a constant velocity to the right across a horizontal table. You drag the box by pulling on a string tied to the box. The string is horizontal because of the force you exert on it. There is some friction acting on the box.*** The motion diagram for the box, which is shown in Figure 3.8, is similar to that for the object drifting through space – the images of the object that are equally spaced. The free-body diagram is similar to that for the box at rest on the table, when you pulled on the string to the right, except that in this case the friction force is the kinetic force of friction. If the box was initially at rest, the tension force you exert via the string would have to be larger than the friction force to start the box moving. Once the box is moving, the tension force simply has to balance the kinetic friction force to maintain the motion.

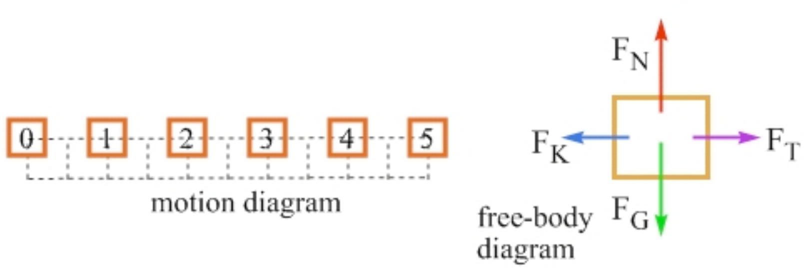


**Figure 3.8**: Motion diagram and free-body diagram for a box being dragged to the right, by means of a string, across a flat surface.

**Step 4** - ***Compare and contrast the free-body diagrams you drew in steps 2 and 3.*** The free-body diagrams are quite different, with one having no forces and the other having four. However, the net force in both cases is zero, because for the box the vertical forces cancel one another and the horizontal forces cancel one another.

**Step 5** - ***What is the connection between the motion diagrams in these cases and the free-body diagrams?*** Even though we considered objects in motion, the free-body diagrams here are equivalent to those we drew in Exploration 3.2A for objects at rest. In all cases, here and in Exploration 3.2A, the net force is zero. The lesson for us is that when no net force acts on an object, the object's velocity is unchanged.

| |
|---|
| **Key ideas for constant-velocity motion**: Again, we see the connection between an object at rest and an object in motion with constant velocity – as far as forces are concerned the situations are the same, with no net force in either case. When no net force acts on an object, its velocity is constant. **Related End-of-Chapter Exercises: 2, 5.** |

In Explorations 3.2A and 3.3A, we learned that when an object experiences no net force its velocity is constant, which means its acceleration is zero. An object with a net force has an acceleration. To see how force is connected to acceleration, let's start by doing some dimensional analysis. The SI unit of force is the newton (N). 1 N = 1 kg m/s$^2$. The SI unit of acceleration is m/s$^2$, so the units differ by a factor of kilograms. The mass of an object has units of kg, so we can speculate that force and acceleration are connected by a factor a mass.

This connection is easy to verify experimentally. When we apply a particular net force to an object of mass $m$ and measure the acceleration $\vec{a}$, the acceleration turns out to be given by:

$$\vec{a} = \frac{\sum \vec{F}}{m}$$ (Equation 3.1: **Connecting acceleration and force**)

The symbol Σ represents a sum, so $\sum \vec{F}$ is the net force (the sum of all the forces) acting on the object. Note that the right-hand side of Equation 3.1 has units of N/kg, so the units of acceleration can be stated as N/kg or as m/s$^2$.

**EXPLORATION 3.3B – A race**

Take two objects of different mass and hold one in one hand and one in the other. If you simultaneously release them from rest from the same distance above the floor, which object hits the ground first? Be sure to use objects that will not be affected much by air resistance, such as a pen and a ball. A piece of paper is a poor choice, for instance, unless you crumple it into a tight ball.

When you do the experiment, you should observe that the objects reach the ground at the same time. This contradicts a common belief (and a belief that was held by Greek thinkers such as Aristotle) that objects with more mass fall faster.

| |
|---|
| **Key idea for an object moving under the influence of gravity alone**: If air resistance can be neglected, the acceleration of an object moving under the influence of gravity is independent of the mass of the object. **Related End-of-Chapter Exercises: 34, 35.** |

***Essential Question 3.3***: If a free-body diagram shows a net force acting on an object at all times, can the object be at rest?

***Answer to Essential Question 3.3***: Yes, but only for an instant. If an object experiences a net force, its motion changes. If the object is initially at rest, it will start to move. If the object is initially moving, the net force might bring it to rest for an instant and then reverse its direction.

## 3-4 Connecting Force and Motion

Why would someone think that an object with more mass falls faster than an object with less mass? One reason is that an object with more mass has a larger force of gravity acting on it. Consider the following statement, made by a student before taking a physics course: "The force of gravity is what makes an object fall to the floor when we let go of it, so an object with more mass should fall faster." That sounds logical, but it is incorrect. What directly determines how much time something takes to fall to the ground is the acceleration, not the force. Force and acceleration are directly related, but they are not the same.

The force of gravity acting on an object is proportional to its mass. If we are dropping objects relatively small distances when we are at, or near, the surface of the Earth, the force of gravity is constant and is given by:

$\vec{F}_G = m\vec{g}$ , (Equation 3.2: **Force of gravity at the surface of the Earth**)

where $\vec{g}$ is commonly referred to as the acceleration due to gravity. As we discussed in chapter 2, at the surface of the Earth, the value of $\vec{g}$ is about 9.8 N/kg directed down. A better name for $\vec{g}$ is "the value of the local gravitational field," but we will address that in chapter 8 when we talk about gravity in detail, and when we show where the value of 9.8 N/kg comes from.

Figure 3.9 shows the free-body diagrams of two objects, one with a mass of *m* and the other with a mass of 3*m*, when they are in free fall. Because the objects move under the influence of gravity alone, only one force, the force of gravity, appears on each free-body diagram. The force of gravity is proportional to mass, so the force of gravity acting on the second object is three times larger than the force acting on the first object. Figure 3.9 is correct, but these free-body diagrams reinforce the incorrect idea that an object with more mass falls faster. Let's go beyond the free-body diagrams, and apply Equation 3.1.

For object 1: $\vec{a}_1 = \frac{\sum \vec{F}}{m} = \frac{m\vec{g}}{m} = \vec{g}$ ;

For object 2: $\vec{a}_2 = \frac{\sum \vec{F}}{3m} = \frac{3m\vec{g}}{3m} = \vec{g}$ .

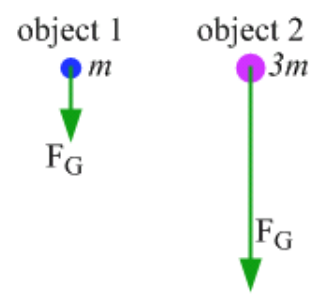


**Figure 3.9**: Free-body diagrams for two objects in free fall. Object 2 has three times the mass of object 1, so the force of gravity acting on it is three times as large as that on object 1. Despite this, the objects have equal accelerations.

Even though the forces have different magnitudes, the accelerations are the same. This is why both objects reach the ground at the same time.

It is easy to confuse force and acceleration, and we will consider more situations later where we must carefully distinguish the two. As a final thought, consider the following.

*Question*: Take two identical objects and apply a net force to the second one that is three times larger than the net force applied to the first one, as shown in Figure 3.10. If both objects start from rest at the same time, which object has a larger acceleration?

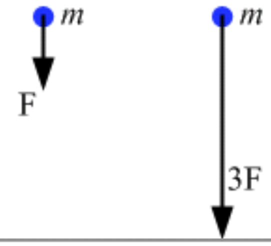


**Figure 3.10**: Free-body diagrams for two identical objects, one experiencing a force three times larger than that experienced by the other.

*Answer*: Now the obvious answer is the correct one – the second object has an acceleration three times larger than the first because its net force is three times larger. This is true only because the objects have the same mass! Compare this situation to that shown in Figure 3.9, in which we dropped objects of different mass.

Force and motion are connected by acceleration. Knowing about forces can give us an acceleration we can use in the constant-acceleration equations. Conversely, we can use the equations to find acceleration and then find the net force. Here is an example of that process.

**EXAMPLE 3.4 – Combining forces with the constant-acceleration equations**

Cindy kicks a soccer ball, with a mass of 0.40 kg. If the ball starts from rest on the ground and ends up with a velocity of 15 m/s directed horizontally, what is the average force exerted on the ball by Cindy's foot if her foot is in contact with the ball for 0.10 s?

**SOLUTION**

A diagram of the situation and a free-body diagram of the ball are shown in Figure 3.11. Table 3.1 summarizes what we know about the motion.

| | |
|---|---|
| Initial position | $\vec{x}_i = 0$ |
| Initial velocity | $\vec{v}_i = 0$ |
| Final velocity | $\vec{v} = +15 \text{ m/s}$ |
| Time | $t = 0.10 \text{ s}$ |

**Table 3.1**: A summary of the data for the ball.

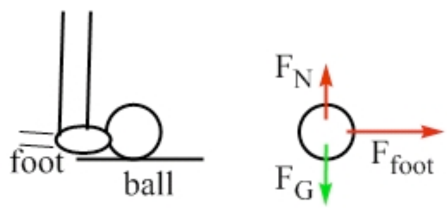


**Figure 3.11**: A diagram, and free-body diagram, for the ball.

There is enough information here to solve for the ball's acceleration using Equation 2.7, $\vec{v} = \vec{v}_i + \vec{a}t$ . Re-arranging this equation to solve for the acceleration gives:

$$\vec{a} = \frac{\vec{v} - \vec{v}_i}{t} = \frac{+15 \text{ m/s} - 0}{0.10 \text{ s}} = +150 \text{ m/s}^2 .$$

We can apply a re-arranged version of Equation 3.1, $\sum \vec{F} = m\vec{a}$ , to determine the force Cindy exerts on the ball. Assume that $\vec{F}_{foot}$ , the force Cindy's foot exerts on the ball, is horizontal, so the normal force the ground exerts on the ball balances the force of gravity acting on the ball.

$$\vec{F}_{foot} = (0.40 \text{ kg})(+150 \text{ m/s}^2) = +60 \text{ N} .$$

**Related End-of-Chapter Exercises: 14, 26, 27, 52, 55.**

***Essential Question 3.4***: Let's say that, in Example 3.4, the ball is rolling toward Cindy at a speed of 8.0 m/s at the instant she kicks it, and she exerts the same force on the ball for the same time period as in Example 3.4 above. What is the ball's final velocity in this new situation?

***Answer to Essential Question 3.4***: In this case, we can use the definition of acceleration to write Equation 3.1 as $\vec{F}_{net} = m\vec{a} = m\Delta\vec{v} / \Delta t$. The net force acting on the ball, the ball's mass, and the time interval over which the force is applied are the same in this situation as in Example 3.4, so the ball's change in velocity, +15 m/s, must also be the same. Because the ball's initial velocity is –8.0 m/s, adding the change of +15 m/s results in a final velocity of +7.0 m/s.

## *3-5 Newton's Laws of Motion*

Sir Isaac Newton (1642 – 1727) made many contributions to mathematics and science, including three laws of motion. Previously, we looked at several situations involving objects at rest and objects moving with constant velocity. We found that, in all such cases, the net force on the object was zero. In contrast, whenever an object's velocity was changing we found that there was a non-zero net force acting on the object. These observations are summarized by:

**Newton's First Law** - If no net force acts on an object, the object's velocity is unchanged: the object either remains at rest or it keeps moving with constant velocity. If there is a non-zero net force acting, then the object's velocity changes.

Recall that the net force is the sum of all the forces acting on an object. Always remember to add forces as vectors. The net force can be symbolized by $\sum \vec{F}$.

When there is a non-zero net force acting on an object, Newton's first law is a rather qualitative statement. It tells us that the velocity of the object changes, but it does not tell us how the velocity changes. This is where Newton's second law comes in.

$$\vec{a} = \frac{\sum \vec{F}}{m}. \qquad \text{(Equation 3.1: } \textbf{Newton's Second Law)}$$

Equation 3.1 is often re-arranged to the following form, but it's the same equation!

$$\sum \vec{F} = m\vec{a} \qquad \text{(Equation 3.1: } \textbf{Newton's Second Law}\text{)}$$

Thus, if we know all the forces that act on an object, and we also know the object's mass, we can determine the object's acceleration. Once we know the acceleration we can go on to analyze the object's motion using the methods, and constant-acceleration equations, of Chapter 2.

How quickly an object's velocity changes when a net force is applied depends on the magnitude of the net force as well as the object's inertia. The more mass an object has, the harder it is to change the object's velocity. In other words, an object's inertia is its mass.

Newton's third law is simple to state but it can be rather counter-intuitive. This law follows from the fact that forces are associated with interactions, and both objects involved in an interaction experience a force of the same magnitude because of that interaction.

**Newton's Third Law** - When one object exerts a force on a second object, the second object exerts a force equal in magnitude, and opposite in direction, on the first object.

Note that Newton's laws apply for observers who are not accelerating while observing a system. For instance, you can use Newton's laws to explain the motion of an apple being tossed up and down by a person on a bus if you are at rest on the sidewalk watching the bus go by, or even if you are on the bus while the bus is moving at constant velocity. Newton's laws give an incomplete picture if you are on the bus, analyzing the motion of the apple while the bus accelerates. A non-accelerating reference frame is known as an inertial frame of reference.

***Question***: A fast-moving train collides with a small car that stalled as it crossed the railroad tracks. (Fortunately, the driver was able to run to safety before the collision.) Which object exerts more force on the other during the collision? Justify your answer.

***Answer***: Despite the fact that the train has much more mass than the car, the force the train exerts on the car is always equal in magnitude, and opposite in direction, to the force the car exerts on the train. Newton's third law addresses the fact that a force comes from an interaction, and the interacting objects are always equal partners in that interaction in the sense that they experience forces of equal magnitude.

So, why do many people think that the train exerts more force on the car than the car exerts on the train? The issue is that while the forces may be equal-and-opposite, the accelerations are different. Because the train's mass is much larger than the car's mass, the train's acceleration (the net force divided by the mass) is much less than the car's. Because the car experiences a large acceleration, so does a person in the car, and the forces exerted on a person in the car can be large enough to cause serious injury or death. Conversely, because the train experiences a small acceleration, someone on the train experiences a modest force and a person on the train may hardly even notice a collision occurred (until the engineer applies the brakes, at least). Thus, although the forces are equal-and-opposite, the effects of the forces differ greatly.

Although Newton's third law can be counter-intuitive, it is easy to verify. One way to verify it is to mount force sensors on carts and set up collisions between the carts, or have one cart push or pull the other. No matter what the situation, even if the carts have different masses and/or one of the carts is initially stationary, the result is that the force that the first cart exerts on the second is always equal in magnitude, and opposite in direction, to the force the second cart exerts on the first. A result from an actual experiment is shown in Figure 3.12, showing graphs of the force, as a function of time, experienced by two carts being pushed together.

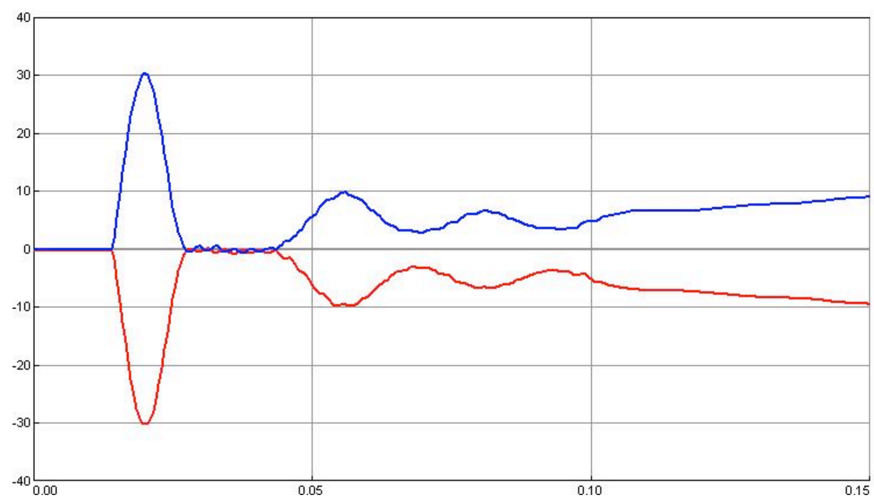


**Figure 3.12**: The top graph shows the force, in newtons, as a function of time, in seconds, that cart A exerts on cart B. The bottom graph shows the force cart B exerts on cart A. Such graphs are always mirror images, providing experimental evidence of Newton's third law.

**Related End-of-Chapter Exercises: 56 and 57.**

***Essential Question 3.5***: Does the Sun exert more force on the Earth, or does the Earth exert more force on the Sun?

***Answer to Essential Question 3.5***: Even though the Sun is enormous compared to the Earth, Newton's third law tells us that the force the Sun exerts on the Earth is equal in magnitude, and opposite in direction, to the force the Earth exerts on the Sun.

## *3-6 Exploring Forces and Free-Body Diagrams*

A force is simply a push or a pull. A force is a vector, so it has a direction. Also, a force represents an interaction between objects. Let's build on these facts and learn more about forces.

**EXPLORATION 3.6A – The normal force**

**Step 1 -** ***Sketch free-body diagrams for the following situations: (a) a book rests on a table; (b) you exert a downward force on the book as it sits on the table; (c) you tie a helium-filled balloon to the book, which remains on the table.***

The diagrams are shown in Figure 3.13. In (a), the normal force applied by the table on the book has to balance the force of gravity acting on the book. If you push down on the book, the normal force increases – it has to balance the force of gravity as well as the force you exert. Tying a helium balloon to the book reduces the normal force because the normal force and the tension in the string combine to balance the force of gravity. The normal force depends on the situation – the magnitude of the normal force is whatever is necessary to prevent the book from falling through the table.

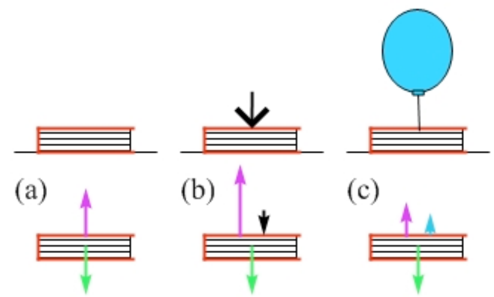


**Figure 3.13**: The upward normal force the table exerts on the book is larger when you exert a downward force (b) and is smaller when a string tied to a helium balloon exerts an upward force (c).

Let's say we have a scale calibrated in force units. The magnitude of the normal force is the force the scale reads if the scale is placed between the objects in contact.

**Step 2 -** ***When does one object lose contact with another? For instance, how many helium balloons would we have to tie to the book to make it lift off the table?*** Objects lose contact when the normal force between them goes to zero. The minimum number of balloons is the number needed to reduce the normal force the table exerts on the book (and the normal force the book exerts on the table) to zero.

**Key ideas about the normal force**: The magnitude of the normal force in a particular situation is whatever is required to prevent one object from passing through another, and is equal to the scale reading if a scale were placed between the objects in contact. Objects lose contact when the normal force between them goes to zero. **Related End-of-Chapter Exercises: 4, 17.**

**EXAMPLE 3.6 – Calculating the normal force**

As shown in Figure 3.14, a large box (box 1), with a weight of $m_1 g = 20$ N, is at rest on the floor. A smaller box (box 2), with a weight of $m_2 g = 10$ N, sits on top of the large box. (a) Draw free-body diagrams for each box. Calculate the normal force (b) exerted on box 2 by box 1, (c) exerted on box 1 by box 2, and (d) exerted on box 1 by the floor.

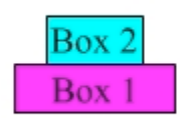


**Figure 3.14**: Two boxes, one on top of the other, at rest on the floor.

**SOLUTION**

(a) The free-body diagrams are shown in Figure 3.15. For box 2, the upward normal force applied by box 1 balances the downward force of gravity acting on box 2. For box 1, the table balances both the force of gravity on box 1 and the downward normal force applied on box 1 by box 2.

(b) For the forces to balance, the normal force applied on box 2 by box 1 is 10 N up.
(c) By Newton's third law, box 2 applies a normal force on box 1 of 10 N down.
(d) For the forces on box 1 to balance, the table applies a normal force of 30 N up.

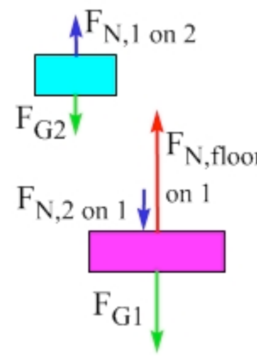


**Figure 3.15**: Free-body diagrams for the two boxes of Example 3.6.

**The Contact Force ($F_C$)**

In general, when two objects are in contact with one another, they exert contact forces that are equal in magnitude but opposite in direction. We usually split the contact force into two components, a normal force perpendicular to the surfaces in contact, and a force of friction that is parallel to the surfaces in contact. It can be useful to look at the whole vector, however.

**EXPLORATION 3.6B – A whole-vector approach**

While unloading a truck, you place a box on a ramp leading from the truck.

**Step 1** - ***The box remains at rest on the ramp. What is the net force acting on the box?*** The velocity of the box remains constant (at $v = 0$, in this case), so there is no net force on the box.

**Step 2** - ***Sketch a diagram of the situation and a free-body diagram showing the forces acting on the box. What is the magnitude and direction of the force the ramp exerts on the box?*** In this case, it is simpler to use the whole contact force, rather than using the two components (a normal force perpendicular to the ramp and a static force of friction directed up the ramp). The net force on the box is zero, so the contact force is directed straight up with a magnitude equal to the force of gravity, as shown in Figure 3.16.

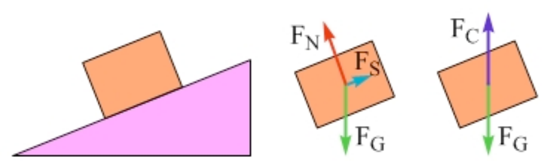


**Figure 3.16**: A diagram and two equivalent free-body diagrams for the box at rest on the ramp.

**Key idea**: It can be helpful to view the contact force as one vector, instead of breaking it into its components, a normal force and a force of friction. **Related End-of-Chapter Exercises: 38, 39.**

**The Force of Gravity, Weight, and Apparent Weight**

The force of gravity, $F_G$, does not require objects to be in contact but acts at a distance. The force of gravity is always attractive, directed toward the object exerting the force. In Chapter 8, we will look at situations in which the distance between objects changes, changing the force of gravity. For now, we will deal with situations in which the force of gravity is constant, as it is at the Earth's surface, where we use $\vec{F}_G = m\vec{g}$, with $\vec{g}$ the acceleration due to gravity. In this book, we generally use the term "force of gravity," but $m\vec{g}$ is often called the **weight**.

Your mass is the same no matter where you are. Near the surface of the Earth, the force of gravity acting on you is also constant. However, you have probably experienced feeling that you weigh more or less than usual, such as when you're on a roller coaster, or in a car going over a hill. Your weight (the force of gravity acting on you) is constant, but your apparent weight is different. Your apparent weight is, in many cases, equal in magnitude to the normal force acting on you, so you often feel a change in your apparent weight when the normal force changes.

***Essential Question 3.6***: Jump straight up into the air. While you are still in contact with the ground, but accelerating upward, how does the normal force applied on you by the ground compare to the force of gravity applied on you by the Earth? In what direction is the net force on you after you lose contact with the ground?

***Answer to Essential Question 3.6***: While you are still in contact with the ground, but accelerating upward, you must have a net force directed up. This comes from an upward normal force on you, applied by the ground, which is larger in magnitude than the downward force of gravity applied on you. After you leave the ground, there is no longer a normal force acting on you, so the downward force of gravity acting on you is the net force in that situation.

## 3-7 Practice with Free-Body Diagrams

Let's start by looking at the forces involved when you are in an elevator.

**EXAMPLE 3.7 – An elevator at rest**

(a) You are standing in an elevator that is at rest. Draw three free-body diagrams. The first should show all the forces acting on you as you stand in the elevator; the second should show all the forces acting on the elevator as you stand in it, and the third should show all the forces acting on the system consisting of you and the elevator combined. Draw them to scale, assuming that the mass of the elevator ($M$) is twice as large as your mass ($m$).

(b) Use your free-body diagrams to help determine an expression for the tension in the cable.

**SOLUTION**

We should start by drawing a diagram, shown below as part a of Figure 3.17. This shows the cable attached to the top of the elevator.

(a) Your free-body diagram is the same as the free-body diagram we would draw if you were simply standing on the floor. We show a downward force of gravity and an upward normal force that is exerted on you by the floor of the elevator. These two forces balance one another, to give a net force of zero, consistent with your constant velocity (of zero).

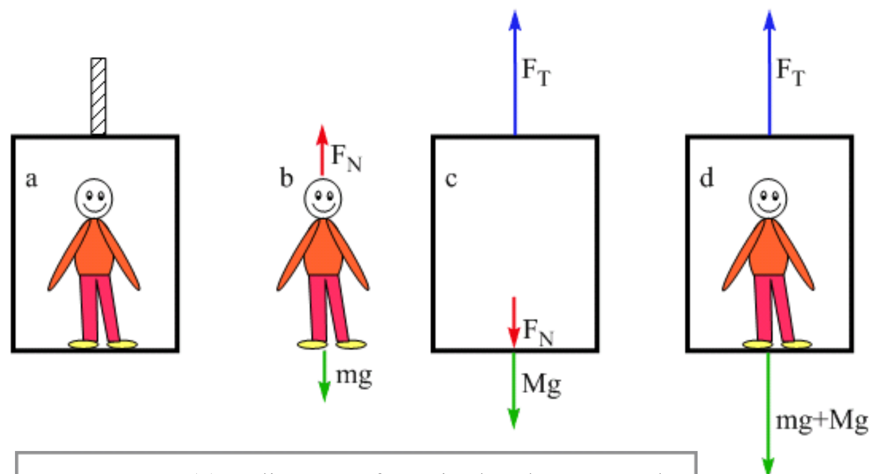


**Figure 3.17**: (a) A diagram of you in the elevator, and free-body diagrams for (b) you, (c) the elevator, and (d) the system consisting of you plus the elevator.

The free-body diagram of the elevator is a bit more challenging. Let's start by drawing a downward force of gravity and an upward tension force, which are the only forces that act on the elevator when the elevator is empty. Even though we draw what looks like an empty elevator, to construct the free-body diagram we have to remember that, in this case, you are in the elevator exerting a downward force on it. How do we represent this on the free-body diagram? Newton's third law is helpful. If the elevator applies an upward normal force on you, then you apply a downward normal force on the elevator of exactly the same magnitude.

A common mistake is to label the downward force the person applies to the elevator, in the elevator's free-body diagram, as $mg$ instead of $F_N$. There are two reasons why doing so is not a good idea. First, the ***forces shown on an object's free-body diagram are forces exerted on that object by other things***. For the elevator, $F_N$ is the force exerted on the elevator by you. $mg$ is exerted on you by the Earth, so that force belongs on your free-body diagram but not the elevator's. Second, while $mg$ and $F_N$ are numerically equal in this situation, we will soon deal with a situation in which they are not, so using $mg$ in place of $F_N$ can actually lead to calculation errors.

The third free-body diagram, showing the forces acting on the system consisting of you and the elevator combined, is the combination of the first two free-body diagrams. We have the tension the cable exerts on the elevator, directed up, and the combined force of gravity acting on the system. When you combine the first two free-body diagrams, you also get the upward normal force the elevator exerts on you and the downward normal force you exert on the elevator. By Newton's third law, these forces are equal-and-opposite, so they cancel one another when they are combined. For this reason, as well as the fact that when we draw a free-body diagram, the forces we draw are exerted by objects external to the system we are considering, we don't include them on the free-body diagram of the combined system.

(b) *Use your free-body diagrams to determine an expression for the tension in the cable.* At this point, we apply Newton's second law. In general $\sum \vec{F} = m\vec{a}$, but, in this situation, the acceleration is zero, so we use the simplified equation $\sum \vec{F} = 0$. Choosing a coordinate system, let's define up to be positive. We will account for the fact that forces are vectors by using a plus sign if the force is directed up, and a minus sign if the force is directed down.

We could solve the problem by applying Newton's second law to the last free-body diagram, but let's consider all three diagrams to make sure everything is consistent.

Apply Newton's second law to the free-body diagram of you:
$\sum \vec{F} = 0$;

$+F_N - mg = 0$ which tells us that $F_N = mg$.

Apply Newton's second law to the elevator's free-body diagram:
$\sum \vec{F} = 0$;

$+F_T - Mg - F_N = 0$ which tells us that $F_T = Mg + F_N$.

Apply Newton's second law to the combined system's free-body diagram:
$\sum \vec{F} = 0$;

$+F_T - (M + m)g = 0$ which tells us that $F_T = Mg + mg$.

Everything is consistent. The second and third free-body diagrams give the same result for the tension because we know $F_N = mg$ from the first free-body diagram.

**Related End-of-Chapter Exercises: 18, 43.**

***Essential Question 3.7:*** If the elevator is traveling up at constant velocity what, if anything, would change on the free-body diagrams? For example, would we need to add one or more forces to any of the free-body diagrams? Would any of the existing forces change in magnitude and/or direction?

***Answer to Essential Question 3.7:*** If the velocity is constant, there is no acceleration. The situation is the same as in part (a). As far as forces are concerned "at rest" and "constant velocity" are equivalent. Nothing changes on any of the free-body diagrams.

## *3-8 A Method for Solving Problems Involving Newton's Laws*

Now that we have explored some of the basic steps involved in solving a typical problem that relies on Newton's laws, let's summarize a general method that we can apply to all such problems. We have not yet addressed all the issues covered by the method (such as the various coordinate systems mentioned in step 3), but we will continue to address these issues in the remaining examples of this chapter as well as in chapter 5.

**A General Method for Solving a Problem Involving Newton's Laws, in One Dimension**

1. Draw a diagram of the situation.
2. Draw one or more free-body diagrams, with each free-body diagram showing all the forces acting on an object.
3. For each free-body diagram, choose an appropriate coordinate system. The different coordinate systems should be consistent with one another. A good rule of thumb is to align each coordinate system with the direction of the acceleration.
4. Apply Newton's second law to each free-body diagram.
5. Put the resulting force equations together and solve.

Let's apply the general method in the following Example.

**EXAMPLE 3.8 – An elevator accelerating up**

Let's say the elevator from Example 3.7, with you in it, has a constant acceleration directed up.

(a) What, if anything, would change on the free-body diagrams we drew in Example 3.7? Determine an expression for the tension in the cable now.
(b) If we know the elevator's acceleration is directed up, with a magnitude of *g*/2, what can we say about the direction the elevator is moving?

**SOLUTION**

(a) By Newton's second law, $\sum \vec{F} = m\vec{a}$, an upward acceleration requires a net upward force. Something must change on each free-body diagram to give us a net upward force. We have already accounted for all the interactions, so we don't add or subtract forces. Instead, one or more of the forces on each free-body diagram (see Figure 3.18) must change in magnitude.

The force of gravity cannot change, so to get a net upward force on the first free-body diagram, the normal force must increase. The normal force now has two jobs. It prevents you from falling through the floor of the elevator, and it also provides the extra upward force needed for the upward acceleration. Applying Newton's second law gives:

$$\sum \vec{F} = m\vec{a} = +\frac{1}{2}mg \, .$$

$F_N - mg = +\frac{1}{2}mg$ which tells us that $F_N = \frac{3}{2}mg$.

On the free-body diagram of just the elevator, our previous results mean that the downward normal force increases. Applying Newton's second law gives:

$$\sum \vec{F} = M\vec{a} = +\frac{1}{2}Mg .$$

$$F_T - Mg - F_N = +\frac{1}{2}Mg$$

which tells us that

$$F_T = +\frac{3}{2}Mg + F_N .$$

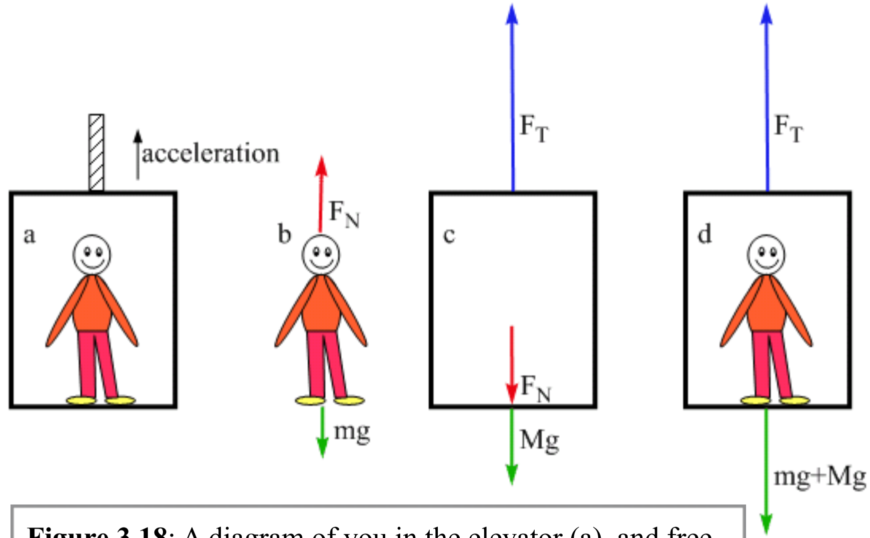


**Figure 3.18**: A diagram of you in the elevator (a), and free-body diagrams for you (b), the elevator (c), and the system consisting of you plus the elevator (d), when the elevator has an upward acceleration with a magnitude of g/2.

Here, it is critical to show the force that you exert on the elevator as a normal force, not a force of gravity, because the normal force is larger in magnitude than the force of gravity acting on you. Note that the increase in the tension offsets the increased normal force and also provides the net force required to accelerate the system upwards.

Applying Newton's second law to the third free-body diagram gives:

$$\sum \vec{F} = (M+m)\vec{a} = +\frac{1}{2}(M+m)g$$

$F_T - (M+m)g = +\frac{1}{2}(M+m)g$, which tells us that $F_T = \frac{3}{2}(Mg + mg)$.

The only change here is an increase in the tension. Check the two expressions for tension to make sure that they are consistent with one another.

(b) The elevator could actually be moving in any direction and have an upward acceleration. For instance, if the elevator is gaining speed while moving up, the acceleration is directed up. However, if the elevator is slowing while moving down, the acceleration is also directed up. A similar situation is a ball thrown straight up into the air. Whether the ball is moving up or down, once you release the ball, the acceleration is directed down because the force of gravity is the only force acting and is directed down. For one instant at the very top, the acceleration is down, yet the ball is at rest. Knowing the direction of the acceleration is not enough to determine the direction of motion.

**Related End-of-Chapter Exercises: 19, 44.**

We'll do another example to become more familiar with applying the method of solving a typical problem involving Newton's laws. First, we'll start with a conceptual question.

***Essential Question 3.8***: Three boxes are placed side-by-side on the floor (see Figure 3.19). The red box has a weight of 40 N, the green box a weight of 60 N, and the blue box a weight of 50 N. When you exert a constant force to the right on the red box, the entire system accelerates to the right. Which box experiences the largest-magnitude net force?

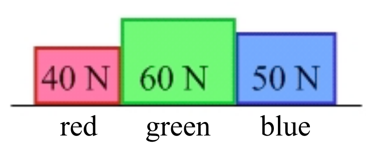


**Figure 3.19**: Three boxes placed side-by-side.

***Answer to Essential Question 3.8***: The boxes will move together as one unit, so the boxes have the same acceleration. The net force acting on a box is the mass of the box multiplied by the acceleration. Thus, the green box, with the largest mass, experiences the largest net force.

## *3-9 Practicing the Method*

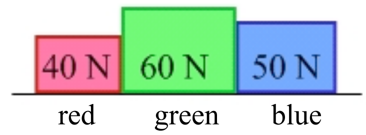


**Figure 3.19**: Three boxes placed side-by-side.

**EXAMPLE 3.9 – Three boxes**

Let's look in more detail at the system of three boxes that are side-by-side on a frictionless floor. The weights of the boxes are given in Figure 3.19. By exerting a constant force of $\vec{F} = 30$ N to the right on the red box, you cause the three boxes to accelerate. Use $g = 10$ m/s$^2$.

(a) What is the acceleration of the boxes?
(b) Using a notation in the form $F_{RG}$, which denotes the magnitude of the force that the red box applies to the green box, sketch free-body diagrams for (i) the red box; (ii) the green box; (iii) the system consisting of the red and green boxes together; and (iv) the system consisting of the green and blue boxes together.
(c) Which of the four free-body diagrams above would you use to determine $F_{RG}$, the magnitude of the force that the red box applies to the green box? What is $F_{RG}$?

**SOLUTION**

(a) Let's begin with a free-body diagram, but which system should we draw a free-body diagram for? Choosing the system carefully can make a problem easier to solve. The free-body diagrams for each box involve horizontal forces we don't yet know the magnitude of. Is there a free-body diagram we could draw so the only horizontal force acting is the 30 N force you apply?

As shown in Figure 3.20, the free-body diagram of the whole system involves only a downward force of gravity, an upward normal force, and the 30 N horizontal force. Let's choose a coordinate system with the positive x direction pointing to the right. Applying Newton's second law in that direction gives: $\sum \vec{F}_x = (m_R + m_G + m_B)\vec{a}_x$.

The only horizontal force acting on the combined system is your 30 N force in the $+x$ direction, so: $30\text{ N} = (m_R + m_G + m_B)\vec{a}_x$.

To find the masses, divide the weights by $g$, which we are taking here to be 10 m/s$^2$. The masses are $m_R = 4.0$ kg, $m_G = 6.0$ kg, and $m_B = 5.0$ kg. Solving for the acceleration gives

$$\vec{a}_x = \frac{+30\text{ N}}{(4.0\text{ kg} + 6.0\text{ kg} + 5.0\text{ kg})} = \frac{+30\text{ N}}{15.0\text{ kg}} = +2.0\text{ m/s}^2.$$

(b) The free-body diagram of the red box shows the 30 N horizontal force you exert, as well as the upward normal force exerted on the red box by the floor, $\vec{F}_{FR}$, and the downward force of gravity exerted on the red box by the Earth, $\vec{F}_{ER}$. The diagram must also account for the interaction between the green and red boxes – the green box exerts a force to the left on the red box, $\vec{F}_{GR}$. This force is smaller in magnitude than your 30 N force because the red box has a net force to the right.

The free-body diagrams of the green and red boxes are similar. In both cases, the upward normal force balances the downward force of gravity, while the fact that there is a net force to the right means that the force to the right is somewhat larger than the force to the left. Your 30 N force is applied only to the red box, so it appears only on the free-body diagram of the red box (or on the free-body diagram of a system involving the red box). The green box experiences a force to the right, from the red box, but it is less than 30 N.

If we combine the red and green boxes into one system (system 1), the system's free-body diagram is the sum of the individual free-body diagrams. The net upward normal force $\vec{F}_{F1} = \vec{F}_{FR} + \vec{F}_{FG}$ balances the net downward force of gravity $\vec{F}_{E1} = \vec{F}_{ER} + \vec{F}_{EG}$. Horizontally, your 30 N force acts to the right, while the force $\vec{F}_{BG}$ that the blue box exerts on the green box is directed left.

We do not have to include $\vec{F}_{RG}$ and $\vec{F}_{GR}$ because, by Newton's third law, these are equal-and-opposite and thus cancel one another. Another reason to exclude this pair of forces is that they are internal forces in the system. Forces that belong on the free-body diagram come from external interactions, forces exerted on the system by things outside the system, such as by you, the floor, the Earth, and the blue box.

Combining the green and blue boxes into one system, system 2, the upward normal force from the floor $\vec{F}_{F2}$ balances the downward force of gravity $\vec{F}_{E2}$. Horizontally, there is only one horizontal force acting, the force the red box exerts on the green box $\vec{F}_{RG}$.

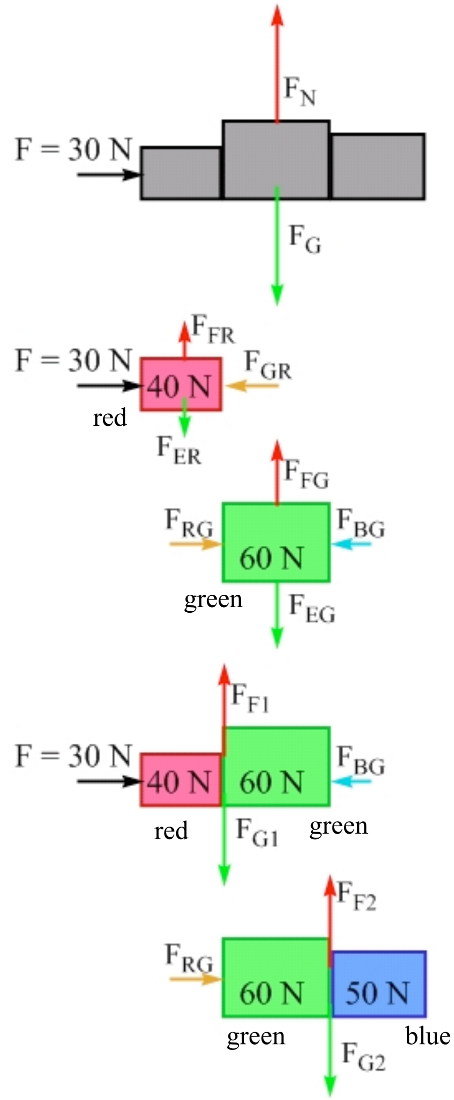


**Figure 3.20**: Various free-body diagrams for the three-box situation. In each case, the vertical forces cancel, so we can focus on the horizontal forces.

(c) To find $\vec{F}_{RG}$, we cannot use the system consisting of the red and green boxes together. $\vec{F}_{RG}$ is an internal force in that system, so it does not appear on the system's free-body diagram. $\vec{F}_{RG}$ appears on the free-body diagram of the green box, as well as on the free-body diagram of the system consisting of the green and blue boxes. In addition, $\vec{F}_{GR}$ appears on the free-body diagram of the red box so we could solve for that, because $\vec{F}_{RG}$ is equal in magnitude to $\vec{F}_{GR}$.

Let's use the last free-body diagram, because $\vec{F}_{RG}$ is the only horizontal force that appears on that diagram. Applying Newton's second law in the horizontal direction gives:

$$\sum \vec{F}_x = (m_G + m_B)\vec{a}_x \text{, so} \qquad \vec{F}_{RG} = (6.0 \text{ kg} + 5.0 \text{ kg}) * (+2.0 \text{ m/s}^2) = +22 \text{ N}.$$

**Related End-of-Chapter Exercises: 36, 45, 58, 59.**

***Essential Question 3.9***: Calculate the net force acting on each of the boxes in Example 3.9.

***Answer to Essential Question 3.9***: By Newton's second law, the net force acting on each box is equal to $m\vec{a}$ for each box. This gives 8.0 N to the right for the red box; 12 N to the right for the green box and 10 N to the right for the blue box. As they should, these net forces add together to 30 N to the right, matching the net force on the system (the 30 N force you apply, directed right).

## Chapter Summary

***Essential Idea: Forces and Newton's Laws***

In this chapter, we covered one of the main methods of analyzing a physical situation, which is to think about all the forces being exerted on an object by external influences, and then apply Newton's second law to determine the acceleration.

***Forces and Newton's Three Laws of Motion***

A force, which is a push or a pull, acts on an object when there is an interaction between that object and another object. Newton's laws give us some guidelines to use when applying forces to solve problems. They are:

**Newton's First Law**: if no net force acts on an object, the object's velocity is unchanged: the object either remains at rest or it keeps moving with constant velocity. If there is a non-zero net force acting, then the object's velocity changes.

**Newton's Second Law** tells us that the connection between an object's net force and its acceleration is given by:

$$\vec{a} = \frac{\sum \vec{F}}{m} \quad \text{, which we can re-write as} \quad \sum \vec{F} = m\vec{a} \,. \qquad \text{(Equation 3.1)}$$

**Newton's Third Law**: Whenever one object exerts a force on a second object, the second object exerts a force equal in magnitude, and opposite in direction, on the first object.

***A General Method for Solving Problems Involving Newton's Laws, in One Dimension***

The most important lesson to take away from this chapter is that most one-dimensional problems involving forces can be solved by applying the following method:

1. Draw a diagram of the situation.

2. Draw one or more free-body diagrams, with each free-body diagram showing all the forces acting on an object.

3. For each free-body diagram, choose an appropriate coordinate system. The coordinate systems for the different free-body diagrams should be consistent with one another. A good rule of thumb is to align each coordinate system with the direction of the acceleration.

4. Apply Newton's second law to each free-body diagram.

5. Put the resulting force equations together, and solve.

## *End-of-Chapter Exercises*

**Exercises 1 – 12 are conceptual questions that are designed to see if you have understood the main concepts of the chapter.**

1. Five possible free-body diagrams of one of your friends are shown in Figure 3.21. (a) Which free-body diagram applies if your friend remains at rest? Which free-body diagram applies if your friend is moving with a constant velocity directed (b) to the right? (c) to the left? (d) straight up? (e) straight down? You can use a free-body diagram more than once if you wish.

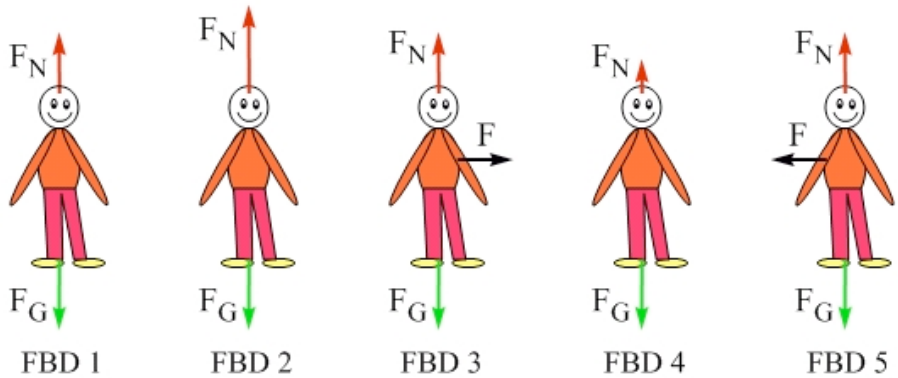


**Figure 3.21**. Five possible free-body diagrams of your friend, for Exercises 1 and 2. Note that the magnitude of $\vec{F}_N$ is equal to that of $\vec{F}_G$ in diagrams 1, 3, and 5.

2. Five possible free-body diagrams of one of your friends are shown in Figure 3.21. Describe a situation in which the applicable free-body diagram is (a) FBD 2 (b) FBD 3 (c) FBD 4.

3. Three possible free-body diagrams are shown in Figure 3.22 for a car moving to the right. $\vec{F}_{air}$ represents a resistive force due to air resistance, while $\vec{F}_{road}$ represents the force the road exerts on the car. Which free-body diagram is consistent with the car (a) moving at constant velocity? (b) speeding up? (c) slowing down? You can use a free-body diagram more than once if you wish. A resistive force is a force that opposes motion.

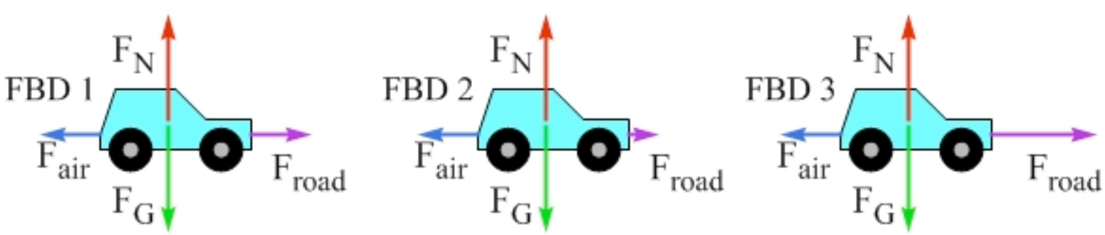


**Figure 3.22**: Three possible free-body diagrams for a car moving to the right. The magnitude of the force of air resistance is equal to that exerted by the road in FBD 1. For Exercises 3 and 4.

4. Consider again the three free-body diagrams shown in Figure 3.22. $\vec{F}_{air}$ represents a force that the air exerts on the car, while $\vec{F}_{road}$ represents the force the road exerts on the car. (a) Are any of the free-body diagrams consistent with the car remaining at rest? If so, which? (b) If you chose a free-body diagram in (a), describe a situation in which that free-body diagram would apply, with the car remaining at rest.

5. In class, you see a demonstration involving a penny and a feather that are dropped simultaneously from rest inside a glass tube. The tube is held so the two objects fall vertically from one end of the tube to the other. At first, the penny easily beats the feather to the lower end of the tube, but then your professor uses a vacuum pump to remove most of the air from inside the tube. When the objects are again released from rest, which object reaches the lower end of the tube first? Why?

6. Two solid steel ball bearings are dropped from rest from the same height above the floor. Ball A is somewhat larger and heavier than ball B. Assuming air resistance can be neglected, rank the balls based on (a) the magnitude of their accelerations as they fall; (b) the magnitude of the net force acting on each ball as they fall; (c) the time it takes them to reach the ground.

7. Three identical blocks are placed in a vertical stack, one on top of the other, as shown in Figure 3.23. The stack of blocks remains at rest on the floor. (a) Which block experiences the largest net force? Explain. (b) Compare the free-body diagram of block 2, in the middle of the stack, to that of block 3, at the bottom of the stack. Comment on any differences, if there are any, between the two free-body diagrams.

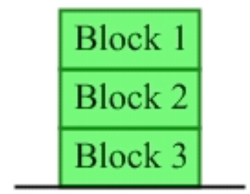


**Figure 3.23**: A stack of three identical blocks, for Exercise 7.

8. What situations can you think of in which one object exerts a larger-magnitude force on a second object than the second object exerts on the first object?

9. Describe a situation that matches each of the following, or state that it is impossible. (a) An object has no net force acting on it, and yet it is moving. (b) An object has a net force acting on it, but it remains at rest. (c) An object has at least one force acting on it, but it remains at rest.

10. A team of construction workers knows that the cable on a crane will break if its tension exceeds 8000 N. They then connect the cable to a load of bricks with a total weight of 7500 N. When the crane operator slowly raises the bricks off the ground, everything looks fine, and the team gives her the signal to go faster. As she increases the speed at which the bricks are being raised, however, the cable breaks, showering bricks on the ground below. Fortunately, everyone is wearing proper safety equipment, so there are no serious injuries. Using your knowledge of physics, can you come up with an explanation of the cause of the accident? Come up with two ways the accident could have been prevented.

11. Yuri, a cosmonaut on the space station, is taking a spacewalk outside of the station to fix a malfunctioning array of solar cells that provide electricity for the station. Unfortunately, he forgets to tether himself to the station, and his rocket pack also is not working, so when he finds himself drifting slowly away from the station Yuri realizes he's in a bit of trouble. Fortunately he is holding a large wrench. Based on the principles of physics we have discussed in this chapter, explain what Yuri can do to get himself back to the space station.

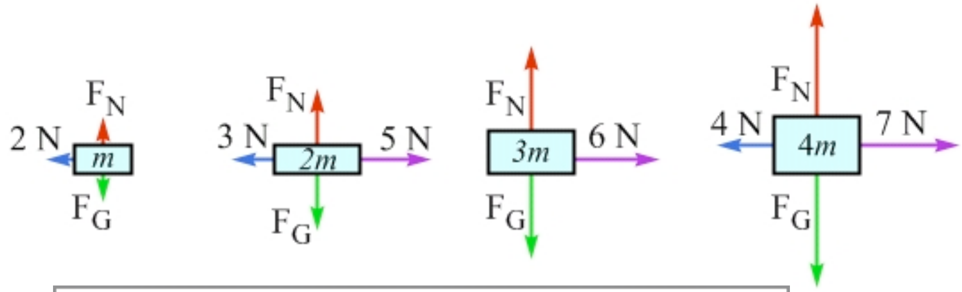


**Figure 3.24**: Four free-body diagrams, for Exercise 12. On each free-body diagram, the magnitude of the normal force, $\vec{F}_N$, is equal to the magnitude of the force of gravity, $\vec{F}_G$.

12. Four free-body diagrams are shown in Figure 3.24, for objects that have masses of *m*, 2*m*, 3*m*, and 4*m*, respectively. Rank these situations, from largest to smallest, based on (a) the net force being applied to the object, and (b) the acceleration of the object. Your answers should have the form 3>2=4>1.

**Exercises 13 - 20 are designed to give you practice with free-body diagrams.**

13. You are at rest, sitting down with your weight completely supported by a chair. Sketch a free-body diagram for (a) you, and (b) the chair.

14. Repeat Exercise 13, except that now you and the chair are inside an elevator that has a constant velocity directed down. Sketch a free-body diagram for (a) you, and (b) the chair. (c) Comment on what, if anything, changes on the free-body diagrams here compared to those you drew in Exercise 13.

15. Repeat Exercise 13, except that now you and the chair are inside an elevator that has a constant acceleration directed down.

16. You step off a chair and allow yourself to drop, feet first, straight down to the floor below. Sketch your free-body diagram while you are (a) dropping to the floor, not in contact with anything, (b) slowing down, after your feet initially make contact with the floor, and (c) at rest, standing on the floor. (d) What would a bathroom scale, on the floor, read if you landed on it instead of the floor while you were in the three positions in (a), (b), and (c)? Would the scale reading equal your mass, or not? (e) Are your answers in (d) consistent with the free-body diagrams you drew in (a) – (c)? Explain.

17. A ball is initially at rest in your hand. You then accelerate the ball upwards, releasing it so that it goes straight up into the air. When it comes down, you catch it and bring it to rest again. Neglect air resistance. Sketch a free-body diagram for the ball when it is (a) accelerating upward in your hand; (b) moving up after you release it; (c) at rest, just for an instant, at the top of its flight; (d) moving down before you catch it; (e) slowing down after it makes contact with your hand again. (f) What is the minimum number of unique free-body diagrams that you can draw to represent the five situations described in (a) – (e)? Explain.


**Figure 3.25**: Two situations involving two boxes placed side-by-side on a frictionless surface, for Exercises 18 – 20.

18. As shown in Figure 3.25 (a), two boxes are initially at rest on a frictionless horizontal surface. The mass of the large box is five times larger than that of the small box. You then exert a horizontal force *F* directed right on the large box. Sketch a free-body diagram for (a) the two-box system (b) the large box (c) the small box. (d) Does the large box exert more force on the small box than the small box exerts on the large box? Explain.

19. Repeat Exercise 18, except that now the position of the boxes is reversed, as shown in Figure 3.25 (b).

20. In which case above, in Exercise 18 or Exercise 19, is the force that the large box exerts on the small box larger in magnitude? Explain.

**Exercises 21 – 30 are designed to give you practice with applying the general method for solving a problem that involves Newton's laws.** For each exercise, start by doing the following: (a) Draw a diagram of the situation. (b) Draw one or more free-body diagram(s) showing all the forces that act on various objects or systems. (c) Choose an appropriate coordinate system for each free-body diagram. (d) Apply Newton's second law to each free-body diagram.

21. You pull on a horizontal string attached to a small block that is initially at rest on a horizontal frictionless surface. The block has an acceleration of 3.0 m/s$^2$ when you exert a force of 6.0 N. Parts (a) – (d) as described above. (e) What is the mass of the block?

22. Jennifer, Katie, and Leah are attempting to push Katie's car, which has run out of gas. The car has a mass of 1500 kg. Each woman exerts a force of 200 N while pushing the car forward, and, once they get the car moving, there is a net resistive force of 570 N opposing the motion. Parts (a) – (d) as described above. (e) What is the magnitude of the car's acceleration?

23. A small box with a weight of 10 N is placed on top of a larger box with a weight of 40 N. The boxes are at rest on the top of a horizontal table. Parts (a) – (d) as described above, in part (b) drawing three free-body diagrams, one for each of the boxes and one for the two-box system. What is the magnitude and direction of the force exerted on the large box by (e) the small box? (f) the table?

24. Repeat Exercise 23, except that now the system of boxes and the table are inside an elevator that has a constant acceleration down of $g/2$.

25. A small box with a weight of 10 N is placed on top of a larger box with a weight of 40 N. The boxes are at rest on the top of a horizontal table. You apply an additional downward force of 10 N to the top of the small box by resting your hand on it. Parts (a) – (d) as described above, in part (c) drawing three free-body diagrams, one for each of the boxes and one for the two-box system. What is the magnitude and direction of the force exerted on the large box by (e) the small box? (f) the table?

26. A small block with a weight of 4 N is hung from a string that is tied to the ceiling of an elevator that is at rest. A large block, with a weight of 8 N, is hung from a second string that hangs down from the small block. Parts (a) – (d) as described above, in part (c) drawing three free-body diagrams, one for the each block and one for the two-block system. If the elevator is at rest, find the tension in (e) the string tied to the ceiling of the elevator; (f) the string between the blocks.

27. Return to the situation described in Exercise 26. Repeat the exercise with the elevator now having an acceleration of $g/4$ directed up.

28. Erin is playing on the floor with a wooden toy train consisting of an engine with a mass of 800 g and two passenger cars, each with a mass of 600 g. The three parts of the train are arranged in a line and are connected by horizontal strings of negligible mass. Erin accelerates the entire train forward at 4.0 m/s$^2$ by pulling horizontally on another string attached to the front of the engine. Neglect friction. Parts (a) – (d) as described above, in part (c) drawing four free-body diagrams, one for the engine, one for each of the passenger cars, and one for the entire train. (e) What is the tension in each of the three strings?

29. Two boxes, one with a mass two times larger than the other, are placed on a frictionless horizontal surface and tied together by a horizontal string, as shown in Figure 3.26(a). You then apply a horizontal force of 30 N to the left by pulling on another string attached to the larger box. Part (a), the diagram, is already done. Parts (b) – (d) as described above, in part (c) drawing three free-body diagrams, one for each box and one for the two-box system. (e) Find the magnitude of the tension in the string between the boxes.


**Figure 3.26**: Two situations involving two boxes on a horizontal surface. The boxes are connected by a string of negligible mass. For Exercises 29 and 30.

30. Repeat Exercise 29, but now you apply a horizontal force of 30 N to the right by pulling on a string attached to the smaller box, as shown in Figure 3.26(b).

**Exercises 31 – 40 are designed to give you some practice connecting the force ideas from this chapter to the motion with constant acceleration ideas from Chapter 2.**

31. A car with a mass of 2000 kg experiences a horizontal net force, directed east, of 4000 N for 10 seconds. What is the car's final velocity if the initial velocity of the car is (a) zero (b) 10 m/s east (c) 20 m/s west.

32. A flea, with a mass of 500 nanograms, reaches a maximum height of 50 cm after pushing on the ground for 1.3 milliseconds. What is the average force the ground exerts on the flea while the flea is in contact with the ground as it accelerates up?

33. Yolanda, having a mass of 50 kg, steps off a 2.0-meter high wall and drops down to the ground below. What is the average force exerted on Yolanda by the ground if, after first making contact with the ground, she comes to rest by bending at the knees so her upper body drops an additional distance of (a) 3 cm (b) 30 cm?

34. In a demonstration known as the vacuum bazooka, a ping-pong ball is placed inside a PVC tube, the ends of the tube are sealed with tape or foil, and most of the air is removed from the tube. The demonstrator then pierces the seal at the end of the tube where the ball is, and the in-rushing air accelerates the ball along the tube until the ball bursts through the seal at the far end and emerges from the tube at high speed. (a) If the mass of the ball is 2.5 g, the tube is approximately horizontal and has a length of 1.5 m, and the average force the air exerts on the ball is 100 N, find an upper limit for the ball's speed when it emerges from the tube. (b) In practice, the ball's speed is impressive but somewhat less than the theoretical maximum speed determined in (a). What are some factors that could reduce the ball's speed when it emerges from the tube?

35. In a tennis match, Serena Williams hits a ball that has a velocity of 20 m/s directed horizontally. If the force of her racket is applied for 0.10 s, causing the ball to completely reverse direction and acquire a velocity of 30 m/s directed horizontally, what is the average horizontal force the racket applies to the ball? A tennis ball has a mass of 57 grams.

36. Consider the motion diagram shown in Figure 3.27. If the vertical marks in the diagram are 1.0 meters apart, the object has a mass of 2.0 kg, and the images of the object are shown at 1.0-second intervals, determine the net force applied to the object if the object is moving with a constant acceleration from (a) left to right (b) right to left.

**Figure 3.27**: Motion diagram for Exercise 36.

37. Consider the motion diagram shown in Figure 3.28. Describe the general behavior, over the 12-second interval shown in the diagram, of a net force that could be applied to the object to produce this motion diagram.

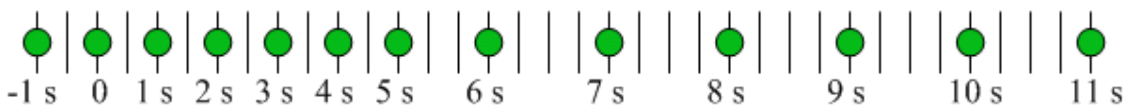


**Figure 3.28**: Motion diagram for Exercise 37.

38. A plot of a cat's velocity as a function of time is shown in Figure 3.29. If the cat has a mass of 5.0 kg, plot the corresponding net force vs. time graph for the cat.

39. Starting from rest, a person on a bicycle travels 200 m in 20 s, moving in a straight line on a horizontal road. Assuming that the acceleration is constant over this time interval, determine the magnitude of the horizontal force applied to the person-bicycle system in the direction of motion if there is a constant resistive force of 20 N acting horizontally opposite to the direction of motion and the person-bicycle system has a combined mass of 80 kg.

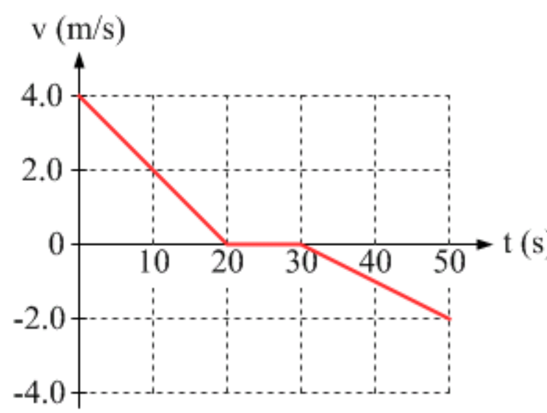


**Figure 3.29**: A graph of velocity versus time, for Exercise 38.

**Exercises 40 – 44 involve applications of forces in one dimension.**

40. A baseball pitcher can accelerate a 150-g baseball from rest to a horizontal velocity of 150 km/h over a distance of 2.0 m. What is the average horizontal force the pitcher exerts on the ball during the throwing motion?

41. You read in the paper about a planet that has been discovered orbiting a distant star. The astrophysicist quoted in the newspaper article states that the acceleration due to gravity on this planet is about 20% larger than that here on Earth. In an attempt to simulate what it would feel like to live on this newly discovered planet, you get into an elevator on the third floor of a five-story building. (a) To have an apparent weight larger than your actual weight immediately when the elevator starts to move, should you press the button for the

first floor or the fifth floor? (b) What does the acceleration of the elevator have to be for you to feel (at least briefly!) like you are living on the newly discovered planet?

42. Modern cars are designed with a number of important safety features to protect you in a crash. These include crumple zones, air bags, and seat belts. Consider how a crumple zone (a section of the car that is designed to compress, like an accordion, as does the front of the car in the photograph of a crash test shown in Figure 3.30) and a seat belt work together in a head-on collision in which you go from a speed of 120 km/h to rest. (a) If you are not wearing a seat belt then, in the crash, you generally keep moving forward until you hit something like the windshield. If you come to rest after decelerating through a distance of 4.0 cm after hitting the windshield, what is the magnitude of your average acceleration? (b) If, instead, you are wearing your seat belt, it keeps you in your seat, and you keep moving forward as the front of the car crumples like an accordion. If the compression of the crumple zone is 80 cm, what is the magnitude of your average acceleration? (c) In which case do you think you have a better chance of surviving the crash?

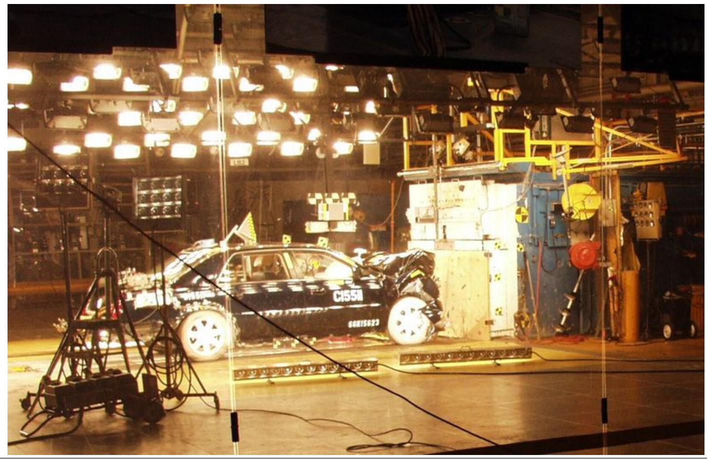

**Figure 3.30**: In this crash-test photo, the crumple zone at the front of the vehicle has compressed like an accordion, leaving the car's passenger cabin intact. For Exercise 42. Photo credit: Douglas Waite, via Wikimedia Commons.

43. A "solar sailboat" is a space probe that is propelled by sunlight reflecting off a shiny sail with a large area. Let's say the probe and sail have a combined mass of 1000 kg and that the net force exerted on the system is 4.0 N directed away from the Sun. (a) What is the acceleration of the probe/sail system? If the system is released from rest, how fast will it be traveling after (b) 1 day? (c) 1 week? The net force will actually decrease in magnitude as the probe gets farther from the Sun, but let's not worry about that.

44. NASA's Goddard Space Center is named after Robert Goddard of Worcester, Massachusetts, who was a pioneer in the field of rocketry. After Goddard published a paper in 1919 about rockets, the New York Times, in 1920, published an editorial lambasting Goddard, and stating that everybody knows that rockets won't travel in the vacuum of space, where there is nothing to push against. (The paper retracted the statement in 1969, after the launch of Apollo 11.) How does a rocket work? How would you respond to the issue raised by the Times?


**Figure 3.31**: In 1964, Robert Goddard was honored by the United States Postal Service, via this image on an 8-cent stamp, for his contributions to rocketry. For Exercise 44. Photo credit: Wikimedia Commons.

## General Problems and Conceptual Questions.

45. Three children are pushing a very large ball, which has a mass of 10 kg, around a field. If each child exerts a force of 12 N, determine the maximum and minimum possible values of the ball's acceleration. Assume the ball is in contact with the ground, and the normal force from the ground acting on the ball exactly balances the force of gravity acting on the ball.

46. A box with a weight of 25 N remains at rest when it is placed on a ramp that is inclined at 30˚ with respect to the horizontal. What is the magnitude and direction of the contact force exerted on the box by the ramp?

47. You exert a horizontal force of 10 N on a box with a weight of 25 N, but it remains at rest on a horizontal tabletop. What is the magnitude of the contact force exerted on the box by the table?

48. In the following situations, which object exerts a larger-magnitude force on the other? (a) The head of a golf club strikes a golf ball. In other words, does the club exert more force on the ball than the ball exerts on the club, is the opposite true, or is there another answer? (b) While stretching, you push on a wall. (c) A large truck and a small car have a head-on collision on the freeway. (d) The Earth orbits the Sun.

49. Three blocks are tied in a vertical line by three strings, and the top string is tied to the ceiling of an elevator that is initially at rest (see Figure 3.32). If the tension in string 3 is $T$ what is the tension in (a) string 2? (b) string 1 (in terms of $T$)?

50. Return to the situation described in Exercise 49. Use $g = 10$ m/s$^2$. What is the magnitude of the tension in the second string if the elevator is (a) at rest? (b) moving at a constant velocity of 2.0 m/s up? (c) accelerating up at 2.0 m/s$^2$? (d) accelerating down at 2.0 m/s$^2$?

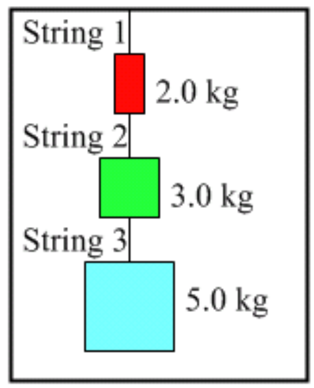


**Figure 3.32**: Three blocks connected by strings and tied to the ceiling of an elevator, for Exercises 49 and 50.

51. Three blocks are placed side-by-side on a horizontal frictionless surface and subjected to a horizontal force $F$, as shown in case 1 of Figure 3.33, which causes the blocks to accelerate to the right. The blocks are then re-arranged, as in case 2, and subjected again to the same horizontal force $F$. (a) In which case does the 2.0 kg block experience a larger net force? (b) In terms of $F$, calculate the magnitude of the net force on the 2.0 kg block in (i) Case 1 (ii) Case 2. (c) In which case does the 5.0 kg block exert more force on the 2.0 kg block? (d) In terms of $F$, calculate the magnitude of the force exerted by the 5.0 kg block on the 2.0 kg block in (i) Case 1 (ii) Case 2.

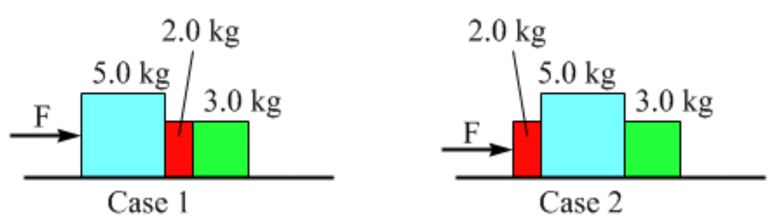


**Figure 3.33**: Two situations involving three blocks being pushed from the left by a horizontal force $F$, for Exercise 51.

52. As shown in Figure 3.34, a mobile made from ten 1.0 N balls is tied to the ceiling. Assume the other parts of the mobile (the strings and rods) have negligible mass. What is the tension in the string (a) above the green ball? (b) above the red rod? (c) tying the mobile to the ceiling?

53. Repeat Exercise 52, but this time let's say that the mobile is tied to the ceiling of an elevator, and that the elevator is accelerating down at *g*/2.

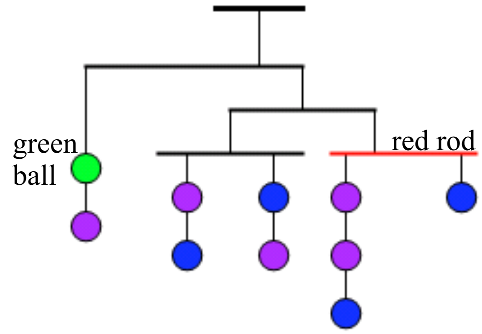


**Figure 3.34**: A mobile made from 10 balls and some light strings and rods, for Exercises 52 and 53.

54. You give a book a small push with your hand so that, after you remove your hand, the book slides for some distance across a table before coming to rest. (a) Sketch a motion diagram for the book as it is sliding, showing the book's position at regular time intervals after you remove your hand. (b) You should see a trend in your motion diagram. Does the distance between successive images of the book on the motion diagram change as time goes by? If so, how? (c) Sketch a free-body diagram for the book, showing all forces acting on the book as it is sliding, and after the period in which your hand was pushing the book. (d) What applies each of the forces on your free-body diagram? (e) Is there a net force acting on the book as it is sliding? If so, in what direction is it? (f) Is the book's motion consistent with this net force?

55. In Exploration 3.2B, we drew a free-body diagram for a ball falling straight down toward the floor. (a) Now, consider the free-body diagram for a ball you toss straight up in the air. While it is in flight (after it leaves your hand) does the free-body diagram differ from that in Exploration 3.2B? If so, in what way(s)? (b) Consider the free-body diagram for a ball you toss across the room to your friend. While the ball is in flight, does the free-body diagram differ from that in Exploration 3.2B? If so, in what way(s)?

56. You overhear two of your classmates discussing the issue of the force experienced by a ball that is tossed straight up into the air. Comment on each of their statements.

    *Sarah: Once the ball leaves my hand, the only force acting on it is gravity, so the ball's acceleration changes at a steady rate.*

    ***Tasha: But, after it leaves your hand, the ball is moving up, and gravity acts down. The ball must have the force of your throw acting on it as it moves up.***

    *Sarah: So what makes the ball slow down?*

    ***Tasha: As time goes by, the force of your throw decreases, and gravity takes over.***

57. A hockey puck of mass *m* is sliding across some ice at a constant speed of 8 m/s. It then experiences a head-on collision with a hockey stick of mass 5*m* that is lying on the ice. The puck is in contact with the stick for 0.10 s. After the collision, the puck is traveling at a constant speed of 2 m/s in the direction opposite what it was going originally. (a) Find the magnitude of the average force exerted on the puck by the stick during the collision. (b) Find the velocity of the stick after the collision. You can assume no friction acts on either object.

58. Consider the following situations involving a car of mass $m$ and a truck of mass $5m$. In each situation, state which force has a larger magnitude, the force the truck exerts on the car or the force the car exerts on the truck. (a) The truck collides with the car, which is parked by the side of the road. (b) The car collides with the truck, which is parked by the side of the road. (c) The vehicles have identical speeds and are going in opposite directions when they have a head-on collision. (d) The vehicles are going in opposite directions when they collide, with the car's speed being five times larger than the truck's speed.

59. Two boxes are side-by-side on a frictionless horizontal surface as shown in Figure 3.35. In Case 1, a horizontal force $F$ directed right is applied to the box of mass $M$. In Case 2, the horizontal force $F$ is instead directed left and applied to the box of mass $m$. Find an expression for the magnitude of $F_{Mm}$, the force the box of mass $M$ exerts on the box of mass $m$, in (a) Case 1 (b) Case 2. Express your answers in terms of variables given in the problem. (c) If $F_{Mm}$ is four times larger in case 2 than it is in case 1, find the ratio of the masses of the boxes.

60. Consider again the situation shown in Figure 3.35 and described in Exercise 59, but now let's say that $M = 2m$. In which case is the magnitude of the (a) acceleration of the two-box system larger? (b) acceleration of the box of mass $m$ larger? (c) force that the box of mass $M$ exerts on the box of mass $m$ larger? (d) force that the box of mass $m$ exerts on the box of mass $M$ larger?


**Figure 3.35**: Two cases involving two boxes on a frictionless surface, with an applied force, for Exercises 59 and 60.

61. You get on an elevator on the fifth floor of a building, stand on a regular bathroom scale, and then push a button in the elevator. The elevator doors close, and the elevator moves from the fifth floor to a different floor, where it stops and the doors open again. At this point, you get off the scale and exit the elevator. A graph of the scale reading as a function of time is shown in Figure 3.36. Use $g = 10$ m/s$^2$. Based on this graph, (a) qualitatively describe the motion of the elevator; (b) determine the magnitude of the peak acceleration of the elevator; (c) determine how far, and in what direction, the elevator moved.

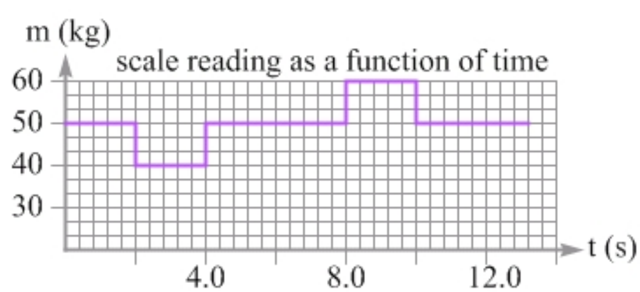


**Figure 3.36**: A graph of a scale reading as a function of time while you are standing on it in an elevator, for Exercise 61.