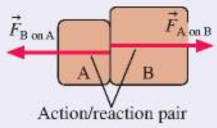
7 Newton's Third Law

The hammer and nail are interacting. The forces of the hammer on the nail and the nail on the hammer are an action/reaction pair of forces.

IN THIS CHAPTER, you will use Newton's third law to understand how objects interact.

What is an interaction?

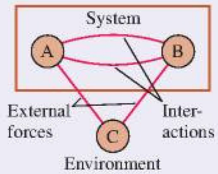
All forces are interactions in which objects exert forces on each other. If A pushes on B, then B pushes back on A. These two forces form an action/reaction pair of forces. One can't exist without the other.



« LOOKING BACK Section 5.5 Forces, interactions, and Newton's second law

What is an interaction diagram?

We will often analyze a problem by defining a system—the objects of interest—and the larger environment that acts on the system. An interaction diagram is a key visual tool for identifying action/reaction forces of interaction *inside* the system and external forces from agents in the environment.

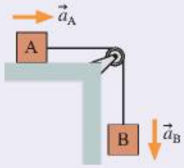


How do we model ropes and pulleys?

A common way that two objects interact is to be connected via a rope or cable or string. Pulleys change the direction of the tension forces. We will often model

- Ropes and strings as massless;
- Pulleys as massless and frictionless.

The objects' accelerations are constrained to have the same magnitude.



What is Newton's third law?

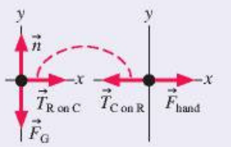
Newton's third law governs interactions:

- Every force is a member of an action/reaction pair.
- The two members of a pair act on different objects.
- The two members of a pair are equal in magnitude but opposite in direction.

How is Newton's third law used?

The dynamics problem-solving strategy of Chapter 6 is still our primary tool.

- Draw a free-body diagram for *each object*.
- Identify and show action/reaction pairs.
- Use Newton's second law for *each object*.
- Relate forces with Newton's third law.



« LOOKING BACK Section 6.2 Problem-Solving Strategy 6.1

Why is Newton's third law important?

We started our study of dynamics with only the first two of Newton's laws in order to practice identifying and using forces. But objects in the real world don't exist in isolation—they *interact* with each other. Newton's third law gives us a much more complete view of mechanics. The third law is also an essential tool in the practical application of physics to problems in engineering and technology.

7.1 Interacting Objects

FIGURE 7.1 The hammer and nail are interacting with each other.

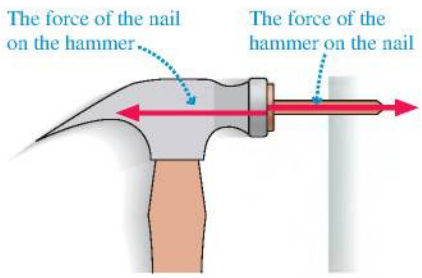
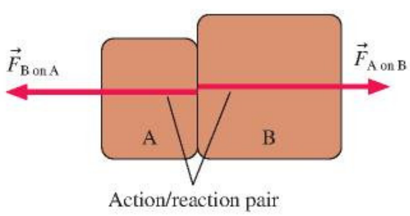


FIGURE 7.1 shows a hammer hitting a nail. The hammer exerts a force on the nail as it drives the nail forward. At the same time, the nail exerts a force on the hammer. If you're not sure that it does, imagine hitting the nail with a glass hammer. It's the force of the nail on the hammer that would cause the glass to shatter.

In fact, any time an object A pushes or pulls on another object B, B pushes or pulls back on A. When you pull someone with a rope in a tug-of-war, that person pulls back on you. Your chair pushes up on you (the normal force) as you push down on the chair. These are examples of an **interaction,** the mutual influence of two objects on each other.

To be more specific, if object A exerts a force $\vec{F}_{\text{A on B}}$ on object B, then object B exerts a force $\vec{F}_{\text{B on A}}$ on object A. This pair of forces, shown in FIGURE 7.2, is called an **action/reaction pair.** Two objects interact by exerting an action/reaction pair of forces on each other. Notice the very explicit subscripts on the force vectors. The first letter is the *agent;* the second letter is the object on which the force acts. $\vec{F}_{\text{A on B}}$ is a force exerted *by* A *on* B.

FIGURE 7.2 An action/reaction pair of forces.



NOTE The name "action/reaction pair" is somewhat misleading. The forces occur simultaneously, and we cannot say which is the "action" and which the "reaction." **An action/reaction pair of forces exists as a pair, or not at all.**

The hammer and nail interact through contact forces. Does the same idea hold true for long-range forces such as gravity? Newton was the first to realize that it does. His evidence was the tides. Astronomers had known since antiquity that the tides depend on the phase of the moon, but Newton was the first to understand that tides are the ocean's response to the gravitational pull of the moon on the earth.

Objects, Systems, and the Environment

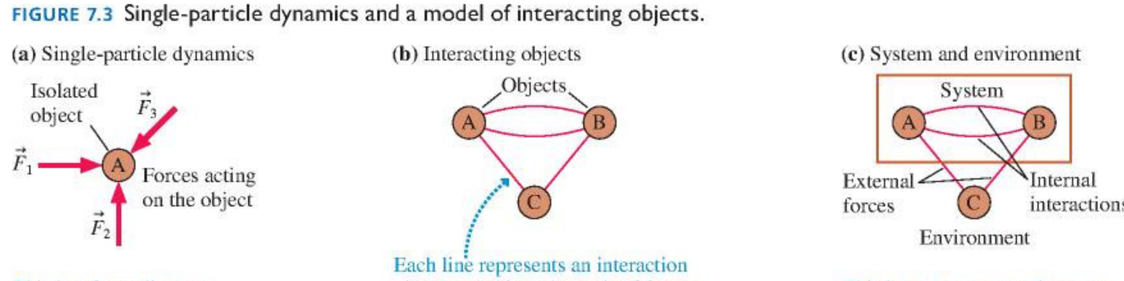
Chapters 5 and 6 considered forces acting on a single object that we modeled as a particle. FIGURE 7.3a shows a diagrammatic representation of single-particle dynamics. We can use Newton's second law, $\vec{a} = \vec{F}_{\text{net}}/m$, to determine the particle's acceleration.

We now want to extend the particle model to situations in which two or more objects, each represented as a particle, interact with each other. For example, FIGURE 7.3b shows three objects interacting via action/reaction pairs of forces. The forces can be given labels such as $\vec{F}_{\text{A on B}}$ and $\vec{F}_{\text{B on A}}$. How do these particles move?

We will often be interested in the motion of some of the objects, say objects A and B, but not of others. For example, objects A and B might be the hammer and the nail, while object C is the earth. The earth interacts with both the hammer and the nail via gravity, but in a practical sense the earth remains "at rest" while the hammer and nail move. Let's define the **system** as those objects whose motion we want to analyze and the **environment** as objects external to the system.

FIGURE 7.3c is a new kind of diagram, an **interaction diagram,** in which we've enclosed the objects of the system in a box and represented interactions as lines

FIGURE 7.3 Single-particle dynamics and a model of interacting objects.



connecting objects. This is a rather abstract, schematic diagram, but it captures the essence of the interactions. Notice that interactions with objects in the environment are called **external forces.** For the hammer and nail, the gravitational force on each—an interaction with the earth—is an external force.

NOTE *Every* force is one member of an action/reaction pair, so there is no such thing as a true "external force." What we call an external force is simply an interaction between an object of interest, one we've chosen to place inside the system, and an object whose motion is not of interest.

The bat and the ball are interacting with each other.

7.2 Analyzing Interacting Objects

TACTICS BOX 7.1

Analyzing interacting objects

1. **Represent each object as a circle** with a name and label. Place each in the correct position relative to other objects. The surface of the earth (label S; contact forces) and the entire earth (label EE; long-range forces) should be considered separate objects.
2. **Identify interactions.** Draw *one* connecting line between relevant circles to represent each interaction.
   - Every interaction line connects two and only two objects.
   - A surface can have two interactions: friction (parallel to the surface) and a normal force (perpendicular to the surface).
   - The entire earth interacts only by the long-range gravitational force.
3. **Identify the system.** Identify the objects of interest; draw and label a box enclosing them. This completes the interaction diagram.
4. **Draw a free-body diagram for each object in the system.** Include only the forces acting *on* each object, not forces exerted by the object.
   - Every interaction line crossing the system boundary is one external force acting on an object. The usual symbols, such as $\vec{n}$ and $\vec{T}$ can be used.
   - Every interaction line within the system represents an action/reaction pair of forces. There is one force vector on *each* of the objects, and these forces point in opposite directions. Use labels like $\vec{F}_{\text{A on B}}$ and $\vec{F}_{\text{B on A}}$.
   - Connect the two action/reaction forces—which must be on *different* free-body diagrams—with a dashed line.

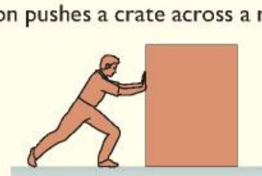
Exercises 1–7

We'll illustrate these ideas with two concrete examples. The first example will be much longer than usual because we'll go carefully through all the steps in the reasoning.

EXAMPLE 7.1 Pushing a crate

FIGURE 7.4 shows a person pushing a large crate across a rough surface. Identify all interactions, show them on an interaction diagram, then draw free-body diagrams of the person and the crate.

FIGURE 7.4 A person pushes a crate across a rough floor.



VISUALIZE The interaction diagram of FIGURE 7.5 on the next page starts by representing every object as a circle in the correct position but separated from all other objects. The person and the crate are obvious objects. The earth is also an object that both exerts and experiences forces, but it's necessary to distinguish between the surface, which exerts contact forces, and the entire earth, which exerts the long-range gravitational force.

Figure 7.5 also identifies the various interactions. Some, like the pushing interaction between the person and the crate, are fairly

Continued

FIGURE 7.5 The interaction diagram.

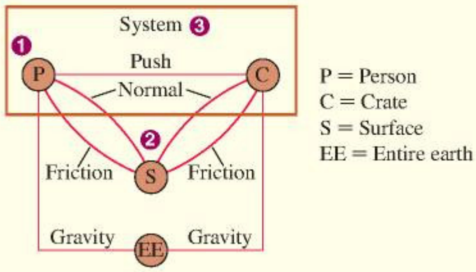
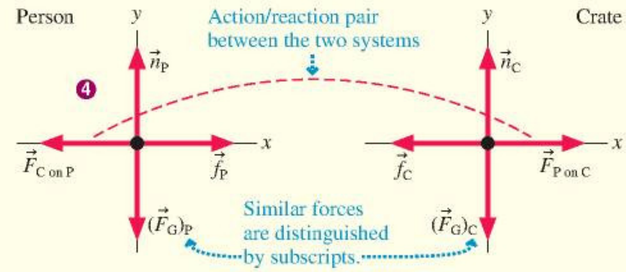


FIGURE 7.6 Free-body diagrams of the person and the crate.



obvious. The interactions with the earth are a little trickier. Gravity, a long-range force, is an interaction between each object and the earth as a whole. Friction forces and normal forces are contact interactions between each object and the earth's surface. These are two different interactions, so two interaction lines connect the crate to the surface and the person to the surface. Finally, we've enclosed the person and crate in a box labeled System. These are the objects whose motion we wish to analyze.

NOTE Interactions are between two *different* objects. None of the interactions are between an object and itself.

We can now draw free-body diagrams for the objects in the system, the crate and the person. **FIGURE 7.6** correctly locates the crate's free-body diagram to the right of the person's free-body diagram. For each, three interaction lines cross the system boundary and thus represent external forces. These are the gravitational force from the entire earth, the upward normal force from the surface, and a friction force from the surface. We can use familiar labels such as $\vec{n}_P$ and $\vec{f}_C$, but **it's very important to distinguish different forces with subscripts.** There's now more than one normal force. If you call both simply $\vec{n}$, you're almost certain to make mistakes when you start writing out the second-law equations.

The directions of the normal forces and the gravitational forces are clear, but we have to be careful with friction. Friction force $\vec{f}_C$ is kinetic friction of the crate sliding across the surface, so it points left, opposite the motion. But what about friction between the person and the surface? It is tempting to draw force $\vec{f}_P$ pointing to the left. After all, friction forces are supposed to be in the direction opposite the motion. But if we did so, the person would have two forces to the left, $\vec{F}_{C\text{ on }P}$ and $\vec{f}_P$, and none to the right, causing the person to accelerate *backward!* That is clearly not what happens, so what is wrong?

Imagine pushing a crate to the right across loose sand. Each time you take a step, you tend to kick the sand to the *left*, behind you. Thus friction force $\vec{f}_{P\text{ on }S}$, the force of the person pushing against the earth's surface, is to the *left*. In reaction, the force of the earth's surface against the person is a friction force to the *right*. It is force $\vec{f}_{S\text{ on }P}$, which we've shortened to $\vec{f}_P$, that causes the person to accelerate in the forward direction. Further, as we'll discuss more below, this is a *static* friction force; your foot is planted on the ground, not sliding across the surface.

Finally, we have one internal interaction. The crate is pushed with force $\vec{F}_{P\text{ on }C}$. If A pushes or pulls on B, then B pushes or pulls back on A, so the reaction to force $\vec{F}_{P\text{ on }C}$ is $\vec{F}_{C\text{ on }P}$, the crate pushing back against the person's hands. Force $\vec{F}_{P\text{ on }C}$ is a force exerted on the crate, so it's shown on the crate's free-body diagram. Force $\vec{F}_{C\text{ on }P}$ is exerted on the person, so it is drawn on the person's free-body diagram. **The two forces of an action/reaction pair never occur on the same free-body diagram.** We've connected forces $\vec{F}_{P\text{ on }C}$ and $\vec{F}_{C\text{ on }P}$ with a dashed line to show that they are an action/reaction pair.

Propulsion

The friction force $\vec{f}_P$ (force of surface on person) is an example of **propulsion.** It is the force that a system with an internal source of energy uses to drive itself forward. Propulsion is an important feature not only of walking or running but also of the forward motion of cars, jets, and rockets. Propulsion is somewhat counterintuitive, so it is worth a closer look.

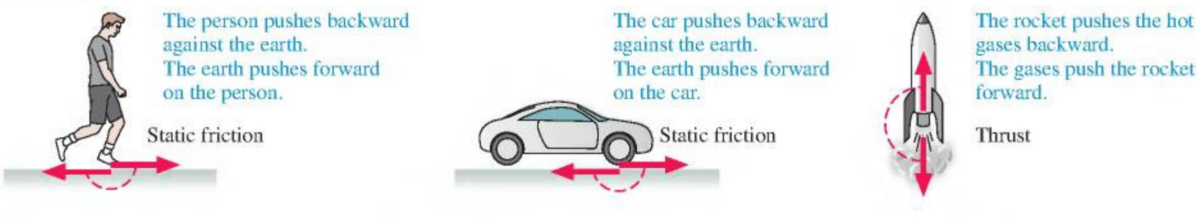
If you try to walk across a frictionless floor, your foot slips and slides *backward*. In order for you to walk, the floor needs to have friction so that your foot *sticks* to the floor as you straighten your leg, moving your body forward. The friction that prevents slipping is *static* friction. Static friction, you will recall, acts in the direction that prevents slipping. The static friction force $\vec{f}_P$ has to point in the *forward* direction to prevent your foot from slipping backward. It is this forward-directed static friction force that propels you forward! The force of your foot on the floor, the other half of the action/reaction pair, is in the opposite direction.

The distinction between you and the crate is that you have an *internal source of energy* that allows you to straighten your leg by pushing backward against the surface.

In essence, you walk by pushing the earth away from you. The earth's surface responds by pushing you forward. These are static friction forces. In contrast, all the crate can do is slide, so *kinetic* friction opposes the motion of the crate.

FIGURE 7.7 shows how propulsion works. A car uses its motor to spin the tires, causing the tires to push backward against the ground. This is why dirt and gravel are kicked backward, not forward. The earth's surface responds by pushing the car forward. These are also *static* friction forces. The tire is rolling, but the bottom of the tire, where it contacts the road, is instantaneously at rest. If it weren't, you would leave one giant skid mark as you drove and would burn off the tread within a few miles.

FIGURE 7.7 Examples of propulsion.



EXAMPLE 7.2 Towing a car

A tow truck uses a rope to pull a car along a horizontal road, as shown in **FIGURE 7.8**. Identify all interactions, show them on an interaction diagram, then draw free-body diagrams of each object in the system.

FIGURE 7.8 A truck towing a car.

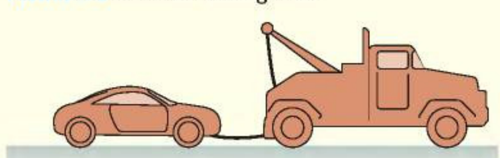
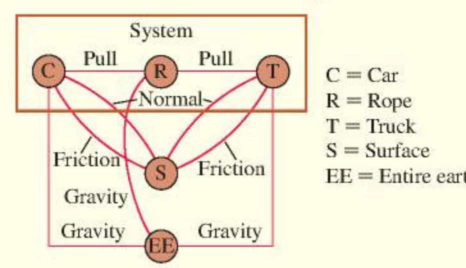


FIGURE 7.9 The interaction diagram.

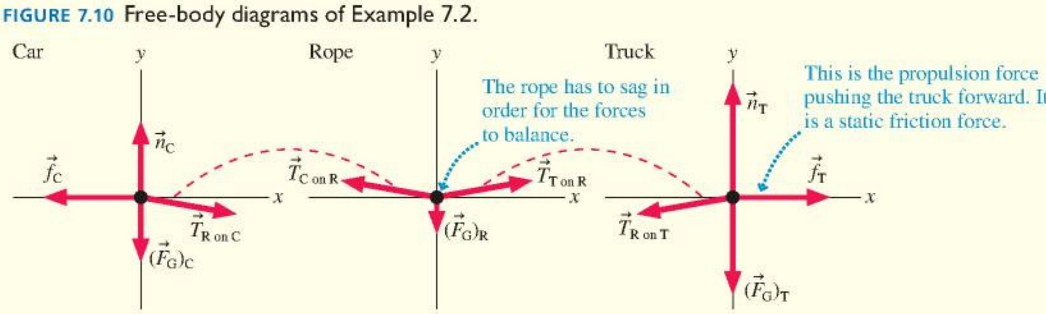


VISUALIZE The interaction diagram of **FIGURE 7.9** represents the objects as separate circles, but with the correct relative positions. The rope is shown as a separate object. Many of the interactions are identical to those in Example 7.1. The system—the objects in motion—consists of the truck, the rope, and the car.

The three objects in the system require three free-body diagrams, shown in **FIGURE 7.10**. Gravity, friction, and normal forces at the surface are all interactions that cross the system boundary and are shown as external forces. The car is an inert object rolling along. It would slow and stop if the rope were cut, so the surface must exert a rolling friction force $\vec{f}_C$ to the left. The truck, however, has an internal source of energy. The truck's drive wheels push the ground to the left with force $\vec{f}_{T \text{ on } S}$. In reaction, the ground propels the truck forward, to the right, with force $\vec{f}_T$.

We next need to identify the forces between the car, the truck, and the rope. The rope pulls on the car with a tension force $\vec{T}_{R \text{ on } C}$. You might be tempted to put the reaction force on the truck because we say that "the truck pulls the car," but the truck is not in contact

FIGURE 7.10 Free-body diagrams of Example 7.2.



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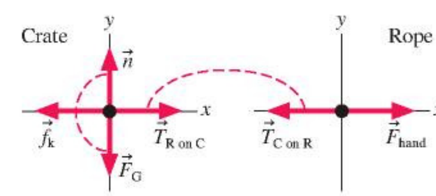
with the car. The truck pulls on the rope, then the rope pulls on the car. Thus the reaction to $\vec{T}_{\text{R on C}}$ is a force on the *rope:* $\vec{T}_{\text{C on R}}$. These are an action/reaction pair. At the other end, $\vec{T}_{\text{T on R}}$ and $\vec{T}_{\text{R on T}}$ are also an action/reaction pair.

NOTE Drawing an interaction diagram helps you avoid mistakes because it shows very clearly what is interacting with what.

Notice that the tension forces of the rope *cannot* be horizontal. If they were, the rope's free-body diagram would show a net downward force, because of its weight, and the rope would accelerate downward. The tension forces $\vec{T}_{\text{T on R}}$ and $\vec{T}_{\text{C on R}}$ have to angle slightly upward to balance the gravitational force, so any real rope has to sag at least a little in the center.

ASSESS Make sure you avoid the common error of considering $\vec{n}$ and $\vec{F}_G$ to be an action/reaction pair. These are both forces on the *same* object, whereas the two forces of an action/reaction pair are always on two *different* objects that are interacting with each other. The normal and gravitational forces are often equal in magnitude, as they are in this example, but that doesn't make them an action/reaction pair of forces.

STOP TO THINK 7.1 A rope of negligible mass pulls a crate across the floor. The rope and crate are the system; the hand pulling the rope is part of the environment. What, if anything, is wrong with the free-body diagrams?



7.3 Newton's Third Law

Newton was the first to recognize how the two members of an action/reaction pair of forces are related to each other. Today we know this as **Newton's third law:**

Newton's third law Every force occurs as one member of an action/reaction pair of forces.

- The two members of an action/reaction pair act on two *different* objects.
- The two members of an action/reaction pair are equal in magnitude but opposite in direction: $\vec{F}_{\text{A on B}} = -\vec{F}_{\text{B on A}}$.

We deduced most of the third law in Section 7.2. There we found that the two members of an action/reaction pair are always opposite in direction (see Figures 7.6 and 7.10). According to the third law, this will always be true. But the most significant portion of the third law, which is by no means obvious, is that the two members of an action/reaction pair have *equal* magnitudes. That is, $F_{\text{A on B}} = F_{\text{B on A}}$. This is the quantitative relationship that will allow you to solve problems of interacting objects.

Newton's third law is frequently stated as "For every action there is an equal but opposite reaction." While this is indeed a catchy phrase, it lacks the preciseness of our preferred version. In particular, it fails to capture an essential feature of action/reaction pairs—that they each act on a *different* object.

NOTE Newton's third law extends and completes our concept of *force.* We can now recognize force as an *interaction* between objects rather than as some "thing" with an independent existence of its own. The concept of an interaction will become increasingly important as we begin to study the laws of energy and momentum.

Reasoning with Newton's Third Law

Newton's third law is easy to state but harder to grasp. For example, consider what happens when you release a ball. Not surprisingly, it falls down. But if the ball and the earth exert equal and opposite forces on each other, as Newton's third law alleges, why doesn't the earth "fall up" to meet the ball?

The key to understanding this and many similar puzzles is that **the forces are equal but the accelerations are not.** Equal causes can produce very unequal effects. FIGURE 7.11 shows equal-magnitude forces on the ball and the earth. The force on ball B is simply the gravitational force of Chapter 6:

$$\vec{F}_{\text{earth on ball}} = (\vec{F}_{\text{G}})_{\text{B}} = -m_{\text{B}}g\hat{j} \tag{7.1}$$

where m_B is the mass of the ball. According to Newton's second law, this force gives the ball an acceleration

$$\vec{a}_{\text{B}} = \frac{(\vec{F}_{\text{G}})_{\text{B}}}{m_{\text{B}}} = -g\hat{j} \tag{7.2}$$

This is just the familiar free-fall acceleration.

According to Newton's third law, the ball pulls up on the earth with force $\vec{F}_{\text{ball on earth}}$. Because $\vec{F}_{\text{earth on ball}}$ and $\vec{F}_{\text{ball on earth}}$ are an action/reaction pair, $\vec{F}_{\text{ball on earth}}$ must be equal in magnitude and opposite in direction to $\vec{F}_{\text{earth on ball}}$. That is,

$$\vec{F}_{\text{ball on earth}} = -\vec{F}_{\text{earth on ball}} = -(\vec{F}_{\text{G}})_{\text{B}} = +m_{\text{B}}g\hat{j} \tag{7.3}$$

Using this result in Newton's second law, we find the upward acceleration of the earth as a whole is

$$\vec{a}_{\text{E}} = \frac{\vec{F}_{\text{ball on earth}}}{m_{\text{E}}} = \frac{m_{\text{B}}g\hat{j}}{m_{\text{E}}} = \left(\frac{m_{\text{B}}}{m_{\text{E}}}\right)g\hat{j} \tag{7.4}$$

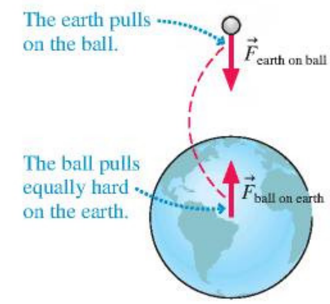
The upward acceleration of the earth is less than the downward acceleration of the ball by the factor m_B/m_E. If we assume a 1 kg ball, we can estimate the magnitude of $\vec{a}_E$:

$$\vec{a}_{\text{E}} = \frac{\vec{F}_{\text{ball on earth}}}{m_{\text{E}}} = \frac{m_{\text{B}}g\hat{j}}{m_{\text{E}}} = \left(\frac{m_{\text{B}}}{m_{\text{E}}}\right)g\hat{j}$$

With this incredibly small acceleration, it would take the earth 8×10^{15} years, approximately 500,000 times the age of the universe, to reach a speed of 1 mph! So we certainly would not expect to see or feel the earth "fall up" after we drop a ball.

NOTE Newton's third law equates the size of two forces, not two accelerations. The acceleration continues to depend on the mass, as Newton's second law states. **In an interaction between two objects of different mass, the lighter mass will do essentially all of the accelerating even though the forces exerted on the two objects are equal.**

FIGURE 7.11 The action/reaction forces of a ball and the earth are equal in magnitude.



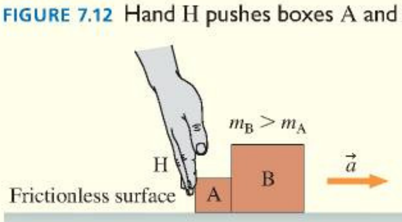
EXAMPLE 7.3 The forces on accelerating boxes

The hand shown in FIGURE 7.12 pushes boxes A and B to the right across a frictionless table. The mass of B is larger than the mass of A.

a. Draw free-body diagrams of A, B, and the hand H, showing only the *horizontal* forces. Connect action/reaction pairs with dashed lines.

b. Rank in order, from largest to smallest, the horizontal forces shown on your free-body diagrams.

FIGURE 7.12 Hand H pushes boxes A and B.



VISUALIZE a. The hand H pushes on box A, and A pushes back on H. Thus $\vec{F}_{\text{H on A}}$ and $\vec{F}_{\text{A on H}}$ are an action/reaction pair. Similarly, A pushes on B and B pushes back on A. **The hand H does not touch box B, so there is no interaction between them.** There is no friction. FIGURE 7.13 on the next page shows five horizontal forces and identifies two action/reaction pairs. Notice that each force is shown on the free-body diagram of the object that it acts *on.*

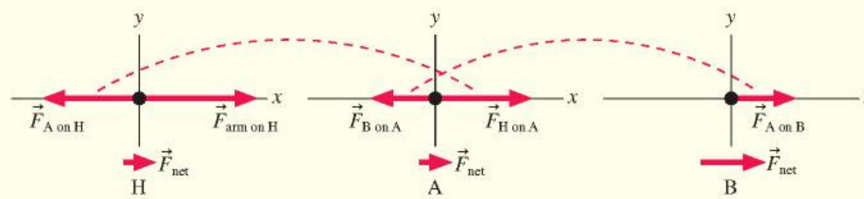
b. According to Newton's third law, $F_{\text{A on H}} = F_{\text{H on A}}$ and $F_{\text{A on B}} = F_{\text{B on A}}$. But the third law is not our only tool. The boxes are *accelerating* to the right, because there's no friction, so Newton's *second* law tells us that box A must have a net force to the right. Consequently, $F_{\text{H on A}} > F_{\text{B on A}}$. Similarly, $F_{\text{arm on H}} > F_{\text{A on H}}$ is needed to accelerate the hand. Thus

$$F_{\text{arm on H}} > F_{\text{A on H}} = F_{\text{H on A}} > F_{\text{B on A}} = F_{\text{A on B}}$$

Continued

ASSESS You might have expected $F_{\text{A on B}}$ to be larger than $F_{\text{H on A}}$ because $m_B > m_A$. It's true that the *net* force on B is larger than the *net* force on A, but we have to reason more closely to judge the individual forces. Notice how we used both the second and the third laws to answer this question.

FIGURE 7.13 The free-body diagrams, showing only the horizontal forces.



STOP TO THINK 7.2 A small car is pushing a larger truck that has a dead battery. The mass of the truck is larger than the mass of the car. Which of the following statements is true?

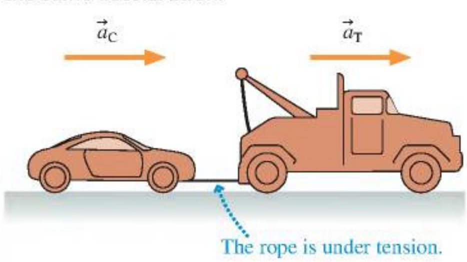
a. The car exerts a force on the truck, but the truck doesn't exert a force on the car.
b. The car exerts a larger force on the truck than the truck exerts on the car.
c. The car exerts the same amount of force on the truck as the truck exerts on the car.
d. The truck exerts a larger force on the car than the car exerts on the truck.
e. The truck exerts a force on the car, but the car doesn't exert a force on the truck.

Acceleration Constraints

Newton's third law is one quantitative relationship you can use to solve problems of interacting objects. In addition, we frequently have other information about the motion in a problem. For example, if two objects A and B move together, their accelerations are *constrained* to be equal: $\vec{a}_A = \vec{a}_B$. A well-defined relationship between the accelerations of two or more objects is called an **acceleration constraint.** It is an independent piece of information that can help solve a problem.

In practice, we'll express acceleration constraints in terms of the x- and y-components of $\vec{a}$. Consider the car being towed in FIGURE 7.14. This is one-dimensional motion, so we can write the acceleration constraint as

FIGURE 7.14 The car and the truck have the same acceleration.

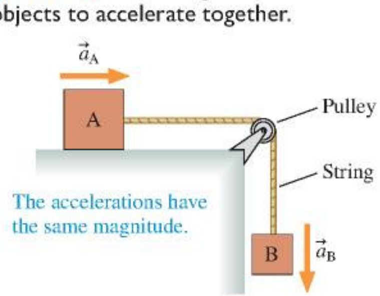


$$a_{Cx} = a_{Tx} = a_x$$

Because the accelerations of both objects are equal, we can drop the subscripts C and T and call both of them a_x.

Don't assume the accelerations of A and B will always have the same sign. Consider blocks A and B in FIGURE 7.15. The blocks are connected by a string, so they are constrained to move together and their accelerations have equal magnitudes. But A has a positive acceleration (to the right) in the x-direction while B has a negative acceleration (downward) in the y-direction. Thus the acceleration constraint is

FIGURE 7.15 The string constrains the two objects to accelerate together.



$$a_{Ax} = -a_{By}$$

This relationship does *not* say that a_{Ax} is a negative number. It is simply a relational statement, saying that a_{Ax} is (-1) times whatever a_{By} happens to be. The acceleration a_{By} in Figure 7.15 is a negative number, so a_{Ax} is positive. In some problems, the signs of a_{Ax} and a_{By} may not be known until the problem is solved, but the *relationship* is known from the beginning.

A Revised Strategy for Interacting-Objects Problems

Problems of interacting objects can be solved with a few modifications to the problem-solving strategy we developed in « Section 6.2.

PROBLEM-SOLVING STRATEGY 7.1

Interacting-objects problems

MODEL Identify which objects are part of the system and which are part of the environment. Make simplifying assumptions.

VISUALIZE Draw a pictorial representation.

- Show important points in the motion with a sketch. You may want to give each object a separate coordinate system. Define symbols, list acceleration constraints, and identify what the problem is trying to find.
- Draw an interaction diagram to identify the forces on each object and all action/reaction pairs.
- Draw a *separate* free-body diagram for each object showing only the forces acting *on* that object, not forces exerted by the object. Connect the force vectors of action/reaction pairs with dashed lines.

SOLVE Use Newton's second and third laws.

- Write the equations of Newton's second law for *each* object, using the force information from the free-body diagrams.
- Equate the magnitudes of action/reaction pairs.
- Include the acceleration constraints, the friction model, and other quantitative information relevant to the problem.
- Solve for the acceleration, then use kinematics to find velocities and positions.

ASSESS Check that your result has the correct units and significant figures, is reasonable, and answers the question.

You might be puzzled that the Solve step calls for the use of the third law to equate just the *magnitudes* of action/reaction forces. What about the "opposite in direction" part of the third law? You have already used it! Your free-body diagrams should show the two members of an action/reaction pair to be opposite in direction, and that information will have been utilized in writing the second-law equations. Because the directional information has already been used, all that is left is the magnitude information.

EXAMPLE 7.4 **Keep the crate from sliding**

You and a friend have just loaded a 200 kg crate filled with priceless art objects into the back of a 2000 kg truck. As you press down on the accelerator, force $\vec{F}_{\text{surface on truck}}$ propels the truck forward. To keep things simple, call this just $\vec{F}_T$. What is the maximum magnitude F_T can have without the crate sliding? The static and kinetic coefficients of friction between the crate and the bed of the truck are 0.80 and 0.30. Rolling friction of the truck is negligible.

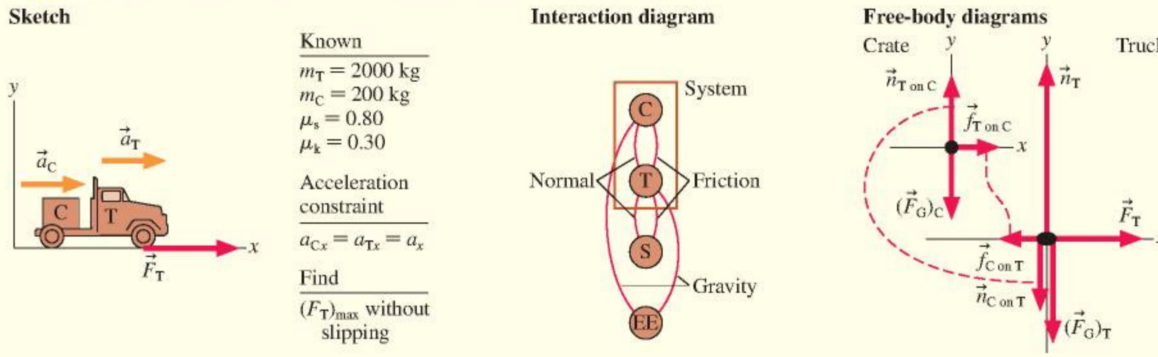
MODEL The crate and the truck are separate objects that form the system. We'll model them as particles. The earth and the road surface are part of the environment.

VISUALIZE The sketch in FIGURE 7.16 on the next page establishes a coordinate system, lists the known information, and—new to problems of interacting objects—identifies the acceleration constraint. As long as the crate doesn't slip, it must accelerate *with* the truck. Both accelerations are in the positive x-direction, so the acceleration constraint in this problem is $a_{Cx} = a_{Tx} = a_x$.

The interaction diagram of Figure 7.16 shows the crate interacting twice with the truck—a friction force parallel to the surface of the truck bed and a normal force perpendicular to this surface. The truck interacts similarly with the road surface, but notice that the crate does not interact with the ground; there's no contact between them. The two interactions within the system are each an action/reaction pair, so this is a total of four forces. You can also see four external forces crossing the system boundary, so the free-body diagrams should show a total of eight forces.

Continued

FIGURE 7.16 Pictorial representation of the crate and truck in Example 7.4.



Finally, the interaction information is transferred to the free-body diagrams, where we see friction between the crate and truck as an action/reaction pair and the normal forces (the truck pushes up on the crate, the crate pushes down on the truck) as another action/reaction pair. It's easy to overlook forces such as $\vec{f}_{C\text{ on }T}$, but you won't make this mistake if you first identify action/reaction pairs on an interaction diagram. Note that $\vec{f}_{C\text{ on }T}$ and $\vec{f}_{T\text{ on }C}$ are *static* friction forces because they are forces that prevent slipping; force $\vec{f}_{T\text{ on }C}$ must point forward to prevent the crate from sliding out the back of the truck.

SOLVE Now we're ready to write Newton's second law. For the crate:

$$\sum (F_{\text{on crate}})_x = f_{T\text{ on }C} = m_C a_{Cx} = m_C a_x$$
$$\sum (F_{\text{on crate}})_y = n_{T\text{ on }C} - (F_G)_C = n_{T\text{ on }C} - m_C g = 0$$

For the truck:

$$\sum (F_{\text{on truck}})_x = F_T - f_{C\text{ on }T} = m_T a_{Tx} = m_T a_x$$
$$\sum (F_{\text{on truck}})_y = n_T - (F_G)_T - n_{C\text{ on }T}$$
$$= n_T - m_T g - n_{C\text{ on }T} = 0$$

Be sure you agree with all the signs, which are based on the free-body diagrams. The net force in the y-direction is zero because there's no motion in the y-direction. It may seem like a lot of effort to write all the subscripts, but it is very important in problems with more than one object.

Notice that we've already used the acceleration constraint $a_{Cx} = a_{Tx} = a_x$. Another important piece of information is Newton's third law, which tells us that $f_{C\text{ on }T} = f_{T\text{ on }C}$ and $n_{C\text{ on }T} = n_{T\text{ on }C}$. Finally, we know that the maximum value of F_T will occur when the static friction on the crate reaches its maximum value:

$$f_{T\text{ on }C} = f_{s\text{ max}} = \mu_s n_{T\text{ on }C}$$

The friction depends on the normal force on the crate, not the normal force on the truck.

Now we can assemble all the pieces. From the y-equation of the crate, $n_{T\text{ on }C} = m_C g$. Thus

$$f_{T\text{ on }C} = \mu_s n_{T\text{ on }C} = \mu_s m_C g$$

Using this in the x-equation of the crate, we find that the acceleration is

$$a_x = \frac{f_{T\text{ on }C}}{m_C} = \mu_s g$$

This is the crate's maximum acceleration without slipping. Now use this acceleration *and* the fact that $f_{C\text{ on }T} = f_{T\text{ on }C} = \mu_s m_C g$ in the x-equation of the truck to find

$$F_T - f_{C\text{ on }T} = F_T - \mu_s m_C g = m_T a_x = m_T \mu_s g$$

Solving for F_T, we find the maximum propulsion without the crate sliding is

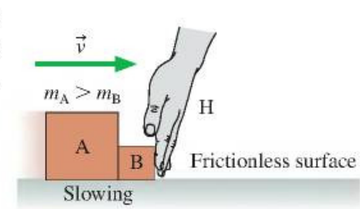
$$(F_T)_{max} = \mu_s(m_T + m_C)g$$
$$= (0.80)(2200\text{ kg})(9.80\text{ m/s}^2) = 17{,}000\text{ N}$$

ASSESS This is a hard result to assess. Few of us have any intuition about the size of forces that propel cars and trucks. Even so, the fact that the forward force on the truck is a significant fraction (80%) of the combined weight of the truck and the crate seems plausible. We might have been suspicious if F_T had been only a tiny fraction of the weight or much greater than the weight.

As you can see, there are many equations and many pieces of information to keep track of when solving a problem of interacting objects. These problems are not inherently harder than the problems you learned to solve in Chapter 6, but they do require a high level of organization. Using the systematic approach of the problem-solving strategy will help you solve similar problems successfully.

STOP TO THINK 7.3 Boxes A and B are sliding to the right across a frictionless table. The hand H is slowing them down. The mass of A is larger than the mass of B. Rank in order, from largest to smallest, the *horizontal* forces on A, B, and H.

a. $F_{B\text{ on }H} = F_{H\text{ on }B} = F_{A\text{ on }B} = F_{B\text{ on }A}$
b. $F_{B\text{ on }H} = F_{H\text{ on }B} > F_{A\text{ on }B} = F_{B\text{ on }A}$
c. $F_{B\text{ on }H} = F_{H\text{ on }B} < F_{A\text{ on }B} = F_{B\text{ on }A}$
d. $F_{H\text{ on }B} = F_{H\text{ on }A} > F_{A\text{ on }B}$



7.4 Ropes and Pulleys

Many objects are connected by strings, ropes, cables, and so on. In single-particle dynamics, we defined *tension* as the force exerted on an object by a rope or string. Now we need to think more carefully about the string itself. Just what do we mean when we talk about the tension "in" a string?

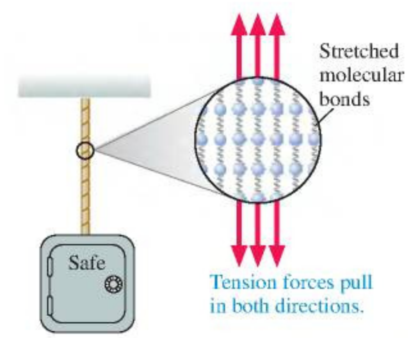
Tension Revisited

FIGURE 7.17 shows a heavy safe hanging from a rope, placing the rope under tension. If you cut the rope, the safe and the lower portion of the rope will fall. Thus there must be a force *within* the rope by which the upper portion of the rope pulls upward on the lower portion to prevent it from falling.

Chapter 5 introduced an atomic-level model in which tension is due to the stretching of spring-like molecular bonds within the rope. Stretched springs exert pulling forces, and the combined pulling force of billions of stretched molecular springs in a string or rope is what we call *tension.*

An important aspect of tension is that it pulls equally *in both directions.* To gain a mental picture, imagine holding your arms outstretched and having two friends pull on them. You'll remain at rest—but "in tension"—as long as they pull with equal strength in opposite directions. But if one lets go, analogous to the breaking of molecular bonds if a rope breaks or is cut, you'll fly off in the other direction!

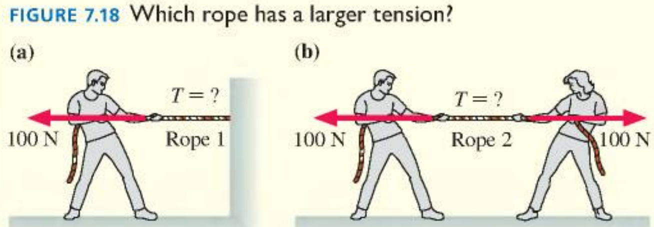
FIGURE 7.17 Tension forces within the rope are due to stretching the spring-like molecular bonds.



EXAMPLE 7.5 Pulling a rope

FIGURE 7.18a shows a student pulling horizontally with a 100 N force on a rope that is attached to a wall. In FIGURE 7.18b, two students in a tug-of-war pull on opposite ends of a rope with 100 N each. Is the tension in the second rope larger than, smaller than, or the same as that in the first rope?

FIGURE 7.18 Which rope has a larger tension?



SOLVE Surely pulling on a rope from both ends causes more tension than pulling on one end. Right? Before jumping to conclusions, let's analyze the situation carefully.

FIGURE 7.19a shows the first student, the rope, and the wall as separate, interacting objects. Force $\vec{F}_{\text{S on R}}$ is the student pulling on the rope, so it has magnitude 100 N. Forces $\vec{F}_{\text{S on R}}$ and $\vec{F}_{\text{R on S}}$ are an action/reaction pair and must have equal magnitudes. Similarly for forces $\vec{F}_{\text{W on R}}$ and $\vec{F}_{\text{R on W}}$. Finally, because the rope is in static equilibrium, *force* $\vec{F}_{\text{W on R}}$ *has to balance force* $\vec{F}_{\text{S on R}}$. Thus

$$F_{\text{R on W}} = F_{\text{W on R}} = F_{\text{S on R}} = F_{\text{R on S}} = 100\text{ N}$$

The first and third equalities are Newton's third law; the second equality is Newton's first law for the rope.

Forces $\vec{F}_{\text{R on S}}$ and $\vec{F}_{\text{R on W}}$ are the pulling forces exerted by the rope and are what we *mean* by "the tension in the rope." Thus the tension in the first rope is 100 N.

FIGURE 7.19b repeats the analysis for the rope pulled by two students. Each student pulls with 100 N, so $F_{\text{S1 on R}} = 100\text{ N}$ and $F_{\text{S2 on R}} = 100\text{ N}$. Just as before, there are two action/reaction pairs and the rope is in static equilibrium. Thus

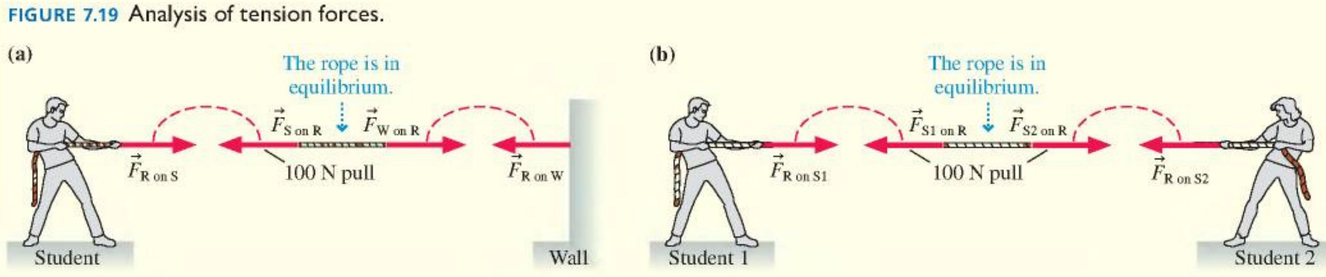
$$F_{\text{R on S2}} = F_{\text{S2 on R}} = F_{\text{S1 on R}} = F_{\text{R on S1}} = 100\text{ N}$$

The tension in the rope—the pulling forces $\vec{F}_{\text{R on S1}}$ and $\vec{F}_{\text{R on S2}}$—is still 100 N!

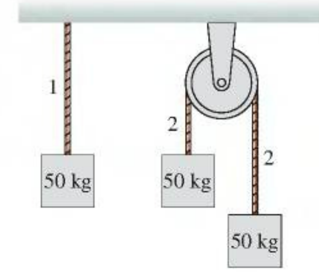
You may have *assumed* that the student on the right in Figure 7.18b is doing something to the rope that the wall in Figure 7.18a does not do. But our analysis finds that the wall, just like the student, pulls to the right with 100 N. The rope doesn't care whether it's pulled by a wall or a hand. It experiences the same forces in both cases, so the rope's tension is the same in both.

ASSESS Ropes and strings exert forces at *both* ends. The force with which they pull—and thus the force pulling on them at each end—*is* the tension in the rope. Tension is not the sum of the pulling forces.

FIGURE 7.19 Analysis of tension forces.

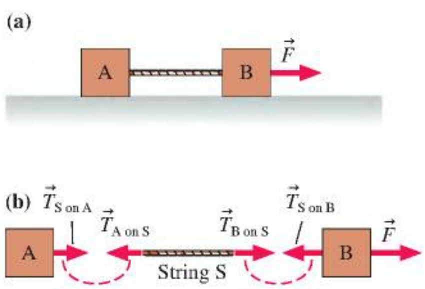


STOP TO THINK 7.4 All three 50 kg blocks are at rest. Is the tension in rope 2 greater than, less than, or equal to the tension in rope 1?



The Massless String Approximation

FIGURE 7.20 Tension pulls forward on block A, backward on block B.



The tension is constant throughout a rope that is in equilibrium, but what happens if the rope is accelerating? For example, FIGURE 7.20a shows two connected blocks being pulled by force $\vec{F}$. Is the string's tension at the right end, where it pulls back on B, the same as the tension at the left end, where it pulls on A?

FIGURE 7.20b shows the horizontal forces acting on the blocks and the string. The only horizontal forces acting on the string are $\vec{T}_{\text{A on S}}$ and $\vec{T}_{\text{B on S}}$, so Newton's second law *for the string* is

$$(F_{\text{net}})_x = T_{\text{B on S}} - T_{\text{A on S}} = m_S a_x \tag{7.5}$$

where m_S is the mass of the string. If the string is accelerating, then the tensions at the two ends can *not* be the same. The tension at the "front" of the string must be greater than the tension at the "back" in order to accelerate the string!

Often in physics and engineering problems the mass of the string or rope is much less than the masses of the objects that it connects. In such cases, we can adopt the **massless string approximation.** In the limit $m_S \rightarrow 0$, Equation 7.5 becomes

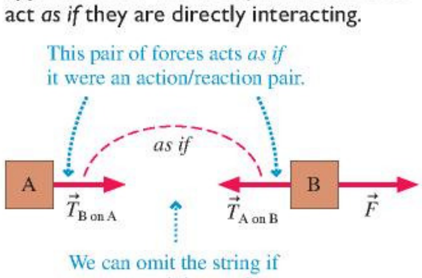
$$T_{\text{B on S}} = T_{\text{A on S}} \quad \text{(massless string approximation)} \tag{7.6}$$

In other words, **the tension in a massless string is constant.** This is nice, but it isn't the primary justification for the massless string approximation.

Look again at Figure 7.20b. If $T_{\text{B on S}} = T_{\text{A on S}}$, then

$$\vec{T}_{\text{S on A}} = -\vec{T}_{\text{S on B}} \tag{7.7}$$

FIGURE 7.21 The massless string approximation allows objects A and B to act *as if* they are directly interacting.



That is, the force on block A is equal and opposite to the force on block B. Forces $\vec{T}_{\text{S on A}}$ and $\vec{T}_{\text{S on B}}$ act *as if* they are an action/reaction pair of forces. Thus we can draw the simplified diagram of FIGURE 7.21 in which the string is missing and blocks A and B interact directly with each other through forces that we can call $\vec{T}_{\text{A on B}}$ and $\vec{T}_{\text{B on A}}$.

In other words, **if objects A and B interact with each other through a massless string, we can omit the string and treat forces $\vec{F}_{\text{A on B}}$ and $\vec{F}_{\text{B on A}}$ as if they are an action/reaction pair.** This is not literally true because A and B are not in contact. Nonetheless, all a massless string does is transmit a force from A to B without changing the magnitude of that force. This is the real significance of the massless string approximation.

NOTE For problems in this book, you can assume that any strings or ropes are massless unless the problem explicitly states otherwise. The simplified view of Figure 7.21 is appropriate under these conditions. But if the string has a mass, it must be treated as a separate object.

EXAMPLE 7.6 Comparing two tensions

Blocks A and B in FIGURE 7.22 are connected by massless string 2 and pulled across a frictionless table by massless string 1. B has a larger mass than A. Is the tension in string 2 larger than, smaller than, or equal to the tension in string 1?

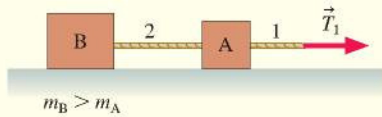


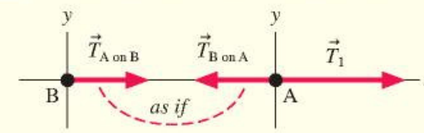
FIGURE 7.22 Blocks A and B are pulled across a frictionless table by massless strings.

MODEL The massless string approximation allows us to treat A and B *as if* they interact directly with each other. The blocks are accelerating because there's a force to the right and no friction.

SOLVE B has a larger mass, so it may be tempting to conclude that string 2, which pulls B, has a greater tension than string 1, which pulls A. The flaw in this reasoning is that Newton's second law tells us only about the *net* force. The net force on B *is* larger than the net force on A, but the net force on A is *not* just the tension $\vec{T}_1$ in the forward direction. The tension in string 2 also pulls *backward* on A!

FIGURE 7.23 shows the horizontal forces in this frictionless situation. Because the string is massless, forces $\vec{T}_{A\text{ on }B}$ and $\vec{T}_{B\text{ on }A}$ act *as if* they are an action/reaction pair.

FIGURE 7.23 The horizontal forces on blocks A and B.



From Newton's third law,

$$T_{A\text{ on }B} = T_{B\text{ on }A} = T_2$$

where T_2 is the tension in string 2. From Newton's second law, the net force on A is

$$(F_{A\text{ net}})_x = T_1 - T_{B\text{ on }A} = T_1 - T_2 = m_A a_{Ax}$$

The net force on A is the *difference* in tensions. The blocks are accelerating to the right, making $a_{Ax} > 0$, so

$$T_1 > T_2$$

The tension in string 2 is *smaller* than the tension in string 1.

ASSESS This is not an intuitively obvious result. A careful study of the reasoning in this example is worthwhile. An alternative analysis would note that $\vec{T}_1$ accelerates *both* blocks, of combined mass $(m_A + m_B)$, whereas $\vec{T}_2$ accelerates only block B. Thus string 1 must have the larger tension.

Pulleys

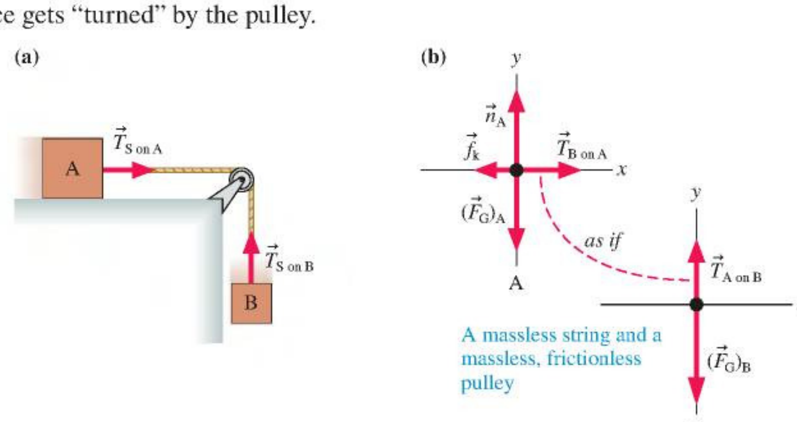
Strings and ropes often pass over pulleys. The application might be as simple as lifting a heavy weight or as complex as the internal cable-and-pulley arrangement that precisely moves a robot arm.

FIGURE 7.24a shows a simple situation in which block B, as it falls, drags block A across a table. As the string moves, static friction between the string and pulley causes the pulley to turn. If we assume that

- The string *and* the pulley are both massless, and
- There is no friction where the pulley turns on its axle,

then no net force is needed to accelerate the string or turn the pulley. Thus **the tension in a massless string remains constant as it passes over a massless, frictionless pulley.**

Because of this, we can draw the simplified free-body diagram of FIGURE 7.24b, in which the string and pulley are omitted. Forces $\vec{T}_{A\text{ on }B}$ and $\vec{T}_{B\text{ on }A}$ act *as if* they are an action/reaction pair, even though they are not opposite in direction because the tension force gets "turned" by the pulley.



◄ FIGURE 7.24 Blocks A and B are connected by a string that passes over a pulley.

TACTICS BOX 7.2

Working with ropes and pulleys

For massless ropes or strings and massless, frictionless pulleys:

- If a force pulls on one end of a rope, the tension in the rope equals the magnitude of the pulling force.
- If two objects are connected by a rope, the tension is the same at both ends.
- If the rope passes over a pulley, the tension in the rope is unaffected.

Exercises 17–22

STOP TO THINK 7.5 In Figure 7.24, on the previous page, is the tension in the string greater than, less than, or equal to the gravitational force acting on block B?

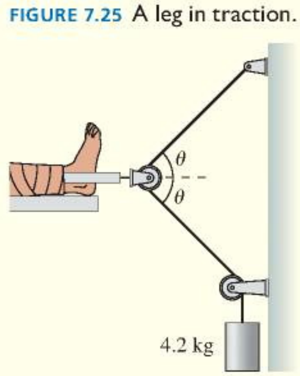
7.5 Examples of Interacting-Objects Problems

We will conclude this chapter with three extended examples. Although the mathematics will be more involved than in any of our work up to this point, we will continue to emphasize the *reasoning* one uses in approaching problems such as these. The solutions will be based on Problem-Solving Strategy 7.1. In fact, these problems are now reaching such a level of complexity that, for all practical purposes, it becomes impossible to work them unless you are following a well-planned strategy. Our earlier emphasis on forces and free-body diagrams will now really begin to pay off!

EXAMPLE 7.7 **Placing a leg in traction**

Serious fractures of the leg often need a stretching force to keep contracting leg muscles from forcing the broken bones together too hard. This is done using *traction*, an arrangement of a rope, a weight, and pulleys as shown in **FIGURE 7.25**. The rope must make the same angle on both sides of the pulley so that the net force on the leg is horizontal, but the angle can be adjusted to control the amount of traction. The doctor has specified 50 N of traction for this patient with a 4.2 kg hanging mass. What is the proper angle?

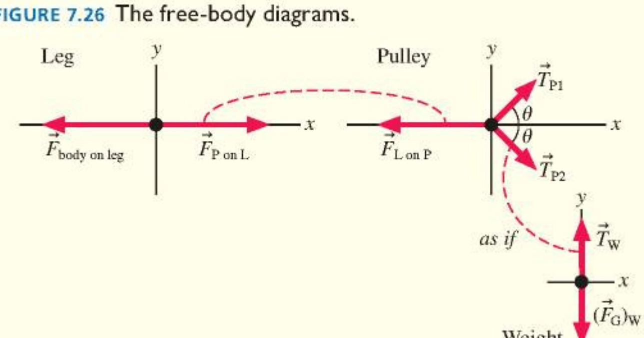
FIGURE 7.25 A leg in traction.



MODEL Model the leg and the weight as particles. The other point where forces are applied is the pulley attached to the patient's foot, which we'll treat as a separate object. We'll assume massless ropes and a massless, frictionless pulley.

VISUALIZE **FIGURE 7.26** shows three free-body diagrams. Forces $\vec{T}_{P1}$ and $\vec{T}_{P2}$ are the tension forces of the rope as it pulls on the pulley. The pulley is in equilibrium, so these forces are balanced by $\vec{F}_{L\text{ on }P}$, which forms an action/reaction pair with the 50 N traction force $\vec{F}_{P\text{ on }L}$. Our model of the rope and pulley makes the tension force constant, $T_{P1} = T_{P2} = T_W$, so we'll call it simply T.

FIGURE 7.26 The free-body diagrams.



SOLVE The x-component equation of Newton's second law for the pulley is

$$\sum (F_{\text{on P}})_x = T_{P1}\cos\theta + T_{P2}\cos\theta - F_{\text{L on P}}$$
$$= 2T\cos\theta - F_{\text{L on P}} = 0$$

Thus the correct angle for the ropes is

$$\theta = \cos^{-1}\left(\frac{F_{\text{L on P}}}{2T}\right)$$

We know, from Newton's third law, that $F_{\text{L on P}} = F_{\text{P on L}} = 50$ N. We can determine the tension force by analyzing the weight. It also is in equilibrium, so the upward tension force exactly balances the downward gravitational force:

$$T = (F_G)_W = m_W g = (4.2 \text{ kg})(9.80 \text{ m/s}^2) = 41 \text{ N}$$

Thus the proper angle is

$$\theta = \cos^{-1}\left(\frac{50 \text{ N}}{2(41 \text{ N})}\right) = 52°$$

ASSESS The traction force would approach 82 N if angle θ approached zero because the two ropes would pull in parallel. Conversely, the traction would approach 0 N if θ approached 90°. The desired traction is roughly midway between these two extremes, so an angle near 45° seems reasonable.

EXAMPLE 7.8 The show must go on!

A 200 kg set used in a play is stored in the loft above the stage. The rope holding the set passes up and over a pulley, then is tied backstage. The director tells a 100 kg stagehand to lower the set. When he unties the rope, the set falls and the unfortunate man is hoisted into the loft. What is the stagehand's acceleration?

MODEL The system is the stagehand M and the set S, which we will model as particles. Assume a massless rope and a massless, frictionless pulley.

VISUALIZE FIGURE 7.27 shows the pictorial representation. The man's acceleration a_{My} is positive, while the set's acceleration a_{Sy} is negative. These two accelerations have the same magnitude because the two objects are connected by a rope, but they have opposite signs. Thus the acceleration constraint is $a_{Sy} = -a_{My}$. Forces $\vec{T}_{\text{M on S}}$ and $\vec{T}_{\text{S on M}}$ are not literally an action/reaction pair, but they act *as if* they are because the rope is massless and the pulley is massless and frictionless. Notice that the pulley has "turned" the tension force so that $\vec{T}_{\text{M on S}}$ and $\vec{T}_{\text{S on M}}$ are *parallel* to each other rather than opposite, as members of a true action/reaction pair would have to be.

SOLVE Newton's second law for the man and the set is

$$\sum (F_{\text{on M}})_y = T_{\text{S on M}} - m_M g = m_M a_{My}$$
$$\sum (F_{\text{on S}})_y = T_{\text{M on S}} - m_S g = m_S a_{Sy} = -m_S a_{My}$$

Only the y-equations are needed. Notice that we used the acceleration constraint in the last step. Newton's third law is

$$T_{\text{M on S}} = T_{\text{S on M}} = T$$

where we can drop the subscripts and call the tension simply T. With this substitution, the two second-law equations can be written

$$T - m_M g = m_M a_{My}$$
$$T - m_S g = -m_S a_{My}$$

These are simultaneous equations in the two unknowns T and a_{My}. We can eliminate T by subtracting the second equation from the first to give

$$(m_S - m_M)g = (m_S + m_M)a_{My}$$

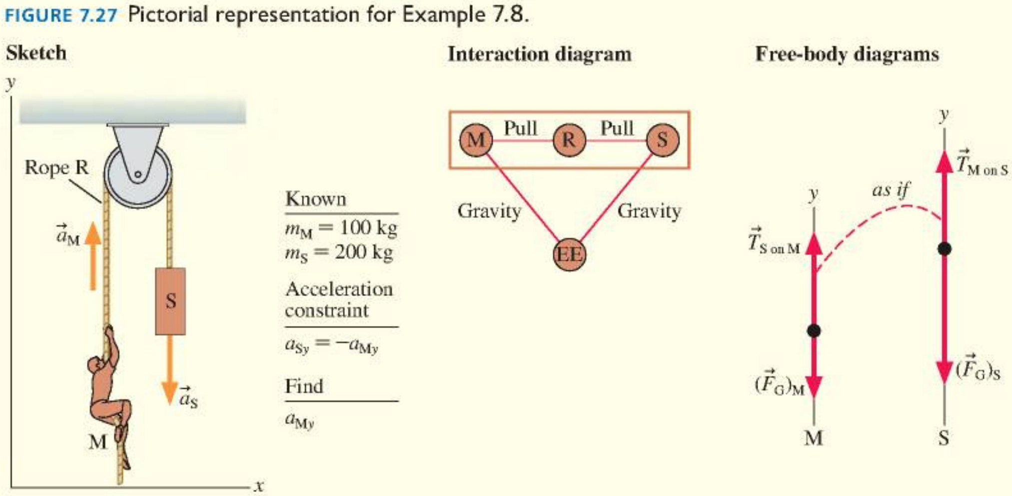
Finally, we can solve for the hapless stagehand's acceleration:

$$a_{My} = \frac{m_S - m_M}{m_S + m_M} g = \frac{100 \text{ kg}}{300 \text{ kg}} 9.80 \text{ m/s}^2 = 3.27 \text{ m/s}^2$$

This is also the acceleration with which the set falls. If the rope's tension was needed, we could now find it from $T = m_M a_{My} + m_M g$.

ASSESS If the stagehand weren't holding on, the set would fall with free-fall acceleration g. The stagehand acts as a *counterweight* to reduce the acceleration.

FIGURE 7.27 Pictorial representation for Example 7.8.



CHALLENGE EXAMPLE 7.9 A not-so-clever bank robbery

Bank robbers have pushed a 1000 kg safe to a second-story floor-to-ceiling window. They plan to break the window, then lower the safe 3.0 m to their truck. Not being too clever, they stack up 500 kg of furniture, tie a rope between the safe and the furniture, and place the rope over a pulley. Then they push the safe out the window. What is the safe's speed when it hits the truck? The coefficient of kinetic friction between the furniture and the floor is 0.50.

MODEL This is a continuation of the situation that we analyzed in Figures 7.15 and 7.24, which are worth reviewing. The system is the safe S and the furniture F, which we will model as particles. We will assume a massless rope and a massless, frictionless pulley.

VISUALIZE The safe and the furniture are tied together, so their accelerations have the same magnitude. The safe has a y-component of acceleration a_{Sy} that is negative because the safe accelerates in the negative y-direction. The furniture has an x-component a_{Fx} that is positive. Thus the acceleration constraint is

$$a_{Fx} = -a_{Sy}$$

The free-body diagrams shown in **FIGURE 7.28** are modeled after Figure 7.24 but now include a kinetic friction force on the furniture. Forces $\vec{T}_{\text{F on S}}$ and $\vec{T}_{\text{S on F}}$ act *as if* they are an action/reaction pair, so they have been connected with a dashed line.

SOLVE We can write Newton's second law directly from the free-body diagrams. For the furniture,

$$\sum (F_{\text{on F}})_x = T_{\text{S on F}} - f_k = T - f_k = m_F a_{Fx} = -m_F a_{Sy}$$
$$\sum (F_{\text{on F}})_y = n - m_F g = 0$$

And for the safe,

$$\sum (F_{\text{on S}})_y = T - m_S g = m_S a_{Sy}$$

Notice how we used the acceleration constraint in the first equation. We also went ahead and made use of Newton's third law: $T_{\text{F on S}} = T_{\text{S on F}} = T$. We have one additional piece of information, the model of kinetic friction:

$$f_k = \mu_k n = \mu_k m_F g$$

where we used the y-equation of the furniture to deduce that $n = m_F g$. Substitute this result for f_k into the x-equation of the furniture, then rewrite the furniture's x-equation and the safe's y-equation:

$$T - \mu_k m_F g = -m_F a_{Sy}$$
$$T - m_S g = m_S a_{Sy}$$

We have succeeded in reducing our knowledge to two simultaneous equations in the two unknowns a_{Sy} and T. Subtract the second equation from the first to eliminate T:

$$(m_S - \mu_k m_F)g = -(m_S + m_F)a_{Sy}$$

Finally, solve for the safe's acceleration:

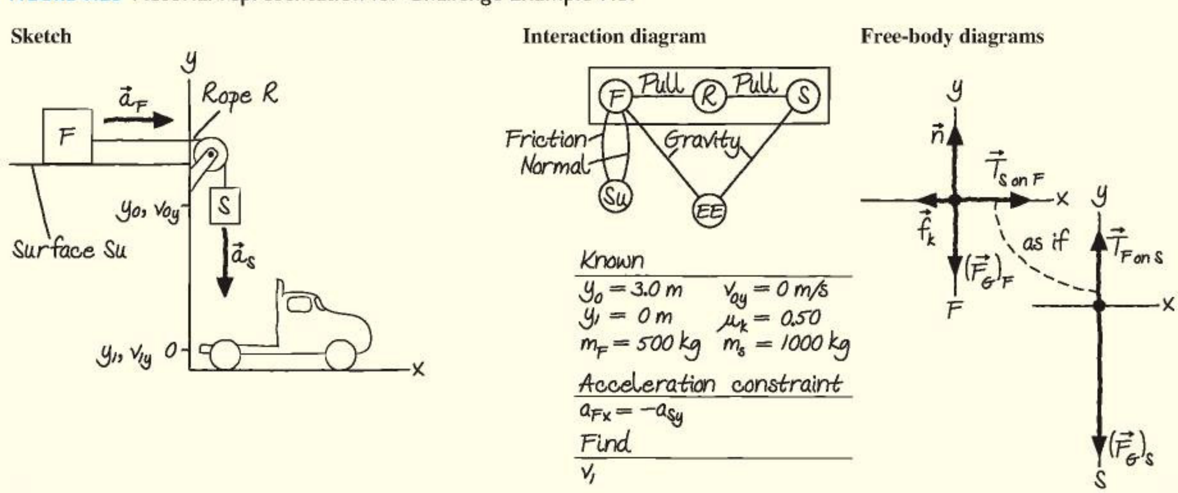
$$a_{Sy} = -\left(\frac{m_S - \mu_k m_F}{m_S + m_F}\right)g$$
$$= -\left(\frac{1000\text{ kg} - (0.50)(500\text{ kg})}{1000\text{ kg} + 500\text{ kg}}\right)9.80\text{ m/s}^2 = -4.9\text{ m/s}^2$$

Now we need to calculate the kinematics of the falling safe. Because the time of the fall is not known or needed, we can use

$$v_{1y}{}^2 = v_{0y}{}^2 + 2a_{Sy}\,\Delta y = 0 + 2a_{Sy}(y_1 - y_0) = -2a_{Sy}y_0$$
$$v_1 = \sqrt{-2a_{Sy}y_0} = \sqrt{-2(-4.9\text{ m/s}^2)(3.0\text{ m})} = 5.4\text{ m/s}$$

ASSESS The value of v_{1y} is negative, but we only needed to find the speed so we took the absolute value. This is about 12 mph, so it seems unlikely that the truck will survive the impact of the 1000 kg safe!

FIGURE 7.28 Pictorial representation for Challenge Example 7.9.



SUMMARY

The goal of Chapter 7 has been to use Newton's third law to understand how objects interact.

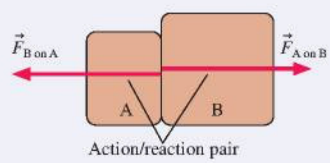
GENERAL PRINCIPLES

Newton's Third Law

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

- Act on two *different* objects.
- Are equal in magnitude but opposite in direction:

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



Solving Interacting-Objects Problems

MODEL Identify which objects form the system.

VISUALIZE Draw a pictorial representation.

- Define symbols and coordinates.
- Identify acceleration constraints.
- Draw an interaction diagram.
- Draw a separate free-body diagram for each object.
- Connect action/reaction pairs with dashed lines.

SOLVE Write Newton's second law for each object.

- Use the free-body diagrams.
- Equate the magnitudes of action/reaction pairs.
- Include acceleration constraints and friction.

ASSESS Is the result reasonable?

IMPORTANT CONCEPTS

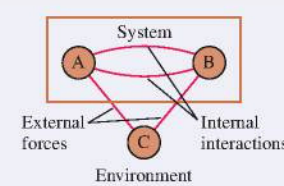
Objects, systems, and the environment

Objects whose motion is of interest are the system.

Objects whose motion is not of interest form the environment.

The objects of interest interact with the environment, but those interactions can be considered external forces.

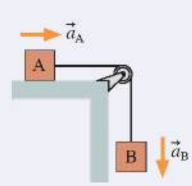
Interaction diagram



APPLICATIONS

Acceleration constraints

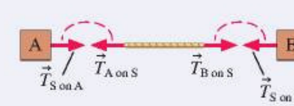
Objects that are constrained to move together must have accelerations of equal magnitude: $a_A = a_B$. This must be expressed in terms of components, such as $a_{Ax} = -a_{By}$.



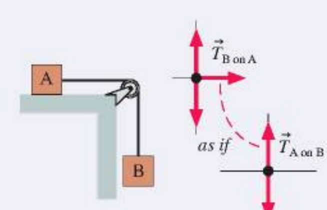
Strings and pulleys

The tension in a string or rope pulls in both directions. The tension is constant in a string if the string is:

- Massless, or
- In equilibrium



Objects connected by massless strings passing over massless, frictionless pulleys act *as if* they interact via an action/reaction pair of forces.



TERMS AND NOTATION

interaction
action/reaction pair
system
environment
interaction diagram
external force
propulsion
Newton's third law
acceleration constraint
massless string approximation

CONCEPTUAL QUESTIONS

1. You find yourself in the middle of a frozen lake with a surface so slippery ($\mu_s = \mu_k = 0$) you cannot walk. However, you happen to have several rocks in your pocket. The ice is extremely hard. It cannot be chipped, and the rocks slip on it just as much as your feet do. Can you think of a way to get to shore? Use pictures, forces, and Newton's laws to explain your reasoning.
2. How does a sprinter sprint? What is the forward force on a sprinter as she accelerates? Where does that force come from? Your explanation should include an interaction diagram and a free-body diagram.
3. How does a rocket take off? What is the upward force on it? Your explanation should include an interaction diagram and free-body diagrams of the rocket and of the parcel of gas being exhausted.
4. How do basketball players jump straight up into the air? Your explanation should include an interaction diagram and a free-body diagram.
5. A mosquito collides head-on with a car traveling 60 mph. Is the force of the mosquito on the car larger than, smaller than, or equal to the force of the car on the mosquito? Explain.
6. A mosquito collides head-on with a car traveling 60 mph. Is the magnitude of the mosquito's acceleration larger than, smaller than, or equal to the magnitude of the car's acceleration? Explain.
7. A small car is pushing a large truck. They are speeding up. Is the force of the truck on the car larger than, smaller than, or equal to the force of the car on the truck?
8. A very smart 3-year-old child is given a wagon for her birthday. She refuses to use it. "After all," she says, "Newton's third law says that no matter how hard I pull, the wagon will exert an equal but opposite force on me. So I will never be able to get it to move forward." What would you say to her in reply?
9. Teams red and blue are having a tug-of-war. According to Newton's third law, the force with which the red team pulls on the blue team exactly equals the force with which the blue team pulls on the red team. How can one team ever win? Explain.
10. Will hanging a magnet in front of the iron cart in FIGURE Q7.10 make it go? Explain.

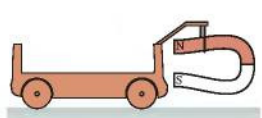


FIGURE Q7.10

11. FIGURE Q7.11 shows two masses at rest. The string is massless and the pulley is frictionless. The spring scale reads in kg. What is the reading of the scale?

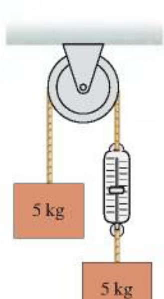


FIGURE Q7.11

12. FIGURE Q7.12 shows two masses at rest. The string is massless and the pullies are frictionless. The spring scale reads in kg. What is the reading of the scale?

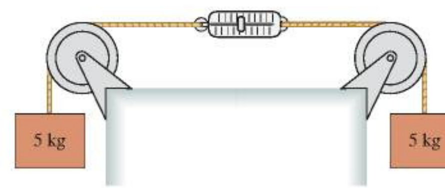


FIGURE Q7.12

13. The hand in FIGURE Q7.13 is pushing on the back of block A. Blocks A and B, with $m_B > m_A$, are connected by a massless string and slide on a frictionless surface. Is the force of the string on B larger than, smaller than, or equal to the force of the hand on A? Explain.

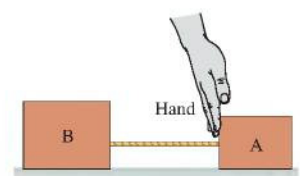


FIGURE Q7.13

14. Blocks A and B in FIGURE Q7.14 are connected by a massless string over a massless, frictionless pulley. The blocks have just been released from rest. Will the pulley rotate clockwise, counterclockwise, or not at all? Explain.

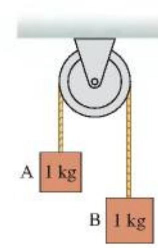


FIGURE Q7.14

15. In case a in FIGURE Q7.15, block A is accelerated across a frictionless table by a hanging 10 N weight (1.02 kg). In case b, block A is accelerated across a frictionless table by a steady 10 N tension in the string. The string is massless, and the pulley is massless and frictionless. Is A's acceleration in case b greater than, less than, or equal to its acceleration in case a? Explain.

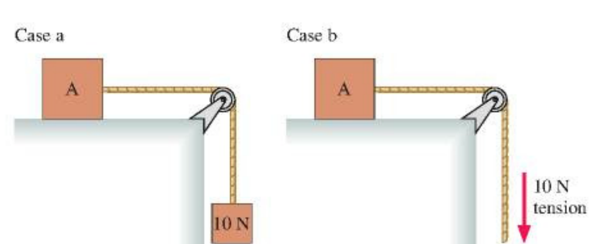


FIGURE Q7.15

EXERCISES AND PROBLEMS

Exercises

Section 7.2 Analyzing Interacting Objects

For Exercises 1 through 5:

a. Draw an interaction diagram.
b. Identify the "system" on your interaction diagram.
c. Draw a free-body diagram for each object in the system. Use dashed lines to connect members of an action/reaction pair.

1. | A soccer ball and a bowling ball have a head-on collision at this instant. Rolling friction is negligible.
2. | A weightlifter stands up at constant speed from a squatting position while holding a heavy barbell across his shoulders.
3. | A steel cable with mass is lifting a girder. The girder is speeding up.
4. || Block A in FIGURE EX7.4 is heavier than block B and is sliding down the incline. All surfaces have friction. The rope is massless, and the massless pulley turns on frictionless bearings. The rope and the pulley are among the interacting objects, but you'll have to decide if they're part of the system.

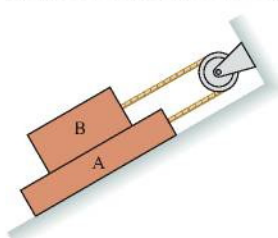


FIGURE EX7.4

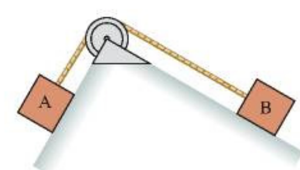


FIGURE EX7.5

5. || Block A in FIGURE EX7.5 is sliding down the incline. The rope is massless, and the massless pulley turns on frictionless bearings, but the surface is not frictionless. The rope and the pulley are among the interacting objects, but you'll have to decide if they're part of the system.

Section 7.3 Newton's Third Law

6. | a. How much force does an 80 kg astronaut exert on his chair while sitting at rest on the launch pad?
   b. How much force does the astronaut exert on his chair while accelerating straight up at 10 m/s^2?
7. | Block B in FIGURE EX7.7 rests on a surface for which the static and kinetic coefficients of friction are 0.60 and 0.40, respectively. The ropes are massless. What is the maximum mass of block A for which the system remains in equilibrium?

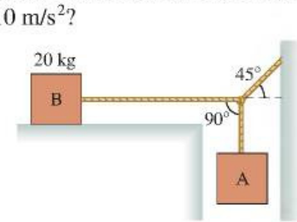


FIGURE EX7.7

8. || A 1000 kg car pushes a 2000 kg truck that has a dead battery. When the driver steps on the accelerator, the drive wheels of the car push against the ground with a force of 4500 N. Rolling friction can be neglected.
   a. What is the magnitude of the force of the car on the truck?
   b. What is the magnitude of the force of the truck on the car?
9. || Blocks with masses of 1 kg, 2 kg, and 3 kg are lined up in a row on a frictionless table. All three are pushed forward by a 12 N force applied to the 1 kg block.
   a. How much force does the 2 kg block exert on the 3 kg block?
   b. How much force does the 2 kg block exert on the 1 kg block?
10. | A 3000 kg meteorite falls toward the earth. What is the magnitude of the *earth's* acceleration just before impact? The earth's mass is 5.98×10^{24} kg.
11. | The foot of a 55 kg sprinter is on the ground for 0.25 s while her body accelerates from rest to 2.0 m/s.
   a. Is the friction between her foot and the ground static friction or kinetic friction?
   b. What is the magnitude of the friction force?
12. || A steel cable lying flat on the floor drags a 20 kg block across a horizontal, frictionless floor. A 100 N force applied to the cable causes the block to reach a speed of 4.0 m/s in a distance of 2.0 m. What is the mass of the cable?
13. || An 80 kg spacewalking astronaut pushes off a 640 kg satellite, exerting a 100 N force for the 0.50 s it takes him to straighten his arms. How far apart are the astronaut and the satellite after 1.0 min?
14. || The sled dog in FIGURE EX7.14 drags sleds A and B across the snow. The coefficient of friction between the sleds and the snow is 0.10. If the tension in rope 1 is 150 N, what is the tension in rope 2?

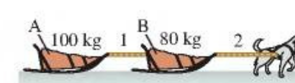


FIGURE EX7.14

15. || Two-thirds of the weight of a 1500 kg car rests on the drive wheels. What is the maximum acceleration of this car on a concrete surface?

Section 7.4 Ropes and Pulleys

16. || FIGURE EX7.16 shows two 1.0 kg blocks connected by a rope. A second rope hangs beneath the lower block. Both ropes have a mass of 250 g. The entire assembly is accelerated upward at 3.0 m/s^2 by force $\vec{F}$.
   a. What is F?
   b. What is the tension at the top end of rope 1?
   c. What is the tension at the bottom end of rope 1?
   d. What is the tension at the top end of rope 2?

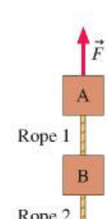


FIGURE EX7.16

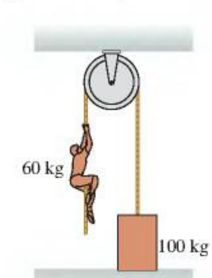


FIGURE EX7.17

17. || What is the tension in the rope of FIGURE EX7.17?

18. ‖ A 2.0-m-long, 500 g rope pulls a 10 kg block of ice across a horizontal, frictionless surface. The block accelerates at 2.0 m/s^2. How much force pulls forward on (a) the ice, (b) the rope? Assume that the rope is perfectly horizontal.

19. | A woman living in a third-story apartment is moving out. Rather than carrying everything down the stairs, she decides to pack her belongings into crates, attach a frictionless pulley to her balcony railing, and lower the crates by rope. How hard must she pull on the horizontal end of the rope to lower a 25 kg crate at steady speed?

20. ‖ Two blocks are attached to opposite ends of a massless rope that goes over a massless, frictionless, stationary pulley. One of the blocks, with a mass of 6.0 kg, accelerates downward at $\frac{3}{4}g$. What is the mass of the other block?

21. ‖ The cable cars in San Francisco are pulled along their tracks by an underground steel cable that moves along at 9.5 mph. The cable is driven by large motors at a central power station and extends, via an intricate pulley arrangement, for several miles beneath the city streets. The length of a cable stretches by up to 100 ft during its lifetime. To keep the tension constant, the cable passes around a 1.5-m-diameter "tensioning pulley" that rolls back and forth on rails, as shown in FIGURE EX7.21. A 2000 kg block is attached to the tensioning pulley's cart, via a rope and pulley, and is suspended in a deep hole. What is the tension in the cable car's cable?

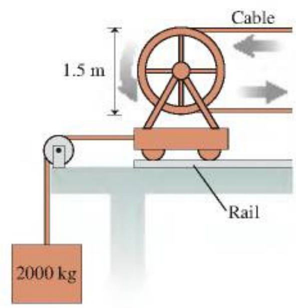


FIGURE EX7.21

22. ‖ A 2.0 kg rope hangs from the ceiling. What is the tension at the midpoint of the rope?

23. ‖ A mobile at the art museum has a 2.0 kg steel cat and a 4.0 kg steel dog suspended from a lightweight cable, as shown in FIGURE EX7.23. It is found that $\theta_1 = 20°$ when the center rope is adjusted to be perfectly horizontal. What are the tension and the angle of rope 3?

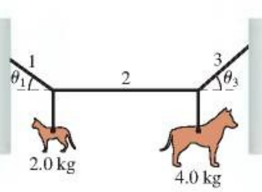


FIGURE EX7.23

24. ‖ The 1.0 kg block in FIGURE EX7.24 is tied to the wall with a rope. It sits on top of the 2.0 kg block. The lower block is pulled to the right with a tension force of 20 N. The coefficient of kinetic friction at both the lower and upper surfaces of the 2.0 kg block is $\mu_k = 0.40$.

a. What is the tension in the rope attached to the wall?
b. What is the acceleration of the 2.0 kg block?

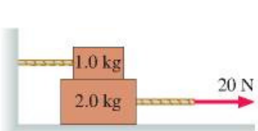


FIGURE EX7.24

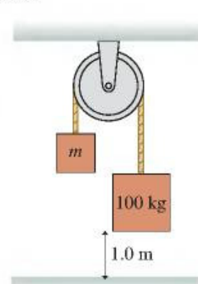


FIGURE EX7.25

25. ‖ The 100 kg block in FIGURE EX7.25 takes 6.0 s to reach the floor after being released from rest. What is the mass of the block on the left? The pulley is massless and frictionless.

Problems

26. ‖ FIGURE P7.26 shows two strong magnets on opposite sides of a small table. The long-range attractive force between the magnets keeps the lower magnet in place.

a. Draw an interaction diagram and draw free-body diagrams for both magnets and the table. Use dashed lines to connect the members of an action/reaction pair.
b. The lower magnet is being pulled upward against the bottom of the table. Suppose that each magnet's weight is 2.0 N and that the magnetic force of the lower magnet on the upper magnet is 6.0 N. How hard does the lower magnet push against the table?

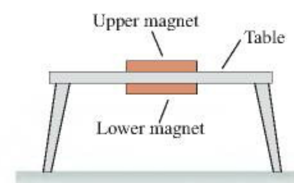


FIGURE P7.26

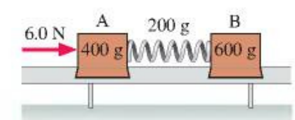


FIGURE P7.27

27. ‖ FIGURE P7.27 shows a 6.0 N force pushing two gliders along an air track. The 200 g spring between the gliders is compressed. How much force does the spring exert on (a) glider A and (b) glider B? The spring is firmly attached to the gliders, and it does not sag.

28. ‖ A rope of length L and mass m is suspended from the ceiling. Find an expression for the tension in the rope at position y, measured upward from the free end of the rope.

29. ‖ While driving to work last year, I was holding my coffee mug in my left hand while changing the CD with my right hand. Then the cell phone rang, so I placed the mug on the flat part of my dashboard. Then, believe it or not, a deer ran out of the woods and on to the road right in front of me. Fortunately, my reaction time was zero, and I was able to stop from a speed of 20 m/s in a mere 50 m, just barely avoiding the deer. Later tests revealed that the static and kinetic coefficients of friction of the coffee mug on the dash are 0.50 and 0.30, respectively; the coffee and mug had a mass of 0.50 kg; and the mass of the deer was 120 kg. Did my coffee mug slide?

30. ‖ A Federation starship (2.0×10^6 kg) uses its tractor beam to pull a shuttlecraft (2.0×10^4 kg) aboard from a distance of 10 km away. The tractor beam exerts a constant force of 4.0×10^4 N on the shuttlecraft. Both spacecraft are initially at rest. How far does the starship move as it pulls the shuttlecraft aboard?

31. ‖ BIO Your forehead can withstand a force of about 6.0 kN before fracturing, while your cheekbone can withstand only about 1.3 kN. Suppose a 140 g baseball traveling at 30 m/s strikes your head and stops in 1.5 ms.

a. What is the magnitude of the force that stops the baseball?
b. What force does the baseball exert on your head? Explain.
c. Are you in danger of a fracture if the ball hits you in the forehead? On the cheek?

32. ‖ Bob, who has a mass of 75 kg, can throw a 500 g rock with a speed of 30 m/s. The distance through which his hand moves as he accelerates the rock from rest until he releases it is 1.0 m.

a. What constant force must Bob exert on the rock to throw it with this speed?
b. If Bob is standing on frictionless ice, what is his recoil speed after releasing the rock?

33. ||| Two packages at UPS start sliding down the 20° ramp shown in FIGURE P7.33. Package A has a mass of 5.0 kg and a coefficient of friction of 0.20. Package B has a mass of 10 kg and a coefficient of friction of 0.15. How long does it take package A to reach the bottom?

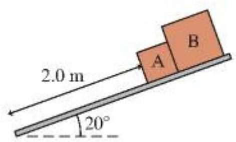


FIGURE P7.33

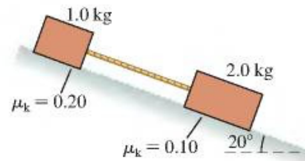


FIGURE P7.34

34. ||| The two blocks in FIGURE P7.34 are sliding down the incline. What is the tension in the massless string?

35. || The coefficient of static friction is 0.60 between the two blocks in FIGURE P7.35. The coefficient of kinetic friction between the lower block and the floor is 0.20. Force $\vec{F}$ causes both blocks to cross a distance of 5.0 m, starting from rest. What is the least amount of time in which this motion can be completed without the top block sliding on the lower block?

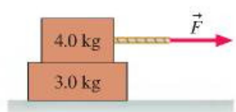


FIGURE P7.35

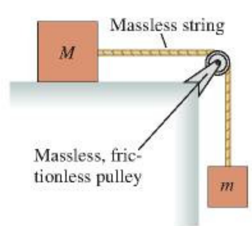


FIGURE P7.36

36. ||| The block of mass M in FIGURE P7.36 slides on a frictionless surface. Find an expression for the tension in the string.

37. || The 10.2 kg block in FIGURE P7.37 is held in place by a force applied to a rope passing over two massless, frictionless pulleys. Find the tensions T_1 to T_5 and the magnitude of force $\vec{F}$.

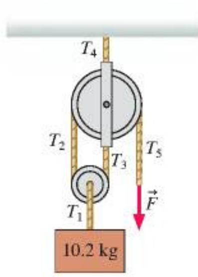


FIGURE P7.37

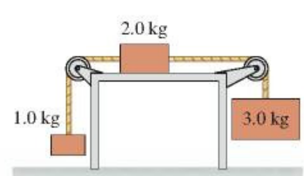


FIGURE P7.38

38. || The coefficient of kinetic friction between the 2.0 kg block in FIGURE P7.38 and the table is 0.30. What is the acceleration of the 2.0 kg block?

39. ||| FIGURE P7.39 shows a block of mass m resting on a 20° slope. The block has coefficients of friction $\mu_s = 0.80$ and $\mu_k = 0.50$ with the surface. It is connected via a massless string over a massless, frictionless pulley to a hanging block of mass 2.0 kg.
   a. What is the minimum mass m that will stick and not slip?
   b. If this minimum mass is nudged ever so slightly, it will start being pulled up the incline. What acceleration will it have?

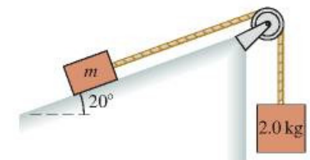


FIGURE P7.39

40. || A 4.0 kg box is on a frictionless 35° slope and is connected via a massless string over a massless, frictionless pulley to a hanging 2.0 kg weight. The picture for this situation is similar to FIGURE P7.39.
   a. What is the tension in the string if the 4.0 kg box is *held* in place, so that it cannot move?
   b. If the box is then released, which way will it move on the slope?
   c. What is the tension in the string once the box begins to move?

41. || The 1.0 kg physics book in FIGURE P7.41 is connected by a string to a 500 g coffee cup. The book is given a push up the slope and released with a speed of 3.0 m/s. The coefficients of friction are $\mu_s = 0.50$ and $\mu_k = 0.20$.
   a. How far does the book slide?
   b. At the highest point, does the book stick to the slope, or does it slide back down?

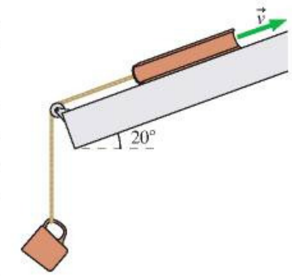


FIGURE P7.41

42. || The 2000 kg cable car shown in FIGURE P7.42 descends a 200-m-high hill. In addition to its brakes, the cable car controls its speed by pulling an 1800 kg counterweight up the other side of the hill. The rolling friction of both the cable car and the counterweight are negligible.
   a. How much braking force does the cable car need to descend at constant speed?
   b. One day the brakes fail just as the cable car leaves the top on its downward journey. What is the runaway car's speed at the bottom of the hill?

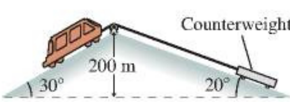


FIGURE P7.42

43. || The century-old *ascensores* in Valparaiso, Chile, are picturesque cable cars built on stilts to keep the passenger compartments level as they go up and down the steep hillsides. As FIGURE P7.43 shows, one car ascends as the other descends. The cars use a two-cable arrangement to compensate for friction; one cable passing around a large pulley connects the cars, the second is pulled by a small motor. Suppose the mass of both cars (with passengers) is 1500 kg, the coefficient of rolling friction is 0.020, and the cars move at constant speed. What is the tension in (a) the connecting cable and (b) the cable to the motor?

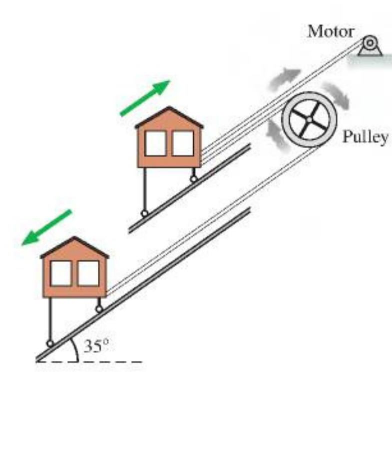


FIGURE P7.43

44. ‖ A 3200 kg helicopter is flying horizontally. A 250 kg crate is suspended from the helicopter by a massless cable that is constantly 20° from vertical. What propulsion force $\vec{F}_{prop}$ is being provided by the helicopter's rotor? Air resistance can be ignored. Give your answer in component form in a coordinate system where $\hat{\imath}$ points in the direction of motion and $\hat{\jmath}$ points upward.

45. ‖ A house painter uses the chair-and-pulley arrangement of **FIGURE P7.45** to lift himself up the side of a house. The painter's mass is 70 kg and the chair's mass is 10 kg. With what force must he pull down on the rope in order to accelerate upward at 0.20 m/s^2?

FIGURE P7.45

46. ‖ A long, 1.0 kg rope hangs from a support that breaks, causing the rope to fall, if the pull exceeds 40 N. A student team has built a 2.0 kg robot "mouse" that runs up and down the rope. What maximum acceleration can the robot have—both magnitude and direction—without the rope falling?

47. ‖ A 50-cm-diameter, 400 g beach ball is dropped with a 4.0 mg ant riding on the top. The ball experiences air resistance, but the ant does not. What is the magnitude of the normal force exerted on the ant when the ball's speed is 2.0 m/s?

48. ‖ A 70 kg tightrope walker stands at the center of a rope. The rope supports are 10 m apart and the rope sags 10° at each end. The tightrope walker crouches down, then leaps straight up with an acceleration of 8.0 m/s^2 to catch a passing trapeze. What is the tension in the rope as he jumps?

49. ‖ Find an expression for the magnitude of the horizontal force F in **FIGURE P7.49** for which m_1 does not slip either up or down along the wedge. All surfaces are frictionless.

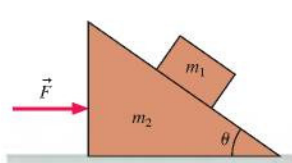


FIGURE P7.49

50. ‖ A rocket burns fuel at a rate of 5.0 kg/s, expelling the exhaust gases at a speed of 4.0 km/s *relative to the rocket*. We would like to find the thrust of the rocket engine.
   a. Model the fuel burning as a steady ejection of small pellets, each with the small mass Δm. Suppose it takes a short time Δt to accelerate a pellet (at constant acceleration) to the exhaust speed v_{ex}. Further, suppose the rocket is clamped down so that it can't recoil. Find an expression for the magnitude of the force that one pellet exerts on the rocket during the short time while the pellet is being expelled.
   b. If the rocket is moving, v_{ex} is no longer the pellet's speed through space but it is still the pellet's speed *relative to the rocket*. By considering the limiting case of Δm and Δt approaching zero, in which case the rocket is now burning fuel continuously, calculate the rocket thrust for the values given above.

Problems 51 and 52 show the free-body diagrams of two interacting systems. For each of these, you are to
   a. Write a realistic problem for which these are the correct free-body diagrams. Be sure that the answer your problem requests is consistent with the diagrams shown.
   b. Finish the solution of the problem.

51.

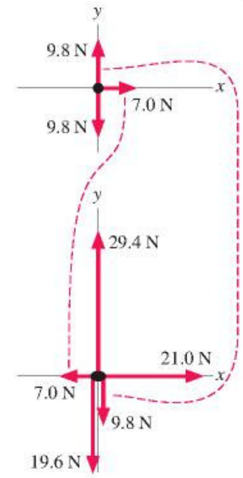


FIGURE P7.51

52.

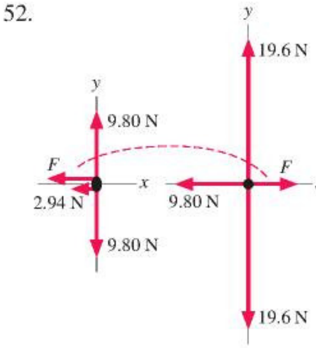


FIGURE P7.52

Challenge Problems

53. ‖| The lower block in **FIGURE CP7.53** is pulled on by a rope with a tension force of 20 N. The coefficient of kinetic friction between the lower block and the surface is 0.30. The coefficient of kinetic friction between the lower block and the upper block is also 0.30. What is the acceleration of the 2.0 kg block?

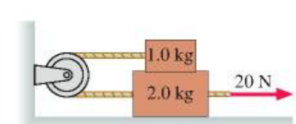


FIGURE CP7.53

54. ‖| In **FIGURE CP7.54**, find an expression for the acceleration of m_1. The pulleys are massless and frictionless.
Hint: Think carefully about the acceleration constraint.

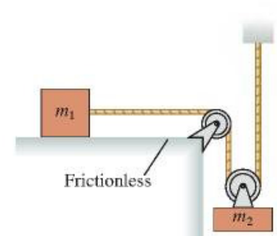


FIGURE CP7.54

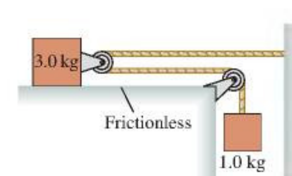


FIGURE CP7.55

55. ‖| What is the acceleration of the 3.0 kg block in **FIGURE CP7.55** across the frictionless table?
Hint: Think carefully about the acceleration constraint.

56. ||| A 40-cm-diameter, 50-cm-tall, 15 kg hollow cylinder is placed on top of a 40-cm-diameter, 30-cm-tall, 100 kg cylinder of solid aluminum, then the two are sent sliding across frictionless ice. The static and kinetic coefficients of friction between the cylinders are 0.45 and 0.25, respectively. Air resistance cannot be neglected. What is the maximum speed the cylinders can have without the top cylinder sliding off?

57. ||| **FIGURE CP7.57** shows a 200 g hamster sitting on an 800 g wedge-shaped block. The block, in turn, rests on a spring scale. An extra-fine lubricating oil having $\mu_s = \mu_k = 0$ is sprayed on the top surface of the block, causing the hamster to slide down. Friction between the block and the scale is large enough that the block does *not* slip on the scale. What does the scale read, in grams, as the hamster slides down?

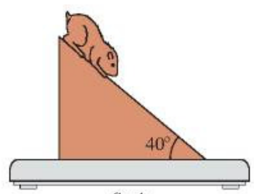


FIGURE CP7.57

58. ||| **FIGURE CP7.58** shows three hanging masses connected by massless strings over two massless, frictionless pulleys.
   a. Find the acceleration constraint for this system. It is a single equation relating a_{1y}, a_{2y}, and a_{3y}.
   Hint: y_A isn't constant.
   b. Find an expression for the tension in string A.
   Hint: You should be able to write four second-law equations. These, plus the acceleration constraint, are five equations in five unknowns.
   c. Suppose: $m_1 = 2.5$ kg, $m_2 = 1.5$ kg, and $m_3 = 4.0$ kg. Find the acceleration of each.
   d. The 4.0 kg mass would appear to be in equilibrium. Explain why it accelerates.

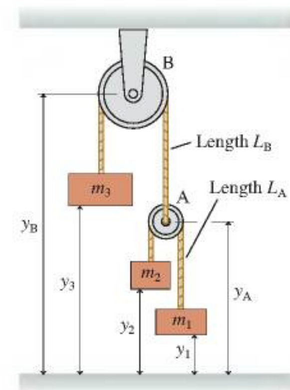


FIGURE CP7.58