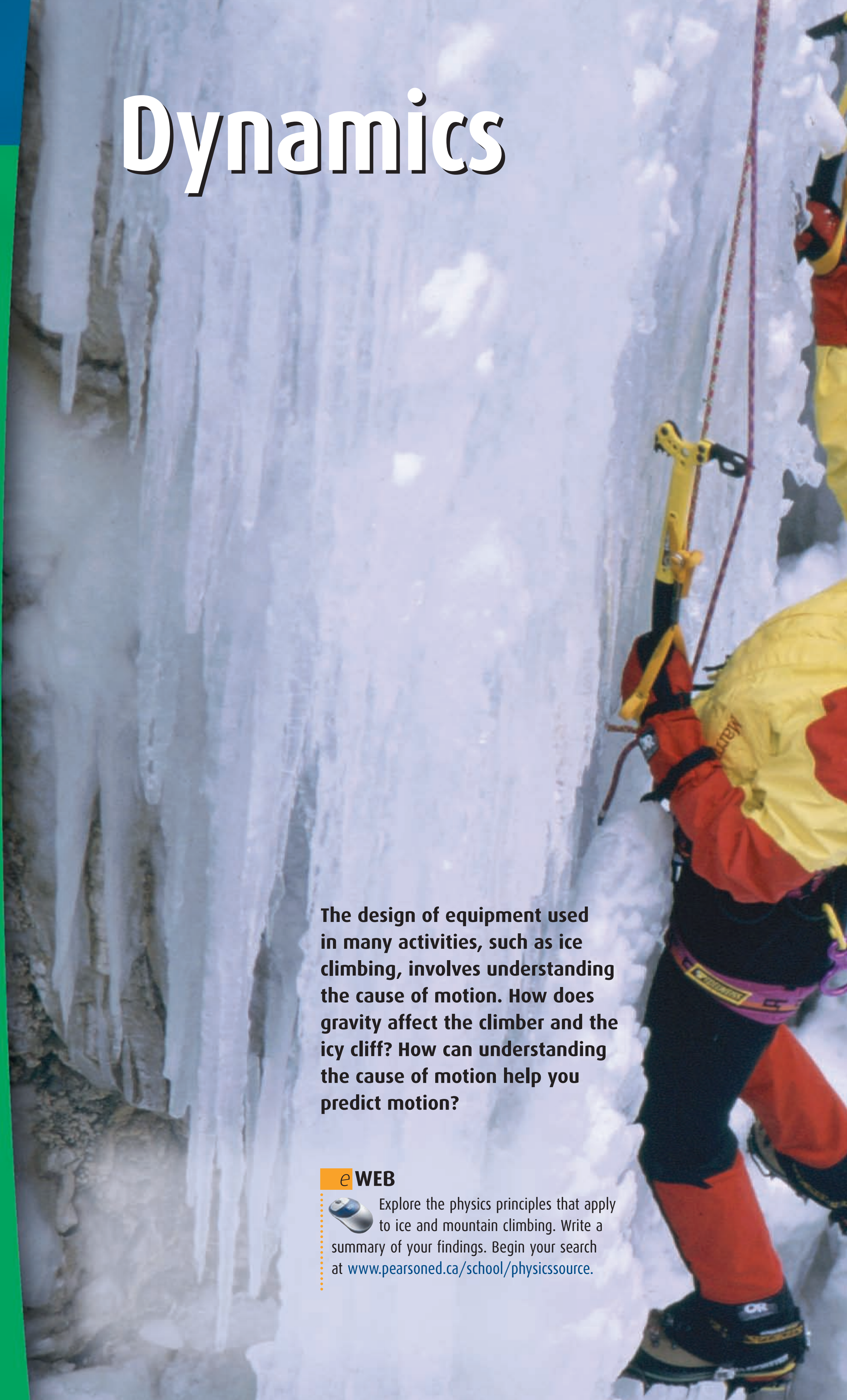
UNIT

II

# Dynamics



**The design of equipment used in many activities, such as ice climbing, involves understanding the cause of motion. How does gravity affect the climber and the icy cliff? How can understanding the cause of motion help you predict motion?**

**e WEB**

Explore the physics principles that apply to ice and mountain climbing. Write a summary of your findings. Begin your search at www.pearsoned.ca/school/physicssource.

# Unit at a Glance


**CHAPTER 3 Forces can change velocity.**

3.1 The Nature of Force

3.2 Newton's First Law

3.3 Newton's Second Law

3.4 Newton's Third Law

3.5 Friction Affects Motion

**CHAPTER 4 Gravity extends throughout the universe.**

4.1 Gravitational Forces due to Earth

4.2 Newton's Law of Universal Gravitation

4.3 Relating Gravitational Field Strength to Gravitational Force


## Unit Themes and Emphases

- Change and Systems
- Social and Environmental Contexts
- Problem-Solving Skills

## Focussing Questions

In this study of dynamics and gravitation, you will investigate different types of forces and how they change the motion of objects and affect the design of various technological systems.

As you study this unit, consider these questions:

- How does an understanding of forces help humans interact with their environment?
- How do the principles of dynamics affect mechanical and other systems?
- What role does gravity play in the universe?

## Unit Project

**Tire Design, Stopping Distance, and Vehicle Mass**

- By the time you complete this unit, you will have the skills to evaluate how tire treads, road surfaces, and vehicle mass affect stopping distances. You will need to consider human reaction times and the amount of moisture on road surfaces to investigate this problem.

CHAPTER

# 3

### Key Concepts

In this chapter, you will learn about:

- vector addition
- Newton's laws of motion
- static and kinetic friction

### Learning Outcomes

When you have completed this chapter, you will be able to:

**Knowledge**

- explain that a non-zero net force causes a change in velocity
- calculate the net force
- apply Newton's three laws to solve motion problems
- explain static and kinetic friction

**Science, Technology, and Society**

- explain that the goal of technology is to provide solutions to practical problems
- explain that science and technology develop to meet societal needs
- explain that science develops through experimentation

# Forces can change velocity.

Screeching tires on the road and the sound of metal and fibreglass being crushed are familiar sounds of a vehicle collision. Depending on the presence of airbags and the correct use of seat belts and headrests, a motorist may suffer serious injury. In order to design these safety devices, engineers must understand what forces are and how forces affect the motion of an object.

When a driver suddenly applies the brakes, the seat belts of all occupants lock. If the vehicle collides head-on with another vehicle, airbags may become deployed. Both seat belts and airbags are designed to stop the forward motion of motorists during a head-on collision (Figure 3.1).

Motorists in a stationary vehicle that is rear-ended also experience forces. The car seats move forward quickly, taking the lower part of each person's body with it. But each person's head stays in the same place until yanked forward by the neck. It is this sudden yank that causes whiplash. Adjustable headrests are designed to prevent whiplash by supporting the head of each motorist.

In this chapter, you will investigate how forces affect motion and how to explain and predict the motion of an object using Newton's three laws.

▲ **Figure 3.1** To design cars with better safety features, accident researchers use dummies to investigate the results of high-speed collisions.

**3-1 QuickLab**

# Accelerating a Cart

## Problem

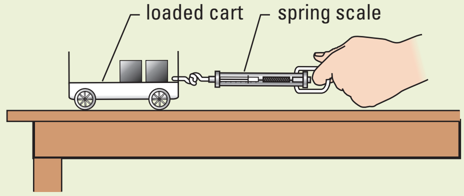
If you pull an object with a force, how do force and mass affect the acceleration of the object?

## Materials

dynamics cart with hook
two 200-g standard masses
one 1-kg standard mass
spring scale (0–5 N)
smooth, flat surface (about 1.5 m long)

## Procedure

1. Place the 200-g standard masses on the cart and attach the spring scale to the hook on the cart.
2. Pull the spring scale so that the cart starts to accelerate forward (Figure 3.2). Make sure that the force reading on the spring scale is 2 N and that the force remains as constant as possible while pulling the cart. Observe the acceleration of the cart.
3. Replace the 200-g masses on the cart with the 1-kg standard mass. Then pull the cart, applying the same force you used in step 2. Observe the acceleration of the cart.
4. Remove all the objects from the cart. Then pull the cart, applying the same force you used in step 2. Observe the acceleration of the cart.
5. Repeat step 4 but this time pull with a force of 1 N.
6. Repeat step 4 but this time pull with a force of 3 N.
7. Repeat step 4 but now only pull with just enough force to start the cart moving. Measure the force reading on the spring scale.




▲ **Figure 3.2**

## Questions

1. Why do you think it was difficult to apply a constant force when pulling the cart each time?
2. Describe how the acceleration of the cart changed from what it was in step 2 when
   (a) you used the 1-kg standard mass instead of the 200-g masses,
   (b) you removed all the objects from the cart,
   (c) you decreased the pulling force to 1 N, and
   (d) you increased the pulling force to 3 N.
3. What force was required to start the cart moving in step 7?
4. Suppose, instead of hooking a spring scale to the cart in steps 2 to 4, you gave the cart a push of the same magnitude each time.
   (a) Which cart would you expect to travel the farthest distance?
   (b) Which cart would you expect to slow down sooner?
   (c) What force do you think makes the cart eventually come to a stop?

## Think About It

1. Describe the motion of a large rocket during liftoff using the concept of force. Include diagrams in your explanation.
2. Is a plane during takeoff accelerating or moving with constant velocity? Explain in words and with diagrams.

Discuss your answers in a small group and record them for later reference. As you complete each section of this chapter, review your answers to these questions. Note any changes to your ideas.

## 3.1 The Nature of Force

*info* **BIT**

Statics is a branch of dynamics that deals with the forces acting on stationary objects. Architecture is primarily a practical application of statics.

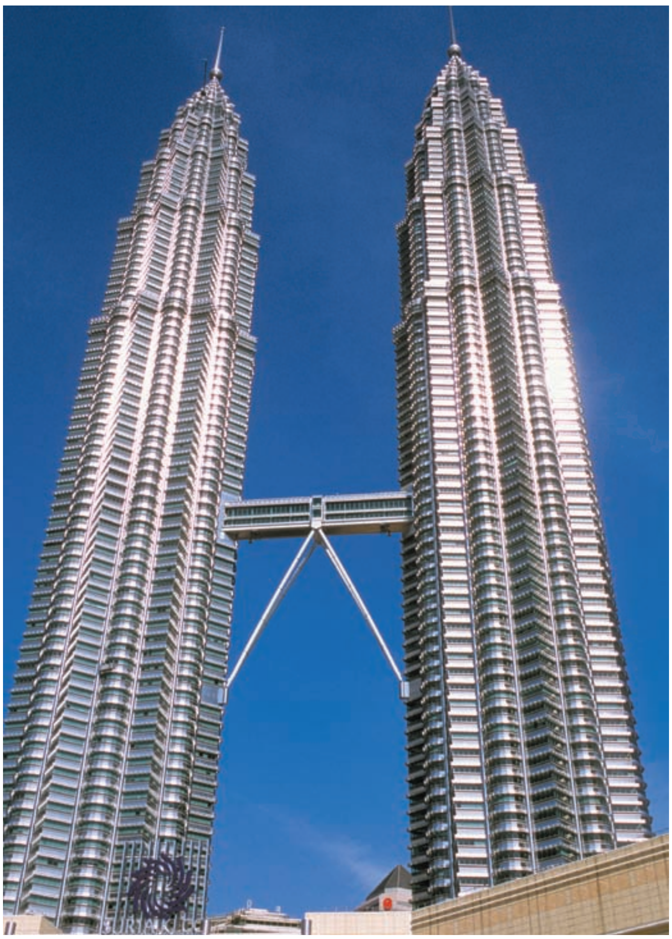
The Petronas Twin Towers in Kuala Lumpur, Malaysia, are currently the world's tallest twin towers. Including the spire on top, each tower measures 452 m above street level. To allow for easier movement of people within the building, architects designed a bridge to link each tower at the 41st floor. What is interesting is that this bridge is *not* stationary. In order for the bridge to not collapse, it must move with the towers as they sway in the wind (Figure 3.3).

In Unit I, you learned that kinematics describes the motion of an object without considering the cause. When designing a structure, the kinematics quantities that an architect considers are displacement, velocity, and acceleration. But to predict how and explain why a structure moves, an architect must understand **dynamics**. Dynamics deals with the effects of forces on objects.

**dynamics:** branch of mechanics dealing with the cause of motion

Structures such as bridges and buildings are required to either remain stationary or move in appropriate ways, depending on the design, so that they are safe to use. Architects must determine all the forces that act at critical points of the structure. If the forces along a particular direction do not balance, acceleration will occur.

Before you can predict or explain the motion of an object, it is important to first understand what a force is and how to measure and calculate the sum of all forces acting on an object.

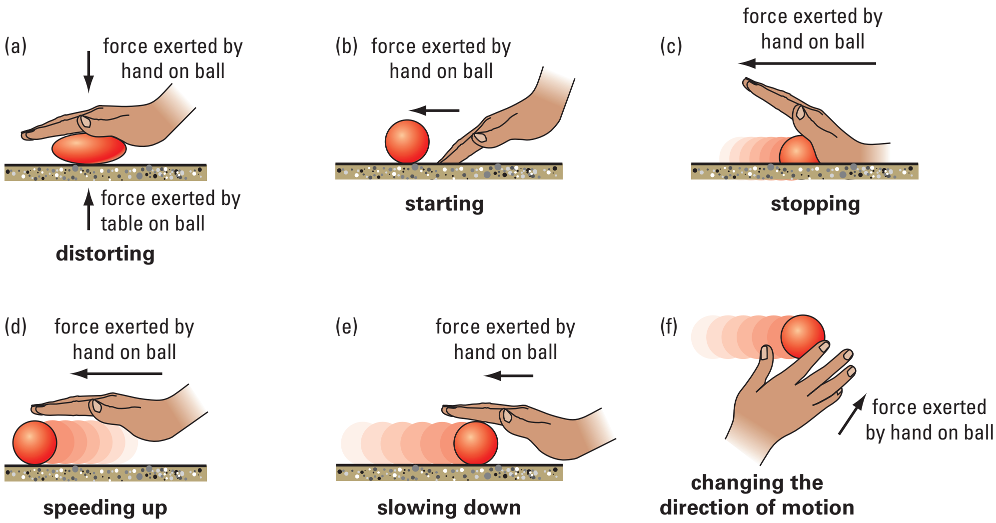


▶ **Figure 3.3** The design of tall buildings involves understanding forces. Towering buildings are susceptible to movement from the wind.

## Force Is a Vector Quantity

You experience a **force** when you push or pull an object. A push or a pull can have different magnitudes and can be in different directions. For this reason, force is a vector quantity. In general, any force acting on an object can change the shape and/or velocity of the object (Figure 3.4). If you want to deform an object yet keep it stationary, at least two forces must be present.

**force:** a quantity measuring a push or a pull on an object



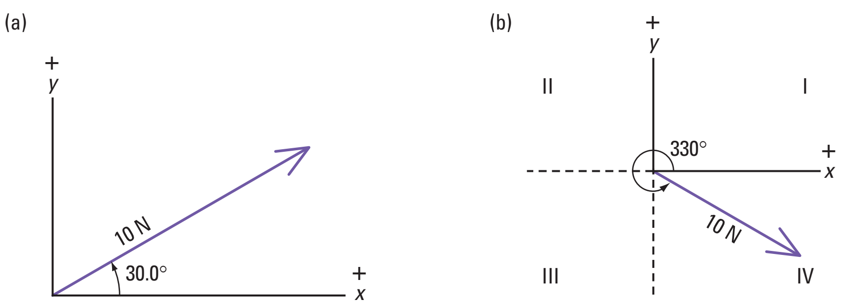

▲ **Figure 3.4** Different forces acting on a ball change either the shape or the motion of the ball. (a) The deformation of the ball is caused by both the hand and the table applying opposing forces on the ball. (b)–(f) The motion of the ball is changed, depending on the magnitude and the direction of the force applied by the hand.

The symbol of force is $\vec{F}$ and the SI unit for force is the newton (N), named in honour of physicist Isaac Newton (1642–1727). One newton is equal to one kilogram-metre per second squared ($1\ \text{kg}\cdot\text{m/s}^2$), which is the force required to move a 1-kg object with an acceleration of $1\ \text{m/s}^2$.

The direction of a force is described using reference coordinates that you choose for a particular situation. You may use [forward] or [backward], compass directions, or polar coordinates. When stating directions using polar coordinates, measure angles counterclockwise from the positive *x*-axis (Figure 3.5).

**info BIT**

One newton is roughly equal to the magnitude of the weight of a medium-sized apple or two golf balls.



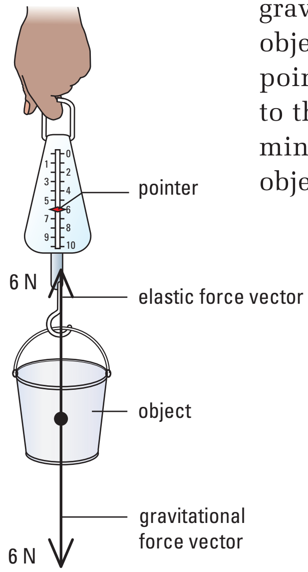

▲ **Figure 3.5** Two vectors of the same magnitude but with different directions. (a) 10 N [30°] (b) 10 N [330°]

## Measuring Force

One way you could measure forces involves using a calibrated spring scale. To measure the force of gravity acting on an object, attach the object to the end of a vertical spring and observe the stretch of the spring. The **weight** of an object is the force of gravity acting on the object. The symbol of weight is $\vec{F}_g$.

When the spring stops stretching, the gravitational and elastic forces acting on the object balance each other (Figure 3.6). At this point, the elastic force is equal in magnitude to the weight of the object. So you can determine the magnitude of the weight of an object by reading the pointer position on a calibrated spring scale once the spring stops stretching.

Find out the relationship between the stretch of a spring and the weight of an object by doing 3-2 QuickLab.




◀ **Figure 3.6** A spring scale is one type of instrument that can be used to measure forces.

**3-2 QuickLab**

# Measuring Force Using a Spring Scale

### Problem

How is the amount of stretch of a calibrated spring related to the magnitude of the force acting on an object?

### Materials

set of standard masses with hooks
spring scale (0–10 N)

### Procedure

1. Hold the spring scale vertically and make sure the pointer reads zero when nothing is attached.
2. Gently suspend a 100-g standard mass from the spring. Use a table to record the mass and the magnitudes of the gravitational and elastic forces acting on the object.
3. Hang additional objects from the spring, up to a total mass of 1000 g. Each time, record the mass and the magnitudes of the corresponding gravitational and elastic forces.

### Questions

**1.** What was the reading on the spring scale when the 100-g mass was attached?

**2.** What happened to the stretch of the spring when the mass of the object attached to the spring scale
(a) doubled?
(b) tripled?
(c) changed by a factor of 10?

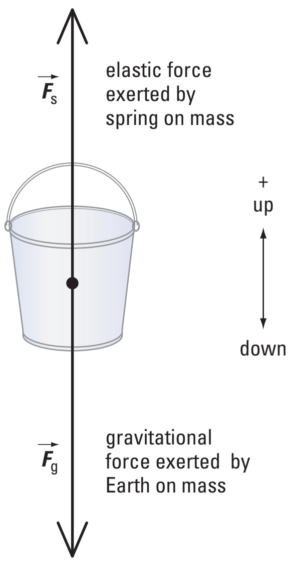
**3.** Why is a spring scale ideal for measuring force?

## Representing Forces Using Free-Body Diagrams

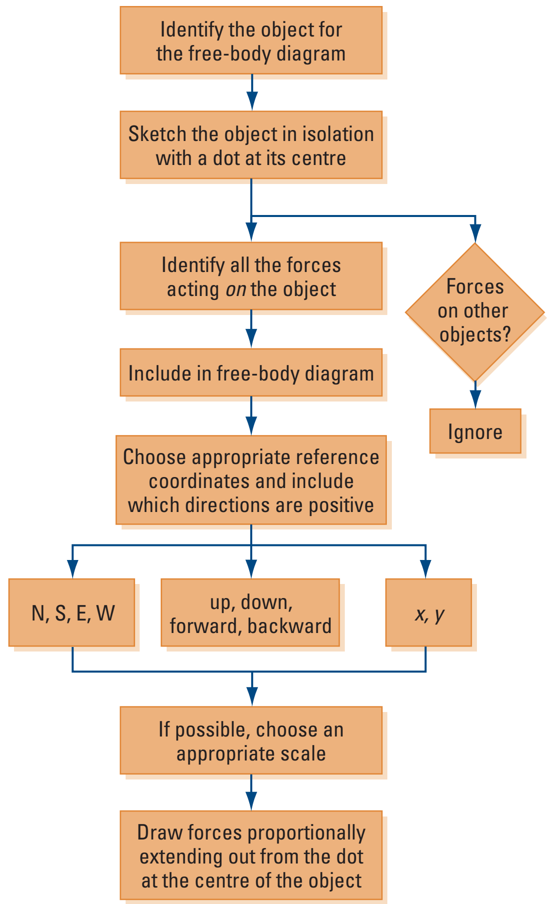
A **free-body diagram** is a powerful tool that can be used to analyze situations involving forces. This diagram is a sketch that shows the object by itself, isolated from all others with which it may be interacting. Only the force vectors exerted *on* the object are included and, in this physics course, the vectors are drawn with their tails meeting at the centre of the object (Figure 3.7). However, it does not necessarily mean that the centre of the object is *where* the forces act.

When drawing a free-body diagram, it is important to show the reference coordinates that apply to the situation in a given problem. Remember to always include which directions you will choose as positive. Figure 3.8 shows the steps for drawing free-body diagrams.

**free-body diagram:** vector diagram of an object in isolation showing all the forces acting *on* it




▲ **Figure 3.7** The free-body diagram for the object in Figure 3.6 that is suspended from the spring scale. The spring scale is not included here because it is not the object being studied.



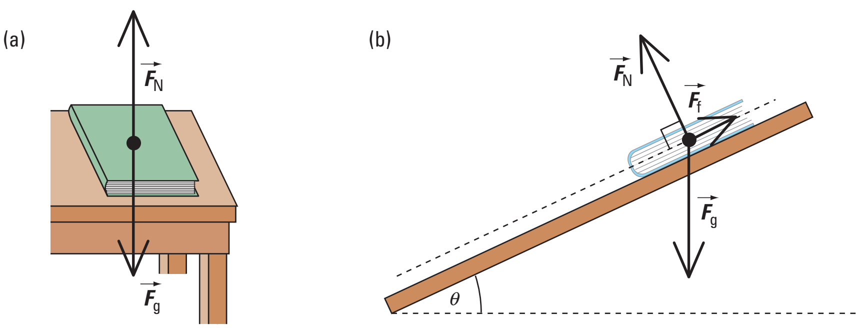

▲ **Figure 3.8** Flowchart summarizing the steps for drawing a free-body diagram

## Some Types of Forces

**normal force:** force on an object that is perpendicular to a common contact surface

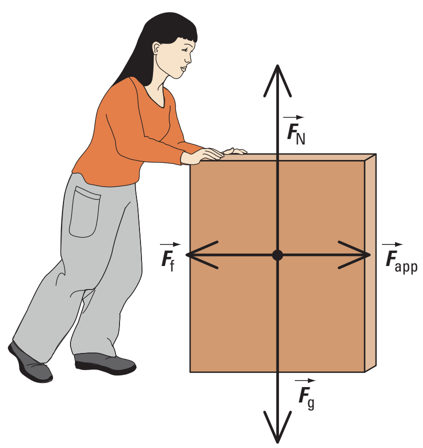
There are different types of forces and scientists distinguish among them by giving these forces special names. When an object is in contact with another, the objects will have a common surface of contact, and the two objects will exert a normal force on each other. The **normal force**, $\vec{F}_N$, is a force that is perpendicular to this common surface. Depending on the situation, another force called **friction**, $\vec{F}_f$, may be present, and this force acts parallel to the common surface.

The adjective "normal" simply means perpendicular. Figure 3.9 (a) shows a book at rest on a level table. The normal force exerted by the table on the book is represented by the vector directed upward. If the table top were slanted and smooth as in Figure 3.9 (b), the normal force acting on the book would not be directed vertically upward. Instead, it would be slanted, but always perpendicular to the contact surface.




▲ **Figure 3.9** Forces acting on (a) a stationary book on a level table and on (b) a book accelerating down a smooth, slanted table.

A stationary object may experience an **applied force**, $\vec{F}_{app}$, if, say, a person pushes against the object (Figure 3.10). In this case, the force of friction acting on the object will oppose the direction of impending motion.




▲ **Figure 3.10** The forces acting on a stationary box

Example 3.1 demonstrates how to draw a free-body diagram for a car experiencing different types of forces. In this situation, the normal force acting on the car is equal in magnitude to the weight of the car.

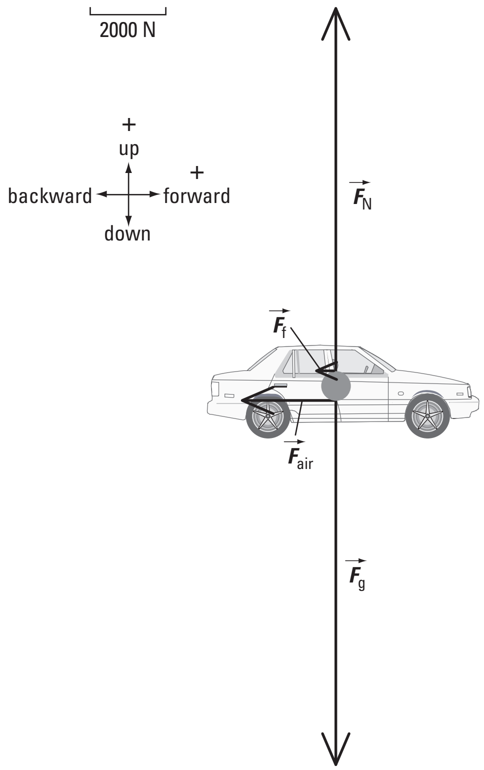
## Example 3.1

A car with a weight, $\vec{F}_g$, of 10 000 N [down] is coasting on a level road. The car experiences a normal force, $\vec{F}_N$, of 10 000 N [up], a force of air resistance, $\vec{F}_{air}$, of 2500 N [backward], and a force of friction, $\vec{F}_f$, exerted by the road on the tires of 500 N [backward]. Draw a free-body diagram for this situation.

### *Analysis and Solution*

While the car is coasting, there is no forward force acting on the car.

The free-body diagram shows four forces (Figure 3.11).




▲ **Figure 3.11**

### Practice Problems

1. The driver in Example 3.1 sees a pedestrian and steps on the brakes. The force of air resistance is 2500 N [backward]. With the brakes engaged, the force of friction exerted on the car is 5000 N [backward]. Draw a free-body diagram for this situation.
2. A car moving at constant velocity starts to speed up. The weight of the car is 12 000 N [down]. The force of air resistance is 3600 N [backward]. With the engine engaged, the force of friction exerted by the road on the tires is 7200 N [forward]. Draw a free-body diagram for this situation.

#### Answers

1. and 2. See page 898.

## Using Free-Body Diagrams to Find Net Force

Free-body diagrams are very useful when you need to calculate the **net force**, $\vec{F}_{net}$, on an object. The net force is a *vector sum* of all the forces acting simultaneously on an object. The force vectors can be added using either a scale vector diagram or using components.

**net force:** vector sum of all the forces acting simultaneously on an object

### *Concept Check*

Can the net force on an object ever equal zero? Explain using an example and a free-body diagram.

## Adding Collinear Forces

**eSIM**

Learn how to use free-body diagrams to find the net force on an object. Follow the eSim links at www.pearsoned.ca/school/physicssource.

Vectors that are parallel are collinear, even if they have opposite directions. Example 3.2 demonstrates how to find the net force on an object given two collinear forces. In this example, a canoe is dragged using two ropes. The magnitude of the force $\vec{F}_T$ exerted by a rope on an object at the point where the rope is attached to the object is called the **tension** in the rope.

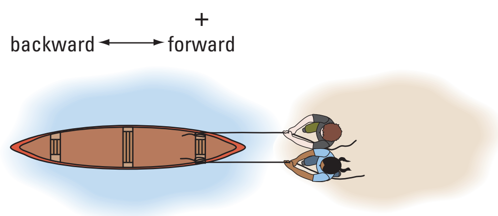
In this physics course, there are a few assumptions that you need to make about ropes or cables to simplify calculations. These assumptions and the corresponding inferences are listed in Table 3.1. Note that a "light" object means that it has negligible mass.

▼ **Table 3.1** Assumptions about Ropes or Cables

| Assumption | Inference |
|---|---|
| The mass of the rope is negligible. | The tension is uniform throughout the length of the rope. |
| The rope has a negligible thickness. | $\vec{F}_T$ acts parallel to the rope and is directed away from the object to which the rope is attached. |
| The rope is taut and does not stretch. | Any objects attached to the rope will have the same magnitude of acceleration as the rope. |

## Example 3.2

Two people, A and B, are dragging a canoe out of a lake onto a beach using light ropes (Figure 3.12). Each person applies a force of 60.0 N [forward] on the rope. The force of friction exerted by the beach on the canoe is 85.0 N [backward]. Starting with a free-body diagram, calculate the net force on the canoe.




▲ **Figure 3.12**

***Given***

$\vec{F}_{T_1} = 60.0\ \text{N [forward]}$

$\vec{F}_{T_2} = 60.0\ \text{N [forward]}$

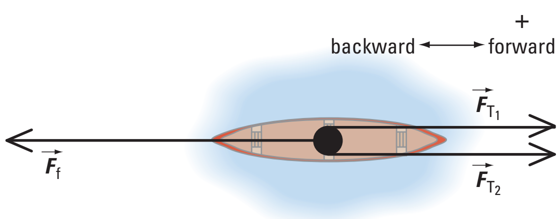
$\vec{F}_f = 85.0\ \text{N [backward]}$

***Required***

net force on canoe ($\vec{F}_{net}$)

***Analysis and Solution***

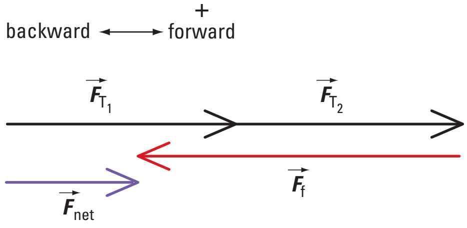
Draw a free-body diagram for the canoe (Figure 3.13).




▲ **Figure 3.13**

### Practice Problems

1. Two dogs, A and B, are pulling a sled across a horizontal, snowy surface. Dog A exerts a force of 200 N [forward] and dog B a force of 150 N [forward]. The force of friction exerted by the snow on the sled is 60 N [backward]. The driver attempts to slow down the sled by pulling on it with a force of 100 N [backward]. Starting with a free-body diagram, calculate the net force on the sled.




▲ **Figure 3.14**

Add the force vectors shown in the vector addition diagram (Figure 3.14).

$$\vec{F}_{net} = \vec{F}_{T_1} + \vec{F}_{T_2} + \vec{F}_f$$
$$F_{net} = F_{T_1} + F_{T_2} + F_f$$
$$= 60.0\text{ N} + 60.0\text{ N} + (-85.0\text{ N})$$
$$= 60.0\text{ N} + 60.0\text{ N} - 85.0\text{ N}$$
$$= 35.0\text{ N}$$
$$\vec{F}_{net} = 35.0\text{ N [forward]}$$

***Paraphrase***

The net force on the canoe is 35.0 N [forward].

## Practice Problems

2. In a tractor pull, four tractors are connected by strong chains to a heavy load. The load is initially at rest. Tractors A and B pull with forces of 5000 N [E] and 4000 N [E] respectively. Tractors C and D pull with forces of 4500 N [W] and 3500 N [W] respectively. The magnitude of the force of friction exerted by the ground on the load is 1000 N.
   (a) Starting with a free-body diagram, calculate the net force on the load.
   (b) If the load is initially at rest, will it start moving? Explain.

### Answers

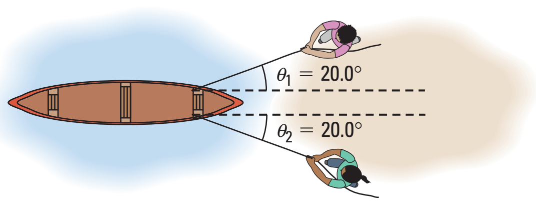
1. 190 N [forward]
2. (a) 0 N, (b) no

## Adding Non-Collinear Forces

Example 3.3 demonstrates how to find the net force on an object if the forces acting on it are neither parallel nor perpendicular. By observing the relationship between the components of the force vectors, you can greatly simplify the calculations.

## Example 3.3

Refer to Example 3.2 on page 132. Person A thinks that if A and B each pull a rope forming an angle of 20.0° with the bow, the net force on the canoe will be greater than in Example 3.2 (Figure 3.15). The canoe is being dragged along the beach using ropes that are parallel to the surface of the beach. Starting with a free-body diagram, calculate the net force on the canoe. Is person A's thinking correct?




▲ **Figure 3.15**

***Given***

$\vec{F}_{T_1} = 60.0\text{ N [along rope]}$  $\vec{F}_{T_2} = 60.0\text{ N [along rope]}$

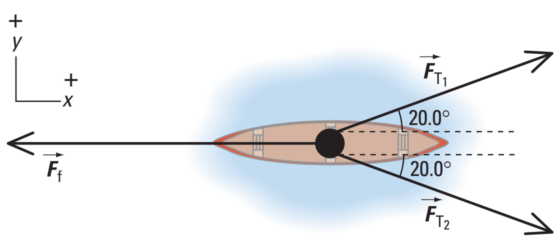
$\vec{F}_f = 85.0\text{ N [backward]}$  $\theta_1 = \theta_2 = 20.0°$

***Required***

net force on canoe ($\vec{F}_{net}$)

***Analysis and Solution***

Draw a free-body diagram for the canoe (Figure 3.16).




▲ **Figure 3.16**

## Practice Problems

1. Refer to Example 3.3. Suppose person A pulls a rope forming an angle of 40.0° with the bow and person B pulls a rope forming an angle of 20.0° with the bow. Each person applies a force of 60.0 N on the rope. The canoe and ropes are parallel to the surface of the beach. If the canoe is being dragged across a horizontal, frictionless surface, calculate the net force on the canoe.
2. Two people, A and B, are dragging a sled on a horizontal, icy surface with two light ropes. Person A applies a force of 65.0 N [30.0°] on one rope. Person B applies a force of 70.0 N [300°] on the other rope. The force of friction on the sled is negligible and the ropes are parallel to the icy surface. Calculate the net force on the sled.

### Answers

1. $1.04 \times 10^2$ N [10.0°]
2. 95.5 N [343°]

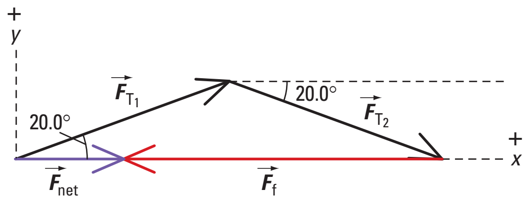
Separate all forces into $x$ and $y$ components.

| Vector | $x$ component | $y$ component |
|---|---|---|
| $\vec{F}_{T_1}$ | (60.0 N)(cos 20.0°) | (60.0 N)(sin 20.0°) |
| $\vec{F}_{T_2}$ | (60.0 N)(cos 20.0°) | −(60.0 N)(sin 20.0°) |
| $\vec{F}_f$ | −85.0 N | 0 |

From the chart, $F_{T_{1y}} = -F_{T_{2y}}$.

So $\vec{F}_{net_y} = \vec{F}_{T_{1y}} + \vec{F}_{T_{2y}}$

$F_{net_y} = F_{T_{1y}} + F_{T_{2y}} = 0 \text{ N}$




◀ **Figure 3.17**

Add the $x$ components of all force vectors in the vector addition diagram (Figure 3.17).

$x$ direction

$$\vec{F}_{net_x} = \vec{F}_{T_{1x}} + \vec{F}_{T_{2x}} + \vec{F}_f$$

$$\begin{aligned} F_{net_x} &= F_{T_{1x}} + F_{T_{2x}} + F_f \\ &= (60.0 \text{ N})(\cos 20.0°) + (60.0 \text{ N})(\cos 20.0°) + (-85.0 \text{ N}) \\ &= (60.0 \text{ N})(\cos 20.0°) + (60.0 \text{ N})(\cos 20.0°) - 85.0 \text{ N} \\ &= 27.8 \text{ N} \end{aligned}$$

$$\vec{F}_{net} = 27.8 \text{ N } [0°]$$

***Paraphrase***

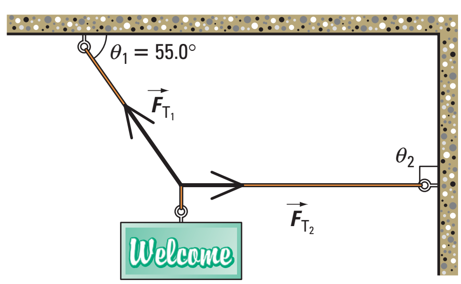
The net force is 27.8 N [0°]. Since the net force in Example 3.3 is less than that in Example 3.2, person A's thinking is incorrect.

## Applying Free-Body Diagrams to Objects in Equilibrium

At the beginning of this section, you learned that architects consider the net force acting at critical points of a building or bridge in order to prevent structure failure. Example 3.4 demonstrates how free-body diagrams and the concept of net force apply to a stationary object. Stationary objects are examples of objects at equilibrium because the net force acting on them equals zero.

## Example 3.4

A store sign that experiences a downward gravitational force of 245 N is suspended as shown in Figure 3.18. Calculate the forces $\vec{F}_{T_1}$ and $\vec{F}_{T_2}$ exerted at the point at which the sign is suspended.




▶ **Figure 3.18**

### Given

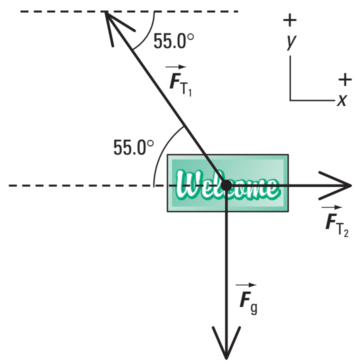
$\vec{F}_g = 245$ N [down] $\quad \theta_1 = 55.0°\quad \theta_2 = 90.0°$

### Required

forces ($\vec{F}_{T_1}$ and $\vec{F}_{T_2}$)

### Analysis and Solution

Draw a free-body diagram for the sign (Figure 3.19). Resolve all forces into $x$ and $y$ components.




▲ **Figure 3.19**

| Vector | $x$ component | $y$ component |
|---|---|---|
| $\vec{F}_{T_1}$ | $-F_{T_1}\cos 55.0°$ | $F_{T_1}\sin 55.0°$ |
| $\vec{F}_{T_2}$ | $F_{T_2}$ | 0 |
| $\vec{F}_g$ | 0 | $-F_g$ |

Since the sign is at equilibrium, the net force in both the $x$ and $y$ directions is zero.

$$F_{net_x} = F_{net_y} = 0 \text{ N}$$

Add the $x$ and $y$ components of all force vectors separately.

$x$ direction

$$\vec{F}_{net_x} = \vec{F}_{T_{1x}} + \vec{F}_{T_{2x}}$$
$$F_{net_x} = F_{T_{1x}} + F_{T_{2x}}$$
$$0 = -F_{T_1}\cos 55.0° + F_{T_2}$$
$$F_{T_2} = F_{T_1}\cos 55.0°$$

$y$ direction

$$\vec{F}_{net_y} = \vec{F}_{T_{1y}} + \vec{F}_g$$
$$F_{net_y} = F_{T_{1y}} + F_g$$
$$0 = F_{T_1}\sin 55.0° + (-F_g)$$
$$0 = F_{T_1} - \frac{F_g}{\sin 55.0°}$$
$$F_{T_1} = \frac{F_g}{\sin 55.0°}$$
$$= \frac{245 \text{ N}}{\sin 55.0°}$$
$$= 299.1\ \frac{\text{kg}\cdot\text{m}}{\text{s}^2}$$
$$= 299 \text{ N}$$

Substitute $F_{T_1}$ into the equation for $F_{T_2}$.

$$F_{T_2} = F_{T_1}\cos 55.0°$$
$$= (299.1 \text{ N})(\cos 55.0°)$$
$$= 171.6 \text{ N}$$
$$\vec{F}_{T_2} = 172 \text{ N } [0°]$$

From Figure 3.19, the direction of $\vec{F}_{T_1}$ measured counterclockwise from the positive $x$-axis is $180° - 55.0° = 125°$.

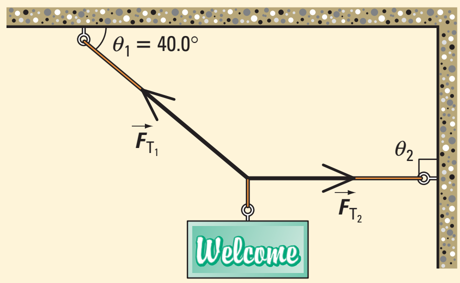
$$\vec{F}_{T_1} = 299 \text{ N } [125°]$$

### Paraphrase

$\vec{F}_{T_1}$ is 299 N [125°] and $\vec{F}_{T_2}$ is 172 N [0°].

## Practice Problems

1. If the sign in Example 3.4 had half the weight, how would the forces $\vec{F}_{T_1}$ and $\vec{F}_{T_2}$ compare?
2. Suppose the sign in Example 3.4 is suspended as shown in Figure 3.20. Calculate the forces $\vec{F}_{T_1}$ and $\vec{F}_{T_2}$.




▲ **Figure 3.20**

3. Refer to the solutions to Example 3.4 and Practice Problem 2 above.
   (a) As $\theta_1$ decreases, what happens to $\vec{F}_{T_1}$ and $\vec{F}_{T_2}$?
   (b) Explain why $\theta_1$ can never equal zero.

### Answers

1. directions of $\vec{F}_{T_1}$ and $\vec{F}_{T_2}$ would remain the same as before, but the respective magnitudes would be half
2. $\vec{F}_{T_1} = 3.81 \times 10^2$ N [140°]
   $\vec{F}_{T_2} = 2.92 \times 10^2$ N [0°]
3. (a) $\vec{F}_{T_1}$ and $\vec{F}_{T_2}$ increase in value
   (b) magnitude of $\vec{F}_{T_{1y}}$ must always equal $F_g$

## 3.1 Check and Reflect

### Knowledge

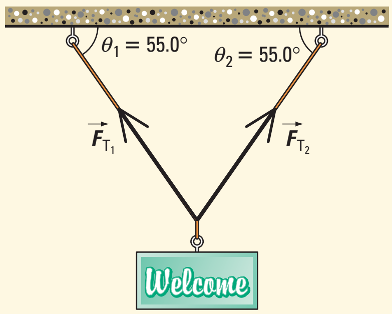
1. (a) Explain what a force is, and state the SI unit of force.
   (b) Why is force a dynamics quantity and not a kinematics quantity?

### Applications

2. Sketch a free-body diagram for
   (a) a bicycle moving west on a level road with decreasing speed
   (b) a ball experiencing forces of 45 N [12.0°], 60 N [100°], and 80 N [280°] simultaneously
3. The total weight of a biker and her motorbike is 1800 N [down]. With the engine engaged, the force of friction exerted by the road on the tires is 500 N [forward]. The air resistance acting on the biker and bike is 200 N [backward]. The normal force exerted by the road on the biker and bike is 1800 N [up].
   (a) Consider the biker and bike as a single object. Draw a free-body diagram for this object.
   (b) Calculate the net force.
4. If two forces act on an object, state the angle between these forces that will result in the net force given below. Explain using sketches.
   (a) maximum net force
   (b) minimum net force
5. Two people, A and B, are pulling on a tree with ropes while person C is cutting the tree down. Person A applies a force of 80.0 N [45.0°] on one rope. Person B applies a force of 90.0 N [345°] on the other rope. Calculate the net force on the tree.
6. Three forces act simultaneously on an object: $\vec{F}_1$ is 65 N [30.0°], $\vec{F}_2$ is 80 N [115°], and $\vec{F}_3$ is 105 N [235°]. Calculate the net force acting on the object.

### Extensions

7. A sign that experiences a downward gravitational force of 245 N is suspended, as shown below. Calculate the forces $\vec{F}_{T_1}$ and $\vec{F}_{T_2}$.




8. The blanket toss is a centuries-old hunting technique that the Inuit used to find herds of caribou. During the toss, several people would hold a hide taut while the hunter would jump up and down, much like on a trampoline, increasing the jump height each time. At the top of the jump, the hunter would rotate 360° looking for the herd. Draw a free-body diagram for a hunter of weight 700 N [down] while
   (a) standing at rest on the taut hide just before a jump
   (b) at the maximum jump height
9. Construct a flowchart to summarize how to add two or more non-collinear forces using components. Refer to Figure 3.8 on page 129 or Student References 4: Using Graphic Organizers on page 869.

**eTEST**

To check your understanding of forces, follow the eTest links at www.pearsoned.ca/school/physicssource.

# 3.2 Newton's First Law

At the 2006 Winter Olympics in Turin, Italy, Duff Gibson charged head-first down a 1.4-km icy track with 19 challenging curves. He reached speeds well over 125 km/h and ended up clinching the gold medal in the men's skeleton event (Figure 3.21). Gibson's success had a lot to do with understanding the physics of motion.

Imagine an ideal situation in which no friction acts on the sled and no air resistance acts on the athlete. Scientist Galileo Galilei (1564–1642) thought that an object moving on a level surface would continue moving forever at constant speed and in the same direction if no external force acts on the object. If the object is initially stationary, then it will remain stationary, provided no external force acts on the object.

In the real world, friction and air resistance are external forces that act on all moving objects. So an object that is in motion will eventually slow down to a stop, unless another force acts to compensate for both friction and air resistance. Galileo recognized the existence of friction, so he used thought experiments, as well as experiments with controlled variables, to understand motion. Thought experiments are theoretical, idealized situations that can be imagined but cannot be created in the real world.

*info* **BIT**

The skeleton is an Olympic sledding sport believed to have originated in St. Moritz, Switzerland.

◄ **Figure 3.21** In the 2006 Winter Olympics, Calgary residents Duff Gibson (shown in photo) and Jeff Pain competed in the men's skeleton. Gibson edged Pain by 0.26 s to win the gold medal. Pain won the silver medal.

## The Concept of Inertia

inertia: property of an object that resists acceleration

Since ancient times, many thinkers attempted to understand how and why objects moved. But it took thousands of years before satisfactory explanations were developed that accounted for actual observations. A major stumbling block was not identifying friction as a force that exists in the real world.

In his study of motion, Galileo realized that every object has **inertia**, a property that resists acceleration. A stationary curling stone on ice requires a force to start the stone moving. Once it is moving, the curling stone requires a force to stop it.

To better understand the concept of inertia, try the challenges in 3-3 QuickLab.

**Concept Check**

Compare the inertia of an astronaut on Earth's surface, in orbit around Earth, and in outer space. Can an object ever have an inertia of zero? Explain.

**3-3 QuickLab**

## Challenges with Inertia

### Problem

What role does inertia play in each of these challenges?

### Materials

glass tumbler
small, stiff piece of cardboard
several loonies
empty soft-drink bottle
plastic hoop (about 2 cm wide, cut from a large plastic bottle)
small crayon with flat ends
ruler (thinner than thickness of one loonie)

### Procedure

1. Set up the tumbler, piece of cardboard, and loonie as shown in Figure 3.22 (a). Remove the cardboard so the loonie falls into the tumbler.

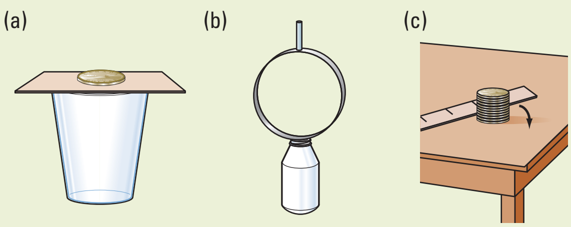
2. Set up the soft-drink bottle, plastic hoop, and a crayon as shown in Figure 3.22 (b). Remove the hoop so the crayon falls into the bottle.

3. Set up a stack of loonies and the ruler as shown in Figure 3.22 (c). Use the ruler to remove the loonie at the very bottom without toppling the stack.

**Caution: Keep your eyes well above the coin stack.**

### Questions

1. (a) What method did you use to successfully perform each step in the procedure?
   (b) Apply the concept of inertia to explain why each of your procedures was effective.




▲ **Figure 3.22**

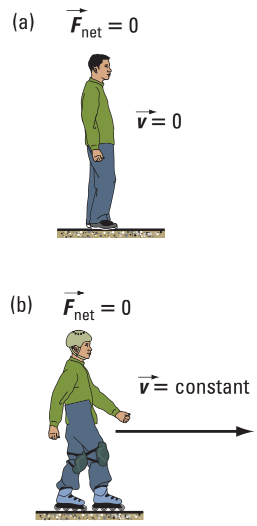
# Newton's First Law and Its Applications

Newton modified and extended Galileo's ideas about inertia in a law, called Newton's first law of motion (Figure 3.23).

An object will continue either being at rest or moving at constant velocity unless acted upon by an external non-zero net force.

If $\vec{F}_{\text{net}} = 0$, then $\Delta\vec{v} = 0$.

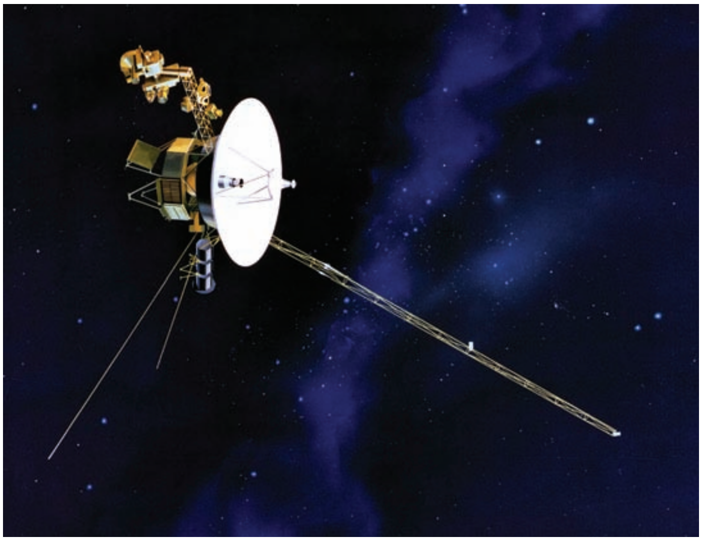
So if you want to change the motion of an object, a non-zero net force must act on the object.




▲ **Figure 3.23** If the net force on an object is zero, (a) a stationary object will remain at rest, and (b) an object in motion will continue moving at constant speed in the same direction.

## Concept Check

The Voyager 1 and 2 space probes are in interstellar space. If the speed of Voyager 1 is 17 km/s and no external force acts on the probe, describe the motion of the probe (Figure 3.24).



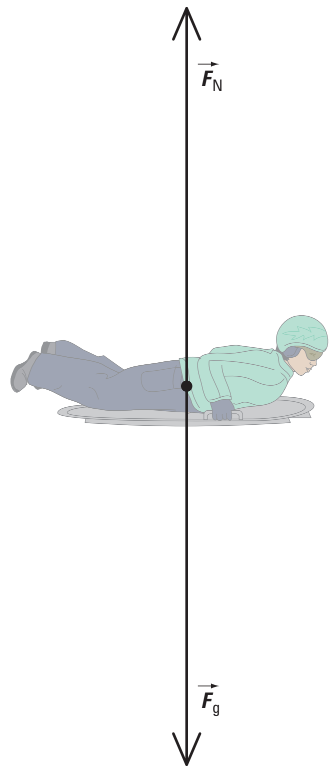
▲ **Figure 3.24** The Voyager planetary mission is NASA's most successful in terms of the number of scientific discoveries.

### Newton's First Law and Sliding on Ice

Many winter sports involve a person sliding on ice. In the case of the skeleton event in the Winter Olympics, an athlete uses a sled to slide along a bobsled track. In hockey, a player uses skates to glide across the icy surface of a rink.

Suppose a person on a sled is sliding along a horizontal, icy surface. If no external force acts on the person-sled system, then according to Newton's first law, the person would maintain the same speed. In fact, the person would not stop at all (Figure 3.25).

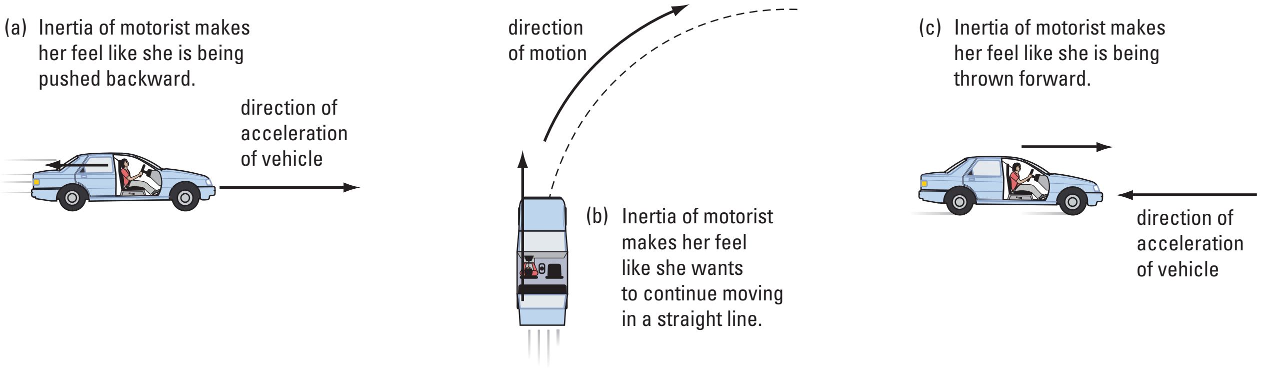
In real life, the external forces of friction and air resistance act on all moving objects. So the system would eventually come to a stop.



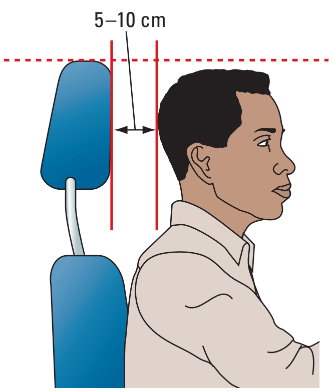

▲ **Figure 3.25** Free-body diagram of a person-sled system sliding on a horizontal, frictionless surface

## Newton's First Law and Vehicle Safety Devices

When you are in a moving car, you can feel the effects of your own inertia. If the car accelerates forward, you feel as if your body is being pushed back against the seat, because your body resists the increase in speed. If the car turns a corner, you feel as if your body is being pushed against the door, because your body resists the change in the direction of motion. If the car stops suddenly, you feel as if your body is being pushed forward, because your body resists the decrease in speed (Figure 3.26).




▲ **Figure 3.26** The inertia of a motorist resists changes in the motion of a vehicle. (a) The vehicle is speeding up, (b) the vehicle is changing direction, and (c) the vehicle is stopping suddenly.

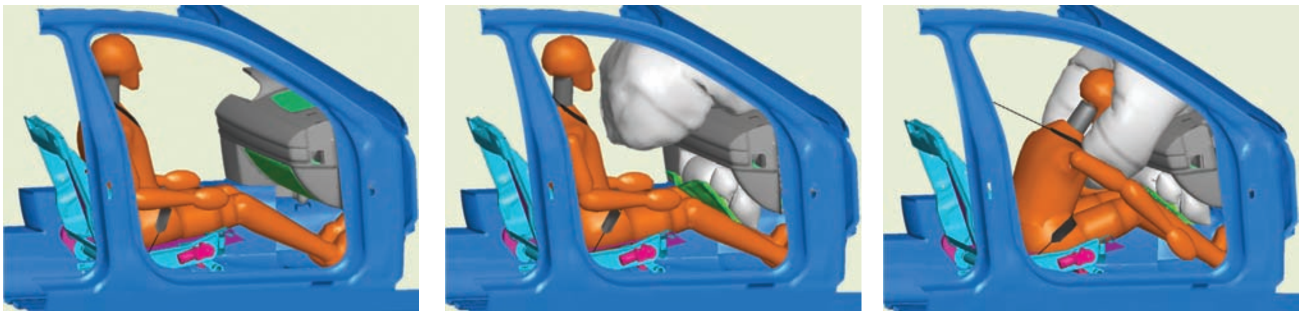



▲ **Figure 3.27** The ideal position for a headrest

When a car is rear-ended, a motorist's body moves forward suddenly as the car seat moves forward. However, the motorist's head resists moving forward. A properly adjusted headrest can minimize or prevent whiplash, an injury resulting from the rapid forward accelerations in a rear-end collision (Figure 3.27). Research shows that properly adjusted headrests can reduce the risk of whiplash-related injuries by as much as 40%. A poorly adjusted headrest, however, can actually worsen the effects of a rear-end collision on the neck and spine.

When a car is involved in a head-on collision, the motorist continues to move forward. When a seat belt is worn properly, the forward motion of a motorist is safely restricted.

If a head-on collision is violent enough, sodium azide undergoes a rapid chemical reaction to produce non-toxic nitrogen gas, which inflates an airbag. The inflated airbag provides a protective cushion to slow down the head and body of a motorist (Figure 3.28).



▲ **Figure 3.28** Airbag systems in vehicles are designed to deploy during vehicle collisions.

## 3-4 Decision-Making Analysis

# The Airbag Debate

**Required Skills**
- Defining the issue
- Developing assessment criteria
- Researching the issue
- Analyzing data and information
- Proposing a course of action
- Justifying the course of action
- Evaluating the decision

### The Issue

Front airbags were introduced in the 1990s to help prevent injury to motorists, especially during head-on collisions. Side airbags can also help. Yet front airbags have also been the cause of serious injury, even death. Furthermore, airbags add to the cost of a vehicle. Airbag advocates want both front and side airbags installed, better airbags, and greater control over their operation. Opponents want airbags removed from cars altogether.

### Background Information

Airbags are connected to sensors that detect sudden changes in acceleration. The process of triggering and inflating an airbag occurs in about 40 ms. It is in that instant that arms and legs have been broken and children have been killed by the impact of a rapidly inflating airbag. Tragically, some of these deaths occurred during minor car accidents.

Manufacturers have placed on/off switches for airbags on some vehicles, and some engineers are now developing “smart” airbags, which can detect the size of a motorist and the distance that person is sitting from an airbag. This information can then be used to adjust the speed at which the airbag inflates.

### Analysis

1. Identify the different stakeholders involved in the airbag controversy.
2. Research the development and safety history of airbags in cars. Research both front and side airbags. Consider head, torso, and knee airbags. Analyze your results, and identify any trends in your data.
3. Propose a solution to this issue, based on the trends you identified.
4. Propose possible changes to current airbag design that could address the issues of safety and cost.
5. Plan a class debate to argue the pros and cons of airbag use. Identify five stakeholders to represent each side in the debate. Support your position with research. Participants will be assessed on their research, organizational skills, debating skills, and attitudes toward learning.

### Concept Check

Use Newton’s first law to explain why
(a) steel barriers usually separate the cab of a truck from the load (Figure 3.29),
(b) trucks carrying tall loads navigate corners slowly, and
(c) customers who order take-out drinks are provided with lids.

◄ **Figure 3.29**

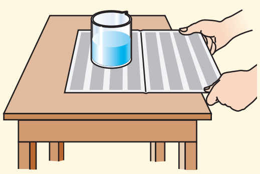
**eTECH**

Explore the motion of an object that experiences a net force of zero. Follow the eTECH links at www.pearsoned.ca/school/physicssource.

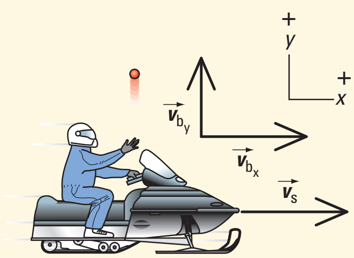
## 3.2 Check and Reflect

### Knowledge

1. In your own words, state Newton's first law.
2. Give two examples, other than those in the text, that illustrate the property of inertia for both a stationary and a moving object.
3. Use Newton's first law to describe the motion of
   (a) a car that attempts to go around an icy curve too quickly, and
   (b) a lacrosse ball after leaving the lacrosse stick.
4. Apply Newton's first law and the concept of inertia to each of these situations.
   (a) How could you remove the newspaper without toppling the plastic beaker?



   (b) While moving at constant speed on a level, snowy surface, a snowmobiler throws a ball vertically upward. If the snowmobile continues moving at constant velocity, the ball returns to the driver. Why does the ball land ahead of the driver if the snowmobile stops? Assume that the air resistance acting on the ball is negligible.




### Applications

5. Design an experiment using an air puck on an air table or spark air table to verify Newton's first law. Report your findings.

**Caution: A shock from a spark air table can be dangerous.**

6. Imagine you are the hockey coach for a team of 10-year-olds. At a hockey practice, you ask the players to skate across the ice along the blue line (the line closest to the net), and shoot the puck into the empty net. Most of the shots miss the net. The faster the children skate, the more they miss. Newton's first law would help the players understand the problem, but a technical explanation might confuse them.
   (a) Create an explanation that would make sense to the 10-year-olds.
   (b) With the aid of a diagram, design a drill for the team that would help the players score in this type of situation.

### Extensions

7. Research why parents use booster seats for young children using information from Safe Kids Canada. Summarize the "seat belt test" that determines whether a child is big enough to wear a seat belt without a booster seat. Begin your search at www.pearsoned.ca/school/physicssource.
8. During a sudden stop or if a motorist tries to adjust a seat belt suddenly, the seat belt locks into position. Research why seat belts lock. Write a brief report, including a diagram, of your findings. Begin your search at www.pearsoned.ca/school/physicssource.
9. Make a web diagram to summarize concepts and ideas associated with Newton's first law. Label the oval in the middle as "Newton's first law." Cluster your words or ideas in other ovals around it. Connect these ovals to the central one and one another, where appropriate, with lines. See Student References 4: Using Graphic Organizers on page 869 for an example.

**e TEST**

To check your understanding of inertia and Newton's first law, follow the eTest links at www.pearsoned.ca/school/physicssource.

# 3.3 Newton's Second Law

If a speed skater wants to win a championship race, the cardiovascular system and leg muscles of the athlete must be in peak condition. The athlete must also know how to effectively apply forces to propel the body forward. World-class speed skaters such as Cindy Klassen know that maximizing the forward acceleration requires understanding the relationship among force, acceleration, and mass (Figure 3.30).

Newton spent many years of his life trying to understand the motion of objects. After many experiments and carefully analyzing the ideas of Galileo and others, Newton eventually found a simple mathematical relationship that models the motion of an object.

This relationship, known as Newton's second law, relates the net force acting on an object, the acceleration of the object, and its mass. Begin by doing 3-5 Inquiry Lab to find the relationship between the acceleration of an object and the net force acting on it.

**info BIT**

Cindy Klassen won a total of five medals during the 2006 Winter Olympics, a Canadian record, and is currently Canada's most decorated Olympian with six medals.

▲ **Figure 3.30** Cindy Klassen, originally from Winnipeg but now a Calgary resident, won the gold medal in the 1500-m speed skating event in the 2006 Winter Olympics in Turin, Italy.

## 3-5 Inquiry Lab

**Required Skills**
- Initiating and Planning
- Performing and Recording
- Analyzing and Interpreting
- Communication and Teamwork

# Relating Acceleration and Net Force

The kinematics equation $\vec{d} = \vec{v}_i \Delta t + \frac{1}{2}\vec{a}(\Delta t)^2$ relates displacement $\vec{d}$, initial velocity $\vec{v}_i$, time interval $\Delta t$, and acceleration $\vec{a}$. If $\vec{v}_i = 0$, the equation simplifies to $\vec{d} = \frac{1}{2}\vec{a}(\Delta t)^2$. If you solve for acceleration, you get $\vec{a} = \frac{2\vec{d}}{(\Delta t)^2}$. Remember to use the scalar form of this equation when solving for acceleration.

## Question

How is the acceleration of an object related to the net force acting on the object?

## Hypothesis

State a hypothesis relating acceleration and net force. Remember to write an "if/then" statement.

## Variables

The variables involved in this lab are the mass of the system, the applied force acting on the system, friction acting on the system, time interval, the distance the system travels, and the acceleration of the system. Read the procedure and identify the controlled, manipulated, and responding variable(s).

## Materials and Equipment

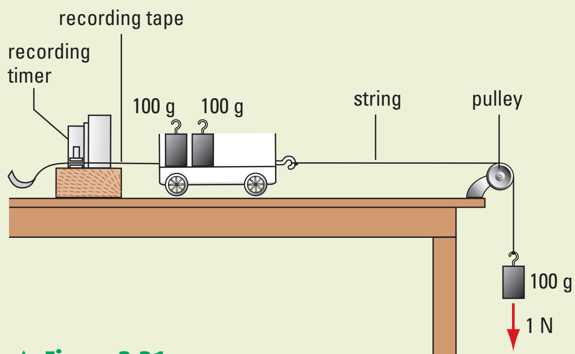
C-clamp
dynamics cart
three 100-g standard masses
pulley
smooth, flat surface (about 1.5 m)
string (about 2 m)
recording tape
recording timer with power supply
metre-stick
masking tape
graph paper

**eLAB**

For a probeware activity, go to www.pearsoned.ca/school/physicssource.

## Procedure

1. Copy Tables 3.2 and 3.3 from page 145 into your notebook.
2. Measure the mass of the cart. Record the value in Table 3.2.
3. Set up the recording timer, pulley, and cart loaded with three 100-g standard masses on a lab bench (Figure 3.31). Make a loop at each end of the string. Hook one loop to the end of the cart and let the other loop hang down over the pulley.




▲ **Figure 3.31**

**Caution: Position a catcher person near the edge of the lab bench. Do not let the cart or hanging objects fall to the ground.**

4. Attach a length of recording tape to the cart and thread it through the timer.
5. While holding the cart still, transfer one 100-g mass from the cart to the loop of string over the pulley and start the timer. When you release the cart, the hanging 100-g mass will exert a force of about 1 N on the system. Release the cart but stop it before it hits the pulley. Label the tape "trial 1; magnitude of $\vec{F}_{app} = 1$ N."
6. Repeat steps 4 and 5 using the same cart but this time transfer another 100-g mass from the cart to the first hanging object. Label the tape "trial 2; magnitude of $\vec{F}_{app} = 2$ N." By transferring objects from the cart to the end of the string hanging over the pulley, the mass of the system remains constant but the net force acting on the system varies.
7. Repeat steps 4 and 5 using the same cart but this time transfer another 100-g mass from the cart to the two hanging masses. Label the tape "trial 3; magnitude of $\vec{F}_{app} = 3$ N."

## Analysis

1. Calculate the mass of the system, $m_T$. Record the value in Table 3.2.

2. Using the tape labelled "trial 3," label the dot at the start $t = 0$ and mark off a convenient time interval. If the period of the timer is $\frac{1}{60}$ s, a time interval of 30 dot spaces represents 0.5 s ($30 \times \frac{1}{60}$ s $= 0.5$ s). Record the time interval in Table 3.2.

3. Measure the distance the system travelled during this time interval. Record this value in Table 3.2.

4. Use the equation $a = \frac{2d}{(\Delta t)^2}$ to calculate the magnitude of the acceleration of the system. Record the value in Tables 3.2 and 3.3.

5. Using the same time interval, repeat questions 3 and 4 for the tapes labelled "trial 1" and "trial 2."

6. Why is it a good idea to choose the time interval using the tape labelled "trial 3"?

7. Plot a graph of the magnitude of the acceleration vs. the magnitude of the applied force (Table 3.3).

8. (a) Describe the graph you drew in question 7.
   (b) Where does the graph intersect the $x$-axis? Why? What conditions would have to be present for it to pass through the origin?
   (c) For each trial, subtract the $x$-intercept from the applied force to find the net force. Record the values in Table 3.3. Then plot a graph of the magnitude of the acceleration vs. the magnitude of the net force.

9. When the magnitude of the net force acting on the system is doubled, what happens to the magnitude of the acceleration of the system?

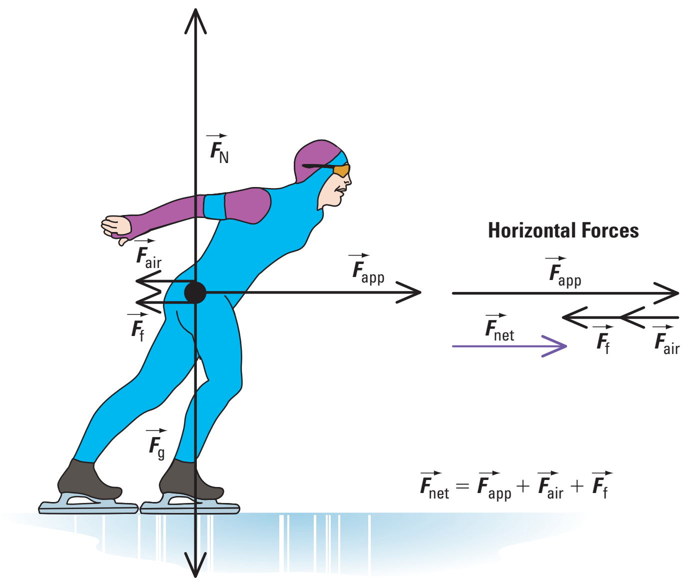
10. What is the relationship between the magnitude of the acceleration and the magnitude of the net force? Write this relationship as a proportionality statement. Does this relationship agree with your hypothesis?

▼ **Table 3.2** Mass, Time, Distance, and Acceleration

| Trial | Mass of Cart $m_c$ (kg) | Mass of Load on Cart $m_l$ (kg) | Mass of Load Hanging over Pulley $m_h$ (kg) | Total Mass $m_T = m_c + m_l + m_h$ (kg) | Time Interval $\Delta t$ (s) | Distance $d$ (m) | Magnitude of $\vec{a}$ (m/s²) |
|---|---|---|---|---|---|---|---|
| 1 | | 0.200 | 0.100 | | | | |
| 2 | | 0.100 | 0.200 | | | | |
| 3 | | 0 | 0.300 | | | | |

▼ **Table 3.3** Force and Acceleration

| Trial | Magnitude of $\vec{F}_{app}$ Acting on System (N) | Magnitude of $\vec{F}_{net}$ Acting on System (N) | Magnitude of $\vec{a}$ of System (m/s²) |
|---|---|---|---|
| 1 | 1 | | |
| 2 | 2 | | |
| 3 | 3 | | |




▲ **Figure 3.32** (left) Free-body diagram showing the forces acting on a speed skater being pushed by a teammate in the short track relay event; (right) vector addition diagram for the horizontal forces.

## Relating Acceleration and Net Force

For the system in 3-5 Inquiry Lab, you discovered that there is a linear relationship between acceleration and net force. This relationship can be written as a proportionality statement:

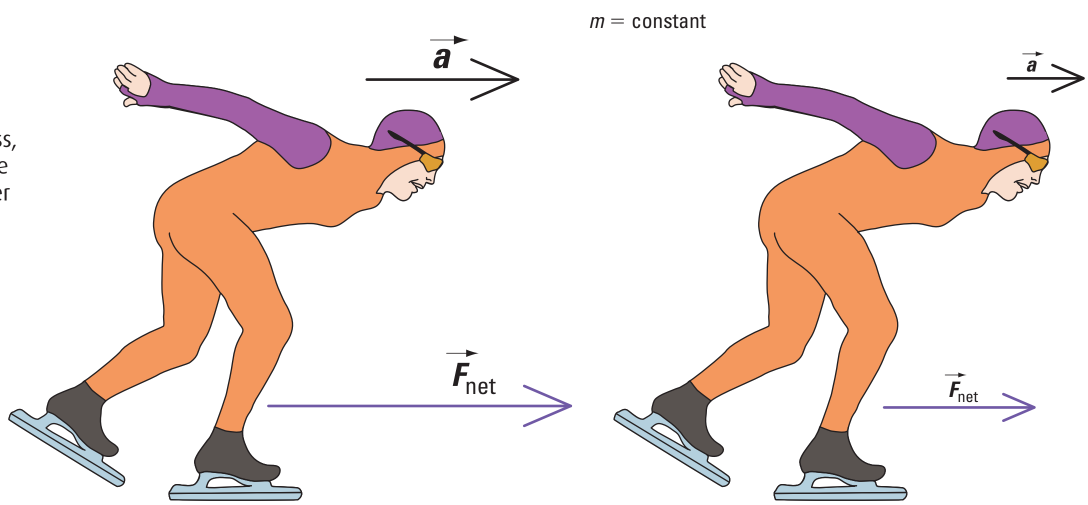
$$a \propto F_{net}$$

This relationship applies to speed skating. In the short track relay event, a speed skater pushes the next teammate forward onto the track when it is the teammate's turn to start skating.

While the teammate is being pushed, the horizontal forces acting on the skater are the applied push force, friction, and air resistance (Figure 3.32). As long as the applied push force is greater in magnitude than the sum of the force of friction acting on the skates and the air resistance acting on the skater's body, the net force on the teammate acts forward.

The harder the forward push, the greater will be the forward net force on the teammate (Figure 3.33). So the acceleration of the teammate will be greater. Note that the acceleration is in the same direction as the net force.

Find out the relationship between the acceleration of an object and its mass by doing 3-6 Design a Lab.




▶ **Figure 3.33** For the same mass, a greater net force results in a greater acceleration.

### *Concept Check*

What is the difference between a net force and an applied force? Can a net force ever equal an applied force? Explain using an example and a free-body diagram.

## 3-6 Design a Lab

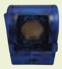
# Relating Acceleration and Mass

In this lab, you will investigate the relationship between acceleration and mass when the net force acting on the system is constant.

### The Question

How is the acceleration of an object related to the mass of the object?

**eLAB**



For a probeware activity, go to www.pearsoned.ca/school/physicssource.

### Design and Conduct Your Investigation

- State a hypothesis relating acceleration and mass.
- Then use the set-up in Figure 3.31 on page 144 to design an experiment. List the materials you will use as well as a detailed procedure. Use the procedure and questions in 3-5 Inquiry Lab to help you.
- Plot a graph of the magnitude of the acceleration vs. the mass of the system. Then plot a graph of the magnitude of the acceleration vs. the reciprocal of the mass of the system.
- Analyze your data and form conclusions. How well did your results agree with your hypothesis?

## Relating Acceleration and Mass

In 3-6 Design a Lab, you discovered that the relationship between acceleration and mass is non-linear. But if you plot acceleration as a function of the reciprocal of mass, you get a straight line. This shows that there is a linear relationship between acceleration and the reciprocal of mass. This relationship can be written as a proportionality statement:

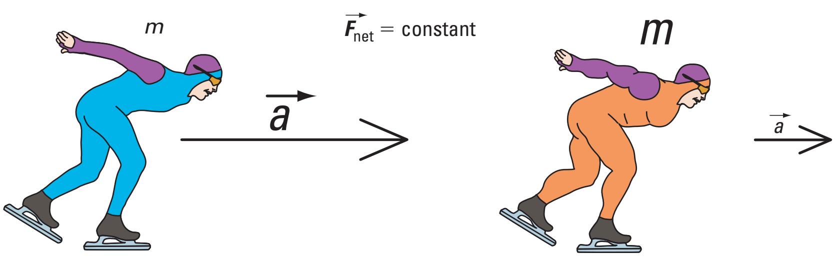
$$a \propto \frac{1}{m}$$

In speed skating, evidence of this relationship is the different accelerations that two athletes of different mass have. Suppose athlete A has a mass of 60 kg and athlete B a mass of 90 kg. If the net force acting on A and B is the same, you would expect A to have a greater acceleration than B (Figure 3.34).

This observation makes sense in terms of inertia, because the inertia of B resists the change in motion more so than the inertia of A does. In fact, you observed this relationship in 3-1 QuickLab when you compared the acceleration of an empty cart and a cart loaded with a 1-kg standard mass.

**eTECH**

Explore how the net force on an object and its mass affect its acceleration. Follow the eTech links at www.pearsoned.ca/school/physicssource.




▲ **Figure 3.34** For the same net force, a more massive person has a smaller acceleration than a less massive one does.

## Newton's Second Law and Inertial Mass

The proportionality statements $a \propto F_{\text{net}}$ and $a \propto \frac{1}{m}$ can be combined into one statement, $a \propto \frac{F_{\text{net}}}{m}$ or $a = k\frac{F_{\text{net}}}{m}$ where $k$ is the proportionality constant. Since 1 N is defined as the net force required to accelerate a 1-kg object at 1 m/s², $k$ is equal to 1. So the equation can be written as $a = \frac{F_{\text{net}}}{m}$.

This mathematical relationship is Newton's second law.

When an external non-zero net force acts on an object, the object accelerates in the direction of the net force. The magnitude of the acceleration is directly proportional to the magnitude of the net force and inversely proportional to the mass of the object.

The equation for Newton's second law is usually written with $\vec{F}_{\text{net}}$ on the left side:

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

**e MATH**

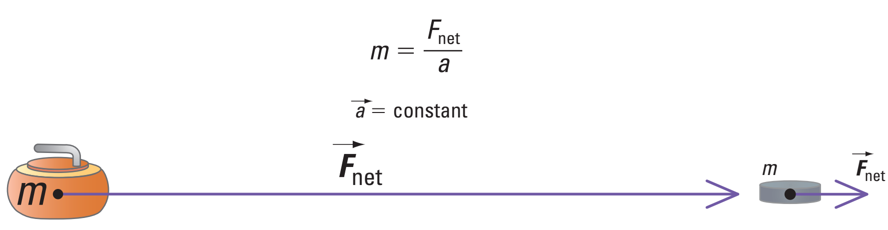
Use technology to explore the relationship among $F_{\text{net}}$, $m$, and $a$ in Newton's second law. Follow the eMath links at www.pearsoned.ca/school/physicssource to download sample data.

### The Concept of Inertial Mass

All objects have mass, so all objects have inertia. From experience, it is more difficult to accelerate a curling stone than to accelerate a hockey puck (Figure 3.35). This means that the inertia of an object is related to its mass. The greater the mass of the object, the greater its inertia.

The mass of an object in Newton's second law is determined by finding the ratio of a known net force acting on an object to the acceleration of the object. In other words, the mass is a measure of the inertia of an object. Because of this relationship, the mass in Newton's second law is called **inertial mass**, which indicates *how* the mass is measured.

**inertial mass:** mass measurement based on the ratio of a known net force on an object to the acceleration of the object




▲ **Figure 3.35** If the acceleration of the curling stone and the hockey puck is the same, $\vec{F}_{\text{net}}$ on the curling stone would be 95 times greater than $\vec{F}_{\text{net}}$ on the hockey puck because the inertial mass of the curling stone is that much greater than the hockey puck.

**Concept Check**

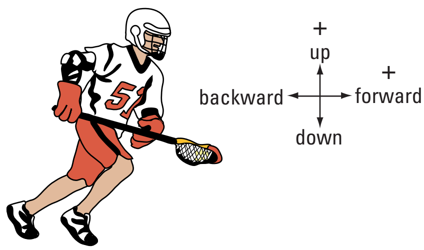
What happens to the acceleration of an object if
(a) the mass and net force both decrease by a factor of 4?
(b) the mass and net force both increase by a factor of 4?
(c) the mass increases by a factor of 4, but the net force decreases by the same factor?
(d) the mass decreases by a factor of 4, and the net force is zero?

## Applying Newton's Second Law to Horizontal Motion

Example 3.5 demonstrates how to use Newton's second law to predict the average acceleration of a lacrosse ball. In this situation, air resistance is assumed to be negligible to simplify the problem.

### Example 3.5

A lacrosse player exerts an average net horizontal force of 2.8 N [forward] on a 0.14-kg lacrosse ball while running with it in the net of his stick (Figure 3.36). Calculate the average horizontal acceleration of the ball while in contact with the lacrosse net.



▲ **Figure 3.36**

***Given***

$\vec{F}_{net} = 2.8 \text{ N [forward]}$

$m = 0.14 \text{ kg}$

***Required***

average horizontal acceleration of ball ($\vec{a}$)

***Analysis and Solution***

The ball is not accelerating up or down.
So in the vertical direction, $\vec{F}_{net} = 0$ N.
In the horizontal direction, the acceleration of the ball is in the direction of the net force. So use the scalar form of Newton's second law.

$$
\begin{aligned}
F_{net} &= ma \\
a &= \frac{F_{net}}{m} \\
&= \frac{2.8 \text{ N}}{0.14 \text{ kg}} \\
&= \frac{2.8 \cancel{\text{kg}} \cdot \dfrac{\text{m}}{\text{s}^2}}{0.14 \cancel{\text{kg}}} \\
&= 20 \text{ m/s}^2 \\
\vec{a} &= 20 \text{ m/s}^2 \text{ [forward]}
\end{aligned}
$$

***Paraphrase***

The average horizontal acceleration of the lacrosse ball is 20 m/s² [forward].

### Practice Problems

1. The net force acting on a 6.0-kg grocery cart is 12 N [left]. Calculate the acceleration of the cart.
2. A net force of 34 N [forward] acts on a curling stone causing it to accelerate at 1.8 m/s² [forward] on a frictionless icy surface. Calculate the mass of the curling stone.

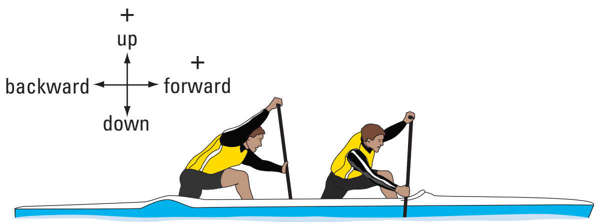
**Answers**

1. 2.0 m/s² [left]
2. 19 kg

In Example 3.6, a free-body diagram is used to first help determine the net force acting on a canoe. Then Newton's second law is applied to predict the average acceleration of the canoe.

## Example 3.6

Two athletes on a team, A and B, are practising to compete in a canoe race (Figure 3.37). Athlete A has a mass of 70 kg, B a mass of 75 kg, and the canoe a mass of 20 kg. Athlete A can exert an average force of 400 N [forward] and B an average force of 420 N [forward] on the canoe using the paddles. During paddling, the magnitude of the water resistance on the canoe is 380 N. Calculate the initial acceleration of the canoe.




◀ **Figure 3.37**

### Practice Problem

1. In the men's four-man bobsled event in the Winter Olympics, the maximum mass of a bobsled with two riders, a pilot, and a brakeman is 630 kg (Figure 3.39).

▲ **Figure 3.39**

During a practice run, riders A and B exert average forces of 1220 N and 1200 N [forward] respectively to accelerate a bobsled of mass 255 kg, a pilot of mass 98 kg, and a brakeman of mass 97 kg. Then they jump in for the challenging ride down a 1300-m course. During the pushing, the magnitude of the force of friction acting on the bobsled is 430 N. Calculate the average acceleration of the bobsled, pilot, and brakeman.

**Answer**

1. 4.4 m/s$^2$ [forward]

***Given***

$m_A = 70$ kg $\quad m_B = 75$ kg $\quad m_c = 20$ kg

$\vec{F}_A = 400$ N [forward] $\quad \vec{F}_B = 420$ N [forward]

$\vec{F}_f = 380$ N [backward]

***Required***

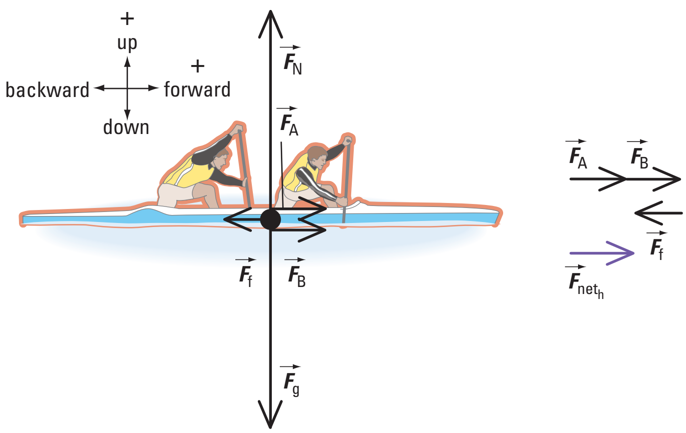
initial acceleration of canoe ($\vec{a}$)

***Analysis and Solution***

The canoe and athletes are a system because they move together as a unit. Find the total mass of the system.

$$\begin{aligned} m_T &= m_A + m_B + m_c \\ &= 70 \text{ kg} + 75 \text{ kg} + 20 \text{ kg} \\ &= 165 \text{ kg} \end{aligned}$$

Draw a free-body diagram for the system (Figure 3.38).




▲ **Figure 3.38**

The system is not accelerating up or down.
So in the vertical direction, $F_{net_v} = 0$ N.
Write equations to find the net force on the system in both the horizontal and vertical directions.

horizontal direction

$$\vec{F}_{\text{net}_\text{h}} = \vec{F}_\text{A} + \vec{F}_\text{B} + \vec{F}_\text{f}$$

$$\begin{aligned} F_{\text{net}_\text{h}} &= F_\text{A} + F_\text{B} + F_\text{f} \\ &= 400\ \text{N} + 420\ \text{N} + (-380\ \text{N}) \\ &= 400\ \text{N} + 420\ \text{N} - 380\ \text{N} \\ &= 440\ \text{N} \end{aligned}$$

vertical direction

$$\vec{F}_{\text{net}_\text{v}} = \vec{F}_\text{N} + \vec{F}_\text{g}$$

$$F_{\text{net}_\text{v}} = 0$$

Calculations in the vertical direction are not required in this problem.

Apply Newton's second law to the horizontal direction.

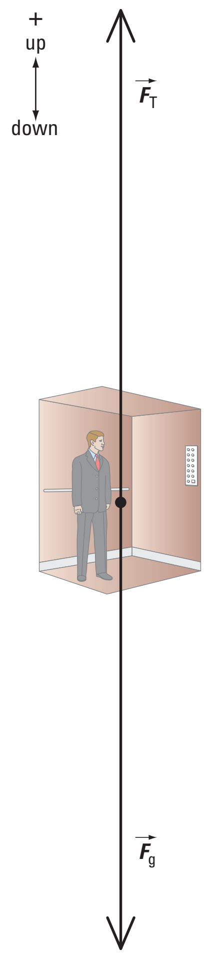
$$\begin{aligned} F_{\text{net}_\text{h}} &= m_\text{T}a \\ a &= \frac{F_{\text{net}_\text{h}}}{m_\text{T}} \\ &= \frac{440\ \text{N}}{165\ \text{kg}} \\ &= \frac{440\ \frac{\cancel{\text{kg}}\cdot\text{m}}{\text{s}^2}}{165\ \cancel{\text{kg}}} \\ &= 2.7\ \text{m/s}^2 \\ \vec{a} &= 2.7\ \text{m/s}^2\ [\text{forward}] \end{aligned}$$

***Paraphrase***

The canoe will have an initial acceleration of 2.7 m/s² [forward].

## Applying Newton's Second Law to Vertical Motion

Example 3.7 demonstrates how to apply Newton's second law to determine the vertical acceleration of a person riding an elevator. To determine the net force on the elevator, use a free-body diagram.




▲ **Figure 3.41 (a)**

## Example 3.7

A person and an elevator have a combined mass of $6.00 \times 10^2$ kg (Figure 3.40). The elevator cable exerts a force of $6.50 \times 10^3$ N [up] on the elevator. Find the acceleration of the person.

***Given***

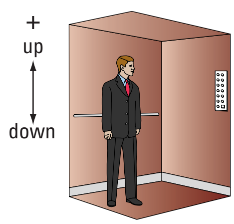
$m_\text{T} = 6.00 \times 10^2$ kg

$\vec{F}_\text{T} = 6.50 \times 10^3$ N [up]

$\vec{g} = 9.81$ m/s² [down]

***Required***

acceleration of person ($\vec{a}$)




▲ **Figure 3.40**

***Analysis and Solution***

Draw a free-body diagram for the person-elevator system [Figure 3.41 (a)].

The system is not accelerating left or right.

So in the horizontal direction, $\vec{F}_\text{net} = 0$ N.

Since the person is standing on the elevator floor, both the person and the elevator will have the same vertical acceleration.

For the vertical direction, write an equation to find the net force on the system [Figure 3.41 (b)].

$$\vec{F}_{net} = \vec{F}_T + \vec{F}_g$$

Apply Newton's second law.

$$m\vec{a} = \vec{F}_T + \vec{F}_g$$

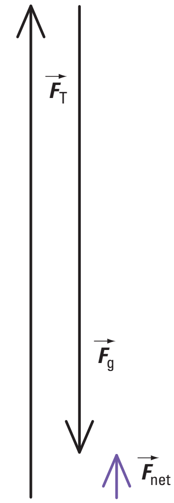
$$ma = F_T + F_g$$

$$ma = F_T + mg$$

$$\frac{\cancel{m}a}{\cancel{m}} = \frac{F_T}{m} + \frac{\cancel{m}g}{\cancel{m}}$$

$$\begin{aligned} a &= \frac{F_T}{m} + g \\ &= \frac{6.50 \times 10^3 \text{ N}}{6.00 \times 10^2 \text{ kg}} + (-9.81 \text{ m/s}^2) \\ &= \frac{6.50 \times 10^3 \frac{\cancel{\text{kg}} \cdot \text{m}}{\text{s}^2}}{6.00 \times 10^2 \cancel{\text{kg}}} - 9.81 \text{ m/s}^2 \\ &= 1.02 \text{ m/s}^2 \end{aligned}$$

$$\vec{a} = 1.02 \text{ m/s}^2 \text{ [up]}$$




▲ **Figure 3.41 (b)**

***Paraphrase***

The acceleration of the person is 1.02 m/s² [up].

## Practice Problems

1. The person in Example 3.7 rides the same elevator when the elevator cable exerts a force of $5.20 \times 10^3$ N [up] on the elevator. Find the acceleration of the person.
2. An electric chain hoist in a garage exerts a force of $2.85 \times 10^3$ N [up] on an engine to remove it from a car. The acceleration of the engine is 1.50 m/s² [up]. What is the mass of the engine?

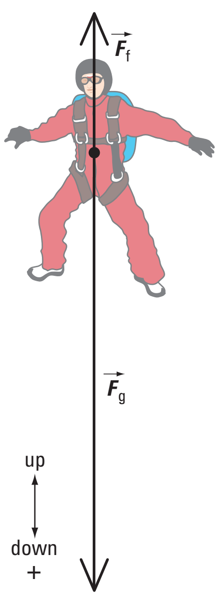
### Answers

1. 1.14 m/s² [down]
2. 252 kg

**e WEB**

Air resistance is the frictional force that acts on all objects falling under the influence of gravity. Research how this force affects the maximum speed that an object reaches during its fall. Write a brief summary of your findings. Begin your search at www.pearsoned.ca/school/physicssource.

In Example 3.8, the force of gravity causes a skydiver to accelerate downward. Since the only motion under consideration is that of the skydiver and the direction of motion is down, it is convenient to choose *down* to be positive.




▲ **Figure 3.42**

## Example 3.8

A skydiver is jumping out of an airplane. During the first few seconds of one jump, the parachute is unopened, and the magnitude of the air resistance acting on the skydiver is 250 N. The acceleration of the skydiver during this time is 5.96 m/s² [down]. Calculate the mass of the skydiver.

***Given***

$\vec{F}_f = 250$ N [up] $\qquad \vec{a} = 5.96$ m/s² [down]

$\vec{g} = 9.81$ m/s² [down]

***Required***

mass of skydiver ($m$)

***Analysis and Solution***

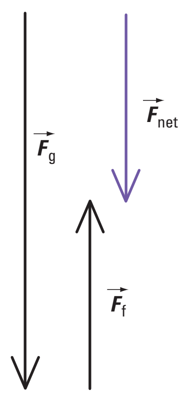
Draw a free-body diagram for the skydiver (Figure 3.42).

The skydiver is not accelerating left or right.

So in the horizontal direction, $\vec{F}_{net} = 0$ N.

For the vertical direction, write an equation to find the net force on the skydiver (Figure 3.43).

$$\vec{F}_{net} = \vec{F}_g + \vec{F}_f$$




▲ **Figure 3.43**

Apply Newton's second law.

$$
\begin{aligned}
m\vec{a} &= \vec{F}_g + \vec{F}_f \\
ma &= F_g + F_f \\
ma &= mg + (-250\text{ N}) \\
&= mg - 250\text{ N} \\
250\text{ N} &= mg - ma \\
&= m(g - a) \\
m &= \frac{250\text{ N}}{g - a} \\
&= \frac{250\text{ N}}{9.81\text{ m/s}^2 - 5.96\text{ m/s}^2} \\
&= \frac{250\text{ kg}\cdot\frac{\cancel{\text{m}}}{\cancel{\text{s}}^2}}{3.85\,\frac{\cancel{\text{m}}}{\cancel{\text{s}}^2}} \\
&= 64.9\text{ kg}
\end{aligned}
$$

***Paraphrase***

The mass of the skydiver is 64.9 kg.

## Practice Problems

1. A 55-kg female bungee jumper fastens one end of the cord (made of elastic material) to her ankle and the other end to a bridge. Then she jumps off the bridge. As the cord is stretching, it exerts an elastic force directed up on her. Calculate her acceleration at the instant the cord exerts an elastic force of 825 N [up] on her.
2. During a bungee jump, the velocity of the 55-kg woman at the lowest point is zero and the cord stretches to its maximum.
   (a) Compare the direction of her acceleration at the lowest point of the jump to the part of the jump where she is accelerating due to gravity.
   (b) At this point, what is the direction of her acceleration?

### Answers

1. 5.2 m/s² [up]
2. (b) up

## Applying Newton's Second Law to Two-Body Systems

When two objects are connected by a light rope as in Example 3.9, applying a force on one of the objects will cause both objects to accelerate at the same rate and in the same direction. In other words, the applied force can be thought to act on a single object whose mass is equivalent to the total mass.

## Example 3.9

Two blocks of identical material are connected by a light rope on a level surface (Figure 3.44). An applied force of 55 N [right] causes the blocks to accelerate. While in motion, the magnitude of the force of friction on the block system is 44.1 N. Calculate the acceleration of the blocks.

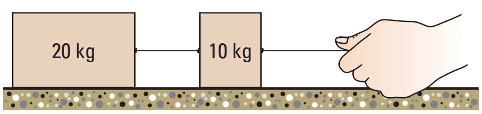
***Given***

$m_A = 20$ kg

$m_B = 10$ kg

$\vec{F}_{app} = 55$ N [right]

$\vec{F}_f = 44.1$ N [left]




▲ **Figure 3.44**

***Required***

acceleration ($\vec{a}$)

***Analysis and Solution***

The two blocks move together as a unit with the same acceleration. So consider the blocks to be a single object. Find the total mass of both blocks.

$$
\begin{aligned}
m_T &= m_A + m_B \\
&= 20\text{ kg} + 10\text{ kg} \\
&= 30\text{ kg}
\end{aligned}
$$

## Practice Problems

1. Two buckets of nails are hung one above the other and are pulled up to a roof by a rope. Each bucket has a mass of 5.0 kg. The tension in the rope connecting the buckets is 60 N. Calculate the acceleration of the buckets.
2. Refer to Example 3.9. The force of friction on the 10-kg block has a magnitude of 14.7 N.
   (a) Calculate the tension in the rope connecting the two blocks.
   (b) Calculate the tension in the rope between the hand and the 10-kg block.

### Answers

1. 2.2 m/s² [up]
2. (a) 37 N
   (b) 55 N

Draw a free-body diagram for this single object (Figure 3.45). The single object is not accelerating up or down.
So in the vertical direction, $\vec{F}_{net} = 0$ N.
Write equations to find the net force on the single object in both the horizontal and vertical directions.

horizontal direction

$$\vec{F}_{net_h} = \vec{F}_{app} + \vec{F}_f$$

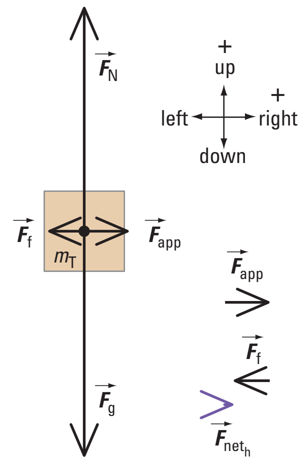
Apply Newton's second law.

$$m_T\vec{a} = \vec{F}_{app} + \vec{F}_f$$
$$m_T a = F_{app} + F_f$$
$$a = \frac{F_{app} + F_f}{m_T}$$
$$= \frac{55 \text{ N} + (-44.1 \text{ N})}{30 \text{ kg}}$$
$$= 0.36 \text{ m/s}^2$$
$$\vec{a} = 0.36 \text{ m/s}^2 \text{ [right]}$$

vertical direction

$$\vec{F}_{net_v} = \vec{F}_N + \vec{F}_g$$
$$F_{net_v} = 0$$

Calculations in the vertical direction are not required in this problem.



▲ **Figure 3.45**

***Paraphrase***

The acceleration of the blocks is 0.36 m/s² [right].

## Applying Newton's Second Law to a Single Pulley System

***e*SIM**

Apply Newton's second law to determine the motion of two blocks connected by a string over a pulley. Follow the eSim links at www.pearsoned.ca/school/physicssource.

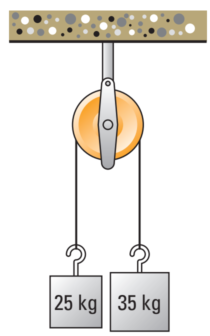
In Example 3.10, two objects are attached by a rope over a pulley. The objects, the rope, and the pulley form a system. You can assume that the rope has a negligible mass and thickness, and the rope does not stretch or break.

To simplify calculations in this physics course, you need to also assume that a pulley has negligible mass and has no frictional forces acting on its axle(s).

In Example 3.10, the external forces on the system are the gravitational forces acting on the hanging objects. The internal forces on the system are the forces along the string that pull on each object. The magnitude of both the internal and external forces acting on the system are not affected by the pulley. The pulley simply redirects the forces along the string that pulls on each object.

### Example 3.10

Two objects, A and B, are connected by a light rope over a light, frictionless pulley (Figure 3.46). A has a mass of 25 kg and B a mass of 35 kg. Determine the motion of each object once the objects are released.



▲ **Figure 3.46**

***Given***

$m_A = 25$ kg  $m_B = 35$ kg
$\vec{g} = 9.81$ m/s² [down]

***Required***

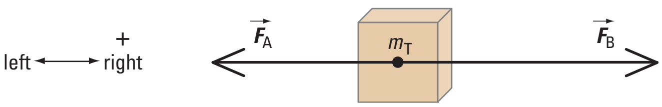
acceleration of each object ($\vec{a}_A$ and $\vec{a}_B$)

*Analysis and Solution*

The difference in mass between objects A and B will provide the net force that will accelerate both objects. Since $m_B > m_A$, you would expect $m_B$ to accelerate down while $m_A$ accelerates up.
The rope has a negligible mass.
So the tension in the rope is the same on both sides of the pulley.
The rope does not stretch.
So the magnitude of $\vec{a}_A$ is equal to the magnitude of $\vec{a}_B$.
Find the total mass of both objects.

$$\begin{aligned} m_T &= m_A + m_B \\ &= 25 \text{ kg} + 35 \text{ kg} \\ &= 60 \text{ kg} \end{aligned}$$

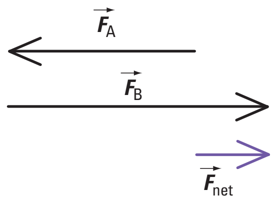
Choose an equivalent system in terms of $m_T$ to analyze the motion [Figure 3.47 (a)].




▲ **Figure 3.47 (a)**

$\vec{F}_A$ is equal to the gravitational force acting on $m_A$, and $\vec{F}_B$ is equal to the gravitational force acting on $m_B$.
Apply Newton's second law to find the net force acting on $m_T$ [Figure 3.47 (b)].

$$\begin{aligned} \vec{F}_{net} &= \vec{F}_A + \vec{F}_B \\ F_{net} &= F_A + F_B \\ &= -m_A g + m_B g \\ &= (m_B - m_A)g \\ &= (35 \text{ kg} - 25 \text{ kg})(9.81 \text{ m/s}^2) \\ &= 98.1 \frac{\text{kg}\cdot\text{m}}{\text{s}^2} \\ &= 98.1 \text{ N} \end{aligned}$$




▲ **Figure 3.47 (b)**

Use the scalar form of Newton's second law to calculate the magnitude of the acceleration.

$$\begin{aligned} F_{net} &= m_T a \\ a &= \frac{F_{net}}{m_T} \\ &= \frac{98.1 \text{ N}}{60 \text{ kg}} \\ &= \frac{98.1 \frac{\cancel{\text{kg}}\cdot\text{m}}{\text{s}^2}}{60 \cancel{\text{kg}}} \\ &= 1.6 \text{ m/s}^2 \end{aligned}$$

$$\vec{a}_A = 1.6 \text{ m/s}^2 \text{ [up] and } \vec{a}_B = 1.6 \text{ m/s}^2 \text{ [down]}$$

*Paraphrase*

Object A will have an acceleration of 1.6 m/s² [up] and object B will have an acceleration of 1.6 m/s² [down].

## Practice Problems

1. Determine the acceleration of the system shown in Example 3.10 for each situation below. State the direction of motion for each object. Express your answer in terms of $g$.

   (a) $m_A = \left(\frac{1}{3}\right) m_B$

   (b) $m_A = 2m_B$

   (c) $m_A = m_B$

2. Use the result of Example 3.10 and a free-body diagram to calculate the tension in the rope.

3. Draw a free-body diagram for each object in Example 3.10.

### Answers

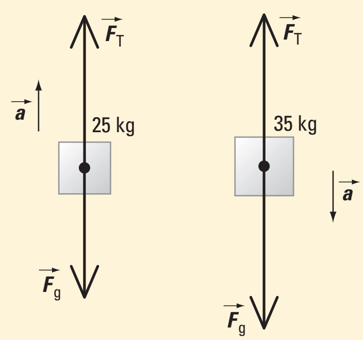
1. (a) $a = \frac{1}{2}g$, $m_A$ moves up, $m_B$ moves down

   (b) $a = \frac{1}{3}g$, $m_A$ moves down, $m_B$ moves up

   (c) $a = 0$, neither mass moves

2. $2.9 \times 10^2$ N

3.

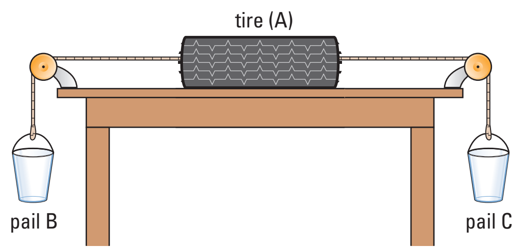


## Applying Newton's Second Law to a Two-Pulley System

In Example 3.11, the system is made up of three objects (A, B, and C). As in Example 3.10, the difference in weight between objects B and C will provide the net force that will accelerate the system.

### Example 3.11

A 20-kg truck tire (object A) is lying on a horizontal, frictionless surface. The tire is attached to two light ropes that pass over light, frictionless pulleys to hanging pails B and C (Figure 3.48). Pail B has a mass of 8.0 kg and C a mass of 6.0 kg. Calculate the magnitude of the acceleration of the system.




▲ **Figure 3.48**

***Given***

$m_A = 20$ kg $\quad m_B = 8.0$ kg $\quad m_C = 6.0$ kg

$\vec{g} = 9.81$ m/s² [down]

***Required***

magnitude of the acceleration of the system ($a$)

***Analysis and Solution***

Since $m_B > m_C$, you would expect $m_B$ to accelerate down while $m_C$ accelerates up. Since object A will accelerate left, choose left to be positive.

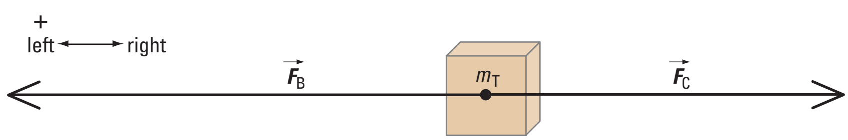
The rope has a negligible mass and the rope does not stretch.

So the magnitude of $\vec{a}_A$ is equal to the magnitude of $\vec{a}_B$, which is also equal to $\vec{a}_C$.

Find the total mass of the system.

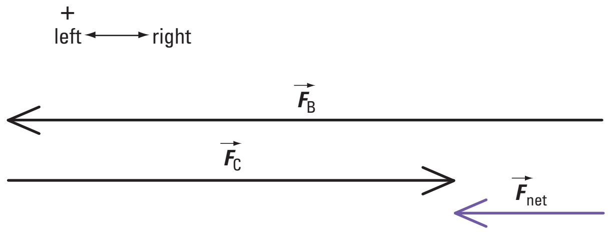
$$\begin{aligned} m_T &= m_A + m_B + m_C \\ &= 20 \text{ kg} + 8.0 \text{ kg} + 6.0 \text{ kg} \\ &= 34 \text{ kg} \end{aligned}$$

Choose an equivalent system in terms of $m_T$ to analyze the motion (Figure 3.49).




▲ **Figure 3.49**

$\vec{F}_B$ is equal to the gravitational force acting on $m_B$, and $\vec{F}_C$ is equal to the gravitational force acting on $m_C$.




▲ **Figure 3.50**

Apply Newton's second law to find the net force acting on $m_T$ (Figure 3.50).

$$\vec{F}_{net} = \vec{F}_B + \vec{F}_C$$

$$\begin{aligned} F_{net} &= F_B + F_C \\ &= m_B g - m_C g \\ &= (m_B - m_C)g \\ &= (8.0\text{ kg} - 6.0\text{ kg})(9.81\text{ m/s}^2) \\ &= 19.6\ \frac{\text{kg}\cdot\text{m}}{\text{s}^2} \\ &= 19.6\text{ N} \end{aligned}$$

Use the scalar form of Newton's second law to calculate the magnitude of the acceleration.

$$\begin{aligned} F_{net} &= m_T a \\ a &= \frac{F_{net}}{m_T} \\ &= \frac{19.6\text{N}}{34\text{ kg}} \\ &= \frac{19.6\ \frac{\cancel{\text{kg}}\cdot\text{m}}{\text{s}^2}}{34\ \cancel{\text{kg}}} \\ &= 0.58\text{ m/s}^2 \end{aligned}$$

***Paraphrase***

The system will have an acceleration of magnitude $0.58\text{ m/s}^2$.

## Practice Problems

1. Calculate the acceleration of the tire in Example 3.11 if the mass of pail B is increased to 12 kg, without changing the mass of pail C.
2. If the tire in Example 3.11 is replaced by a car tire of mass 15 kg, calculate the acceleration of each object.

### Answers

1. $1.5\text{ m/s}^2$ [left]
2. (A) $0.68\text{ m/s}^2$ [left], (B) $0.68\text{ m/s}^2$ [down], (C) $0.68\text{ m/s}^2$ [up]

## 3.3 Check and Reflect

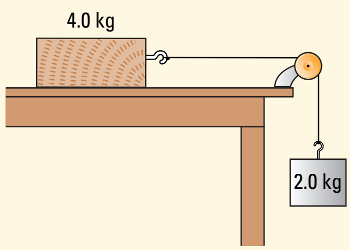
### Knowledge

1. In your own words, state Newton's second law.
2. An applied force $\vec{F}_{app}$ acting on an object of constant mass causes the object to accelerate. Sketch graphs to show the relationship between $a$ and $F_{app}$ when friction is
   (a) present, and
   (b) absent.

   Refer to Student References 5.1: Graphing Techniques on pp. 872–873.
3. Sketch a graph to show the relationship between the magnitude of acceleration and mass for constant net force.
4. Explain why vehicles with more powerful engines are able to accelerate faster.

### Applications

5. A dolphin experiences a force of 320 N [up] when it jumps out of the water. The acceleration of the dolphin is 2.6 m/s² [up].
   (a) Calculate the mass of the dolphin.
   (b) What would be the acceleration of the dolphin if it had the same strength but half the mass?
6. An ice hut used for winter fishing is resting on a level patch of snow. The mass of the hut is 80 kg. A wind exerts a horizontal force of 205 N on the hut, and causes it to accelerate. While in motion, the magnitude of the force of friction acting on the hut is 196 N. What is the acceleration of the hut?
7. Suppose the only horizontal forces acting on a 20-N object on a smooth table are 36 N [45°] and 60 N [125°].
   (a) What is the net force acting on the object?
   (b) Calculate the acceleration of the object.
8. Two boxes, A and B, are touching each other and are at rest on a horizontal, frictionless surface. Box A has a mass of 25 kg and box B a mass of 15 kg. A person applies a force of 30 N [right] on box A which, in turn, pushes on box B. Calculate the acceleration of the boxes.
9. A 4.0-kg oak block on a horizontal, rough oak surface is attached by a light string that passes over a light, frictionless pulley to a hanging 2.0-kg object. The magnitude of the force of friction on the 4.0-kg block is 11.8 N.




   (a) Calculate the acceleration of the system.
   (b) Calculate the tension in the string.

### Extension

10. Summarize concepts and ideas associated with Newton's second law using a graphic organizer of your choice. See Student References 4: Using Graphic Organizers on pp. 869–871 for examples of different graphic organizers. Make sure that the concepts and ideas are clearly presented and are linked appropriately.

**eTEST**

To check your understanding of Newton's second law, follow the eTest links at www.pearsoned.ca/school/physicssource.

# 3.4 Newton's Third Law

Volleyball is a sport that involves teamwork and players knowing how to apply forces to the ball to redirect it. When the velocity of the ball is large, a player will usually bump the ball to slow it down so that another player can redirect it over the net (Figure 3.51).

At the instant the player bumps the ball, the ball exerts a large force on the player's arms, often causing sore arms. Immediately after the interaction, the ball bounces upward. To explain the motion of each object during and after this interaction requires an understanding of Newton's third law.

Newton's first two laws describe the motion of an object or a system of objects *in isolation*. But to describe the motion of objects that are interacting, it is important to examine how the force exerted by one object on another results in a change of motion for both objects. Find out what happens when two initially stationary carts interact by doing 3-7 QuickLab.

**info BIT**

In order to walk, you must apply a force backward on the ground with one foot. The ground then pushes forward on that foot.

▲ **Figure 3.51** Conrad Leinemann of Kelowna, British Columbia, bumps the ball while teammate Jody Holden of Shelburne, Nova Scotia, watches during the beach volleyball competition at the 1999 Pan Am Games in Winnipeg, Manitoba.

**3-7 QuickLab**

# Exploding Carts

## Problem

If a stationary cart exerts a net force on another identical cart, what will be the motion of both carts after the interaction?

## Materials

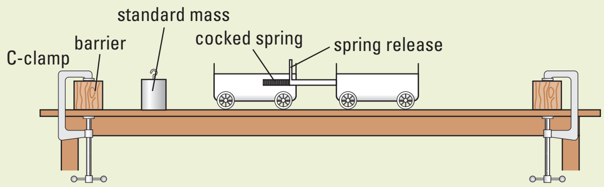
dynamics cart with spring
dynamics cart without spring
500-g standard mass

## Procedure

1. Note the position of the spring on the one cart, and how to cock and release the spring.
2. Cock the spring and place the cart on the table. Release the spring.

**CAUTION: Do not cock the spring unless it is safely attached to the cart. Do not point the spring at anyone when releasing it.**

3. Repeat step 2, this time making the cart with the spring touch the second cart (Figure 3.52). Release the spring.
4. Repeat step 3 but add a 500-g standard mass to one of the carts before releasing the spring.




▲ **Figure 3.52**

## Questions

**1.** What did you observe when you released the spring when the cart was initially at rest and not touching the other cart?

**2.** (a) What did you observe when you released the spring when one cart was touching the other cart?
(b) What evidence do you have that two forces were present?
(c) What evidence do you have that a force was exerted on each cart?
(d) How do the magnitudes and directions of the two forces compare?

**3.** Compare and contrast the results from steps 3 and 4.

## Forces Always Exist in Pairs

**action force:** force initiated by object A on object B

**reaction force:** force exerted by object B on object A

When two objects interact, two forces will always be involved. One force is the **action force** and the other is the **reaction force**. The important points to remember are that the reaction force *always* acts on a different object than the action force, and that the reaction force acts in the opposite direction.

**Concept Check**

Is it possible to have an action force without a reaction force?

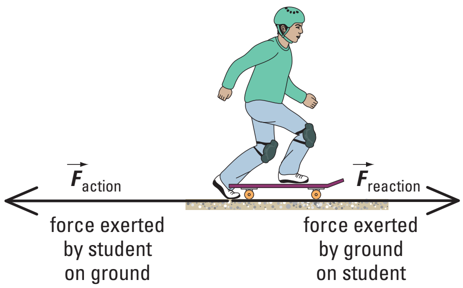
## Newton's Third Law and Its Applications

Newton found that the reaction force is equal in magnitude to the action force, but opposite in direction. This relationship is called Newton's third law of motion.

If object A exerts a force on object B, then B exerts a force on A that is equal in magnitude and opposite in direction.

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

Some people state Newton's third law as "for every action force, there is an equal and opposite reaction force." However, remembering Newton's third law this way does not emphasize that the action and reaction forces are acting on *different* objects (Figure 3.53).




◀ **Figure 3.53** The action force is the backward force that the student exerts on the ground. The reaction force is the forward force that the ground exerts on the student. Only the action-reaction pair are shown here for simplicity.

**PHYSICS INSIGHT**

In order to show action-reaction forces, you must draw *two* free-body diagrams, one for each object.

***Concept Check***

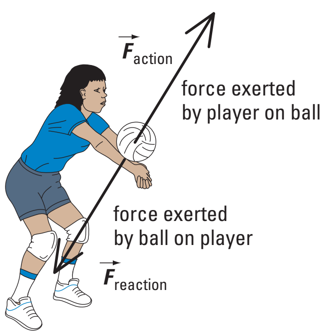
If the action force is equal in magnitude to the reaction force, how can there ever be an acceleration? Explain using an example and free-body diagrams.

### Action-Reaction Forces Acting on Objects in Contact

Let's revisit the scenario of the volleyball player bumping the ball. At the instant that both the ball and the player's arms are in contact, the action force is the upward force that the player exerts on the ball. The reaction force is the downward force that the ball exerts on the player's arms. During the collision, the ball accelerates upward and the player's arms accelerate downward (Figure 3.54).

*e* **TECH**

Explore how a stranded astronaut can return to a spacecraft by throwing away tools. Follow the eTech links at www.pearsoned.ca/school/physicssource.

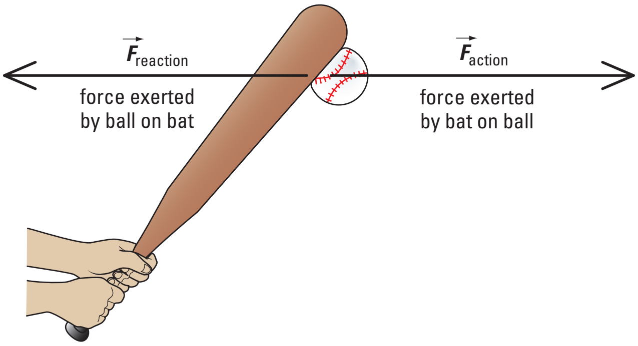



◀ **Figure 3.54** The action-reaction forces at collision time when a volleyball player bumps the ball

**e WEB**

Fire hoses and extinguishers are difficult to control because their contents exit at high speed as they are redirected when putting out a fire. Research the operation and safe use of fire extinguishers. How do Newton's three laws apply to fire extinguishers? Interview an experienced firefighter. Write a brief summary of your findings. Begin your search at www.pearsoned.ca/school/physicssource.

A similar reasoning applies when a baseball bat strikes a baseball. The action force is the forward force that the bat exerts on the ball. The reaction force is the backward force that the ball exerts on the bat. During the collision, the ball accelerates forward and the bat slows down as it accelerates backward (Figure 3.55).



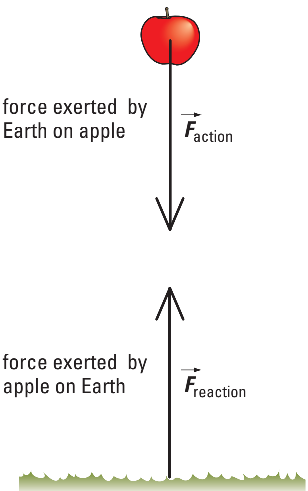

▲ **Figure 3.55** The action-reaction forces at collision time when a baseball bat strikes a baseball

## Action-Reaction Forces Acting on Objects Not in Contact

Sometimes an object can exert a force on another without actually touching the other object. This situation occurs when an object falls toward Earth's surface, or when a magnet is brought close to an iron nail. Action-reaction forces still exist in these interactions.

When an apple falls toward the ground, the action force is the force of gravity that Earth exerts on the apple. The falling apple, in turn, exerts a reaction force upward on Earth. So while the apple is accelerating down, Earth is accelerating up (Figure 3.56).

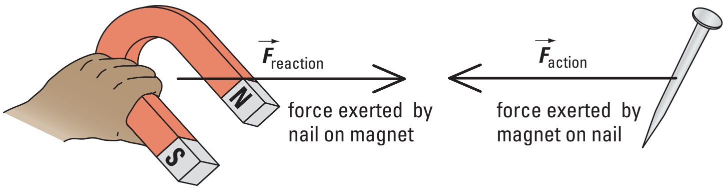
You see the acceleration of the apple but not of Earth because the inertial mass of the apple is far less than that of Earth. In fact, Earth does accelerate but at a negligible rate because the magnitude of the acceleration is inversely proportional to mass.




▲ **Figure 3.56** The action-reaction forces when an apple falls toward Earth's surface

When a magnet is brought close to an iron nail, the action force is the magnetic force that the magnet exerts on the nail. The reaction force is the force that the nail exerts on the magnet. So the nail accelerates toward the magnet, and at the same time the magnet is accelerating toward the nail (Figure 3.57).

Investigate the validity of Newton's third law by doing 3-8 QuickLab.




▲ **Figure 3.57** The action-reaction forces when a magnet is brought close to an iron nail

## 3-8 QuickLab

# Skateboard Interactions

### Problem

How does Newton's third law apply to interactions involving skateboards?

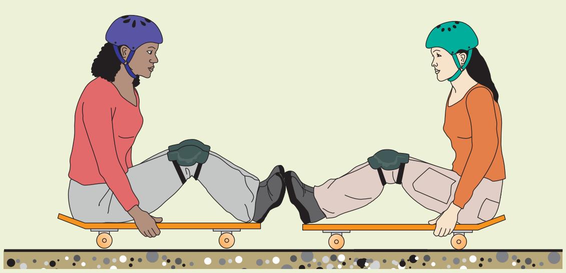
### Materials

two skateboards

**CAUTION: Wear a helmet and knee pads when doing this activity.**

### Procedure

1. Choose a partner with a mass about the same as yours.
2. Sit on skateboards on a hard, level surface with your feet toward one another and touching (Figure 3.58).
3. Give your partner a gentle push with your feet. Observe what happens to both skateboards.
4. Repeat steps 2 and 3 but this time, give your partner a harder push. Observe what happens to both skateboards.
5. Repeat steps 2 and 3 but this time, have you and your partner push simultaneously. Observe what happens to both skateboards.
6. Choose a partner with a significantly different mass than yours.
7. Repeat steps 2 to 5 with your new partner.
8. Sit on a skateboard near a wall. Then push against the wall. Observe the motion of your skateboard.



▲ **Figure 3.58**

### Questions

**1.** Describe the motion of each skateboard when
(a) you pushed a partner of equal mass, and
(b) you pushed a partner of significantly different mass.

**2.** Compare and contrast the results from steps 4 and 5.

**3.** What happened to your skateboard when you pushed against the wall?

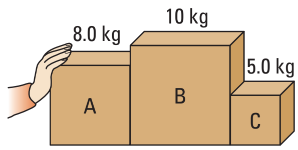
**4.** Explain each interaction in this activity using Newton's laws. Draw a sketch showing the action-reaction forces in each situation.

## Applying Newton's Third Law to Situations Involving Frictionless Surfaces

In Example 3.12, an applied force acts on box A, causing all three boxes to accelerate. Newton's third law is used to calculate the force that box C exerts on box B.

### Example 3.12

Three boxes, A, B, and C, are positioned next to each other on a horizontal, frictionless surface (Figure 3.59). An applied force acting on box A causes all the boxes to accelerate at 1.5 m/s² [right]. Calculate the force exerted by box C on box B.




▲ **Figure 3.59**

***Given***

$m_A = 8.0$ kg   $m_B = 10$ kg   $m_C = 5.0$ kg

$\vec{a} = 1.5$ m/s² [right]

***Required***

force exerted by box C on box B ($\vec{F}_{\text{C on B}}$)

***Analysis and Solution***

Draw a free-body diagram for box C (Figure 3.60).

Box C is not accelerating up or down.

So in the vertical direction, $\vec{F}_{\text{net}} = 0$ N.

Write equations to find the net force on box C in both the horizontal and vertical directions.

horizontal direction

$$\vec{F}_{\text{net}_h} = \vec{F}_{\text{B on C}}$$

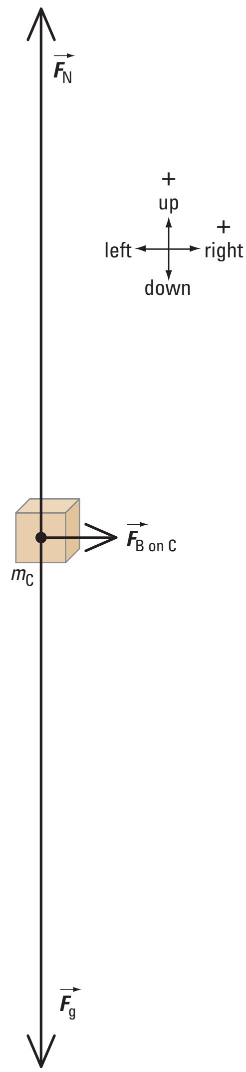
$$F_{\text{net}_h} = F_{\text{B on C}}$$

vertical direction

$$\vec{F}_{\text{net}_v} = \vec{F}_N + \vec{F}_g$$

$$F_{\text{net}_v} = 0$$

Calculations in the vertical direction are not required in this problem.




▲ **Figure 3.60**

Apply Newton's second law.

$$\begin{aligned} F_{\text{B on C}} &= m_C a \\ &= (5.0 \text{ kg})\left(1.5 \frac{\text{m}}{\text{s}^2}\right) \\ &= 7.5 \frac{\text{kg}\cdot\text{m}}{\text{s}^2} \\ &= 7.5 \text{ N} \end{aligned}$$

$\vec{F}_{\text{B on C}} = 7.5$ N [right]

Apply Newton's third law.

$$\begin{aligned} \vec{F}_{\text{C on B}} &= -\vec{F}_{\text{B on C}} \\ &= 7.5 \text{ N [left]} \end{aligned}$$

***Paraphrase***

The force exerted by box C on box B is 7.5 N [left].

### Practice Problems

1. For the situation in Example 3.12, calculate the force that box B exerts on box A.
2. For the situation in Example 3.9 Practice Problem 1 on page 153, calculate the applied force needed to lift both buckets up.

#### Answers

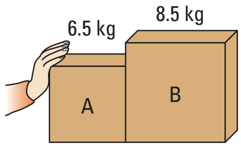
1. 23 N [left]
2. $1.2 \times 10^2$ N [up]

## Applying Newton's Third Law to Situations Involving Friction

In Example 3.13, a rough surface exerts a force of friction on two boxes. Newton's third law is used to calculate the force exerted by box B on box A in this situation.

### Example 3.13

Two boxes, A and B, of identical material but different mass are placed next to each other on a horizontal, rough surface (Figure 3.61). An applied force acting on box A causes both boxes to accelerate at 2.6 m/s² [right]. If the magnitude of the force of friction on box B is 28.3 N, calculate the force exerted by box B on box A.




▲ **Figure 3.61**

***Given***

$m_A = 6.5\text{ kg}$ $\quad m_B = 8.5\text{ kg}$

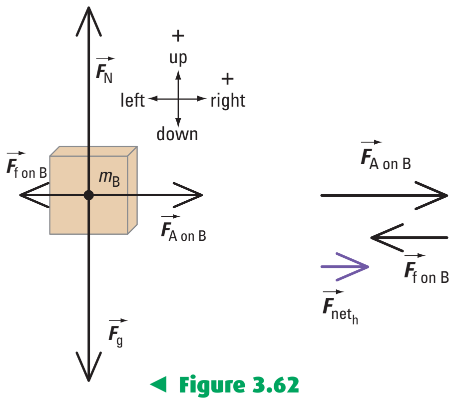
$\vec{F}_{\text{f on B}} = 28.3\text{ N [left]}$ $\quad \vec{a} = 2.6\text{ m/s}^2\text{ [right]}$

***Required***

force exerted by box B on box A ($\vec{F}_{\text{B on A}}$)

***Analysis and Solution***

Draw a free-body diagram for box B (Figure 3.62).
Box B is not accelerating up or down.
So in the vertical direction, $\vec{F}_{\text{net}} = 0\text{ N}$.
Write equations to find the net force on box B in both the horizontal and vertical directions.




◄ **Figure 3.62**

horizontal direction

$$\vec{F}_{\text{net}_h} = \vec{F}_{\text{A on B}} + \vec{F}_{\text{f on B}}$$
$$F_{\text{net}_h} = F_{\text{A on B}} + F_{\text{f on B}}$$

vertical direction

$$\vec{F}_{\text{net}_v} = \vec{F}_N + \vec{F}_g$$
$$F_{\text{net}_v} = 0$$

Calculations in the vertical direction are not required in this problem.

Apply Newton's second law.

$$m_B a = F_{\text{A on B}} + F_{\text{f on B}}$$
$$\begin{aligned} F_{\text{A on B}} &= m_B a - F_{\text{f on B}} \\ &= (8.5\text{ kg})(2.6\text{ m/s}^2) - (-28.3\text{ N}) \\ &= (8.5\text{ kg})(2.6\text{ m/s}^2) + 28.3\text{ N} \\ &= 50\text{ N} \end{aligned}$$
$$\vec{F}_{\text{A on B}} = 50\text{ N [right]}$$

Apply Newton's third law.

$$\begin{aligned} \vec{F}_{\text{B on A}} &= -\vec{F}_{\text{A on B}} \\ &= 50\text{ N [left]} \end{aligned}$$

***Paraphrase***

The force exerted by box B on box A is 50 N [left].

### Practice Problem

1. To minimize the environmental impact of building a road through a forest, a logger uses a team of horses to drag two logs, A and B, from the cutting location to a nearby road. A light chain connects log A with a mass of 150 kg to the horses' harness. Log B with a mass of 250 kg is connected to log A by another light chain.
   (a) The horses can pull with a combined force of 2600 N. The ground exerts a force of friction of magnitude 2400 N on the logs. Calculate the acceleration of the logs.
   (b) If the force of friction on log A is 900 N, calculate the force exerted by log B on log A.

**Answer**

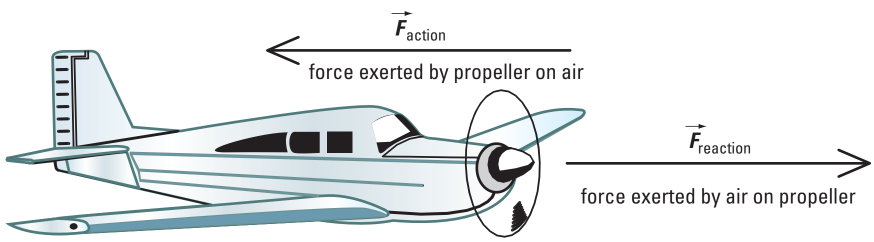
1. (a) 0.500 m/s² [forward]
   (b) $1.63 \times 10^3$ N [backward]

## Applying Newton's Second and Third Laws to Propeller Aircraft

The acceleration of many devices such as propeller aircraft can be controlled in midair. To explain how these machines accelerate involves applying Newton's second and third laws.

A propeller airplane can move through air because as the propeller rotates, it exerts an action force on the air, pushing the air backward. According to Newton's third law, the air, in turn, exerts a reaction force on the propeller, pushing the airplane forward (Figure 3.63).

Propeller blades are slanted so that they scoop new air molecules during each revolution. The faster a propeller turns, the greater is the mass of air accelerated backward and, by Newton's second law, the force exerted by the air on the propeller increases.




▲ **Figure 3.63** The action-reaction forces when a propeller airplane is in flight

### THEN, NOW, AND FUTURE — Wallace Rupert Turnbull (1870–1954)

Wallace Rupert Turnbull was an aeronautical engineer interested in finding ways to make aircraft wings stable (Figure 3.64). In 1902, he built the first wind tunnel in Canada at Rothesay, New Brunswick, for his experiments on propeller design.

In 1909, Turnbull was awarded a bronze medal from the Royal Aeronautical Society for his research on efficient propeller design. One of his major inventions was the variable-pitch propeller, which is still used on aircraft today.

During takeoff, the angle of the blades is adjusted to scoop more air. Air moving at a high speed backward gives a plane thrust, which causes the plane to accelerate forward. Once a plane maintains a constant altitude, the blade angle, or pitch, is decreased, reducing fuel consumption. This allows greater payloads to be carried efficiently and safely through the sky.

By 1925, Turnbull had perfected a propeller that used an electric motor to change its pitch. In 1927, the Canadian Air Force successfully tested the propeller at Borden, Ontario. Turnbull was later inducted into the Canadian Aviation Hall of Fame in 1977.

#### Questions

1. Research the forces that act on airplanes in flight. Define these forces and compare them to forces already discussed in this chapter.
2. Explain how and where the forces on an airplane act to cause changes in its horizontal motion. Use Newton's laws and diagrams to support your explanations.

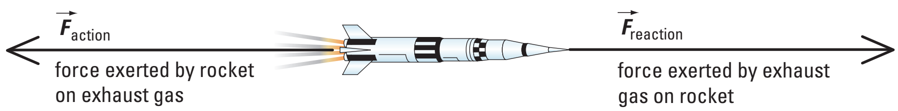
► **Figure 3.64** Canadian inventor Wallace Rupert Turnbull

## Applying Newton's Third Law to Rockets

The motion of rockets is a little different from that of propeller airplanes because a rocket does not have propellers that scoop air molecules. In fact, a rocket can accelerate in outer space where there is a vacuum.

When a rocket engine is engaged, the highly combustible fuel burns at a tremendous rate. The action force of the exhaust gas leaving the rocket, according to Newton's third law, causes a reaction force that pushes against the rocket. It is the action force of the exhaust gas being directed backward that accelerates the rocket forward (Figure 3.65). That is why a rocket can accelerate in outer space.

Test out Newton's third law with a toy rocket by doing 3-9 Design a Lab.

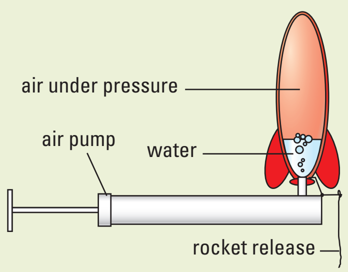



▲ **Figure 3.65** The action-reaction forces when a rocket is in flight

## 3-9 Design a Lab

# Motion of a Toy Rocket

Figure 3.66 shows a toy rocket partially filled with water about to be released from an air pump. The pump is used to add pressurized air into the rocket.




◀ **Figure 3.66**

### The Question

What effect does increasing each of these quantities have on the motion of the rocket?

- the amount of water inside the rocket
- the air pressure inside the rocket

### Design and Conduct Your Investigation

- State a hypothesis. Then design and conduct an experiment to test your hypothesis. Be sure to identify all variables and to control the appropriate ones.

**Caution: Never point the rocket at anyone. Perform this activity outside.**

- Compare the direction of motion of the water and the rocket when the rocket is released.
- Explain the motion of the rocket, water, and air in terms of Newton's third law. Include sketches showing at least three action-reaction pairs of forces.
- How well did your results agree with your hypothesis?

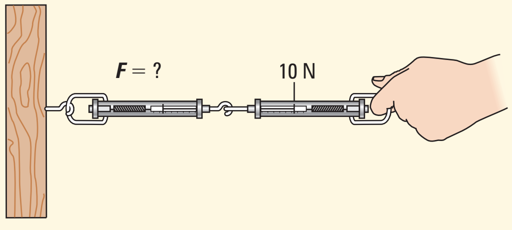
## 3.4 Check and Reflect

### Knowledge

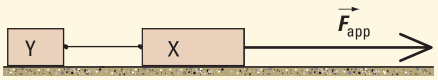
1. In your own words, state Newton's third law.
2. Explain why
   (a) a swimmer at the edge of a pool pushes backward on the wall in order to move forward, and
   (b) when a person in a canoe throws a package onto the shore, the canoe moves away from shore.
3. No matter how powerful a car engine is, a car cannot accelerate on an icy surface. Use Newton's third law and Figure 3.53 on page 161 to explain why.
4. State and sketch the action-reaction forces in each situation.
   (a) Water pushes sideways with a force of 600 N on the centreboard of a sailboat.
   (b) An object hanging at the end of a spring exerts a force of 30 N [down] on the spring.

### Applications

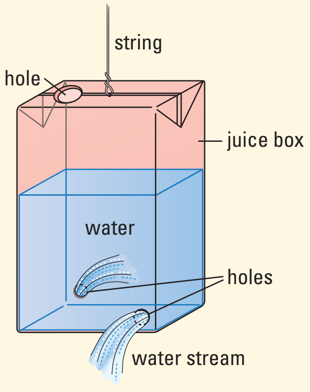
5. An object is resting on a level table. Are the normal force and the gravitational force acting on the object action-reaction forces? Explain your reasoning.
6. A vehicle pushes a car of lesser mass from rest, causing the car to accelerate on a rough dirt road. Sketch all the action-reaction forces in this situation.
7. Suppose you apply a force of 10 N to one spring scale. What is the reading on the other spring scale? What is the force exerted by the anchored spring scale on the wall?




8. Blocks X and Y are attached to each other by a light rope and can slide along a horizontal, frictionless surface. Block X has a mass of 10 kg and block Y a mass of 5.0 kg. An applied force of 36 N [right] acts on block X.




   (a) Calculate the action-reaction forces the blocks exert on each other.
   (b) Suppose the magnitudes of the force of friction on blocks X and Y are 8.0 N and 4.0 N respectively. Calculate the action-reaction forces the blocks exert on each other.
9. A rectangular juice box has two holes punched near the bottom corners on opposite sides, and another hole at the top. The box is hung from a rigid support with a string. Predict what will happen if the box is filled with water through the top hole and the holes at the bottom are open. Use Newton's third law to explain your answer. Test your prediction. Cover the holes at the bottom with tape before filling the box with water. Then remove the tape to let the water out and observe the motion of the box.




**e TEST**

To check your understanding of Newton's third law, follow the eTest links at www.pearsoned.ca/school/physicssource.

# 3.5 Friction Affects Motion

Throughout this chapter, you encountered friction in all the lab activities and when solving several problems. Friction is a force that is present in almost all real-life situations. In some cases, friction is desirable while in other cases, friction reduces the effectiveness of mechanical systems.

Without friction, you would not be able to walk. The wheels on a vehicle would have no traction on a road surface and the vehicle would not be able to move forward or backward. Parachutists would not be able to land safely (Figure 3.67).

On the other hand, friction causes mechanical parts to seize and wear out, and mechanical energy to be converted to heat. For example, snowmobiles cannot move for long distances over bare ice. Instead, snowmobilers must detour periodically through snow to cool the moving parts not in contact with the ice.

To determine the direction of the force of friction acting on an object, you need to first imagine the direction in which the object would move if there were no friction. The force of friction, then, opposes motion in that direction.

*info* **BIT**

Olympic cyclists now wear slipperier-than-skin suits with seams sown out of the airflow to reduce friction and improve race times by as much as 3 s.

**friction:** force that opposes either the motion of an object or the direction the object would be moving in if there were no friction

◀ **Figure 3.67** When a person falls in midair, the air resistance that acts on a parachute slows the fall. In this case, friction allows a parachutist to land without injury.


In a sport such as curling, friction affects how far the stone will travel along the ice. Sweeping the ice in front of a moving stone reduces the force of friction acting on the stone (Figure 3.68). The result is that the stone slides farther.

To better understand how the nature of a contact surface affects the force of friction acting on an object, do 3-10 QuickLab.

◀ **Figure 3.68** Brad Gushue, from St. John's, Newfoundland, and his team won the gold medal in men's curling at the 2006 Winter Olympics in Turin, Italy.

## 3-10 QuickLab

# Friction Acting on a Loonie

### Problem

What factors affect the ability of a loonie to start sliding?

### Materials

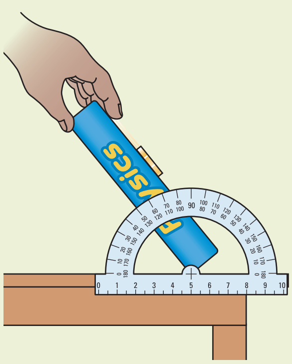
| | |
|---|---|
| textbook | two loonies |
| protractor | tape |

coarse, medium, and fine sandpaper: a 10 cm × 25 cm piece of each

### Procedure

1. Read the procedure and design a chart to record your results.
2. Place your textbook flat on a lab bench and place a loonie at one end of the book.
3. Slowly raise this end of the textbook until the loonie starts to slide down the incline (Figure 3.69).

   Use the protractor to measure the angle the textbook makes with the lab bench when the loonie first starts to slide. Repeat this step several times, and find the average of the angles.



◀ **Figure 3.69**

4. Use a piece of tape to fasten the fine sandpaper on the textbook, sandy-side facing up. Repeat step 3.
5. Repeat step 4 for the medium sandpaper and then for the coarse sandpaper. Carefully remove and save the sandpaper.
6. Repeat steps 2 and 3 but this time increase the mass (not the surface area) by stacking one loonie on top of the other. Use a piece of tape between the two loonies to fasten them together.

### Questions

1. How consistent were your results for each trial?
2. Explain how the angle needed to start the loonie sliding down the incline was affected by
   - the roughness of the contact surface
   - the mass of the coins (number of stacked coins) in contact with the contact surface
3. Identify the controlled, manipulated, and responding variables in this activity.

## Static Friction

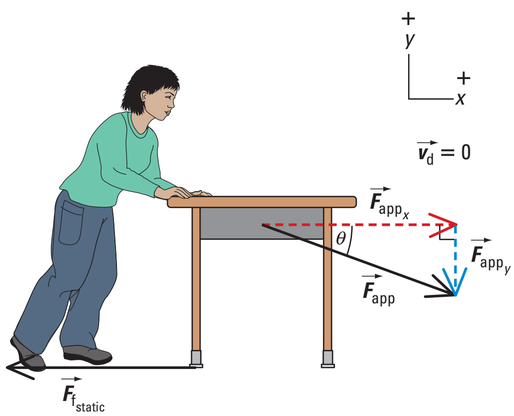
In 3-10 QuickLab, you discovered that the force of friction depends on the nature of the two surfaces in contact. If you drag an object on a smooth surface, the force of friction acting on the object is less than if you drag it on a rough or bumpy surface. If you drag a smooth block and a rough block on the same surface, the force of friction acting on each block will be different. Although there are different types of friction, the force of friction that acts on objects sliding across another surface is the main focus in this section.

Suppose an object A (the desk) is in contact with another object B (the floor) as in Figure 3.70. The contact surface would be the horizontal surface at the bottom of each leg of the desk.

Now suppose that a force acts on the desk, say $\vec{F}_{\text{app}}$, such that $\vec{F}_{\text{app}}$ has a vertical component as well as a horizontal component. If the desk remains at rest, even though $\vec{F}_{\text{app}}$ acts on it, then the net force on the desk is zero, $\vec{F}_{\text{net}} = 0$ N.

**eSIM**

Learn how friction is created and how it affects the net force on an object. Follow the eSim links at www.pearsoned.ca/school/physicssource.




▲ **Figure 3.70** An applied force $\vec{F}_{\text{app}}$ is acting on the desk at a downward angle $\theta$. The floor exerts a force of static friction on the bottom of each leg of the desk.

In the $x$ direction, $F_{\text{net}_x} = 0$ N, which means that $\vec{F}_{\text{app}_x}$ must be balanced by another force. This balancing force is the **force of static friction**, $\vec{F}_{\text{f}_{\text{static}}}$. The equation for the net force acting on the desk in the $x$ direction would then be

**static friction:** force exerted on an object at rest that prevents the object from sliding

$$\vec{F}_{\text{net}_x} = \vec{F}_{\text{app}_x} + \vec{F}_{\text{f}_{\text{static}}}$$

$$F_{\text{net}_x} = F_{\text{app}_x} + F_{\text{f}_{\text{static}}}$$

$$0 = F_{\text{app}}\cos\theta + F_{\text{f}_{\text{static}}}$$

$$F_{\text{f}_{\text{static}}} = -F_{\text{app}}\cos\theta$$

So the direction of $\vec{F}_{\text{f}_{\text{static}}}$ opposes the $x$ component of the applied force acting on the desk.

## The Magnitude of Static Friction

An important point about static friction is that its magnitude does not have a fixed value. Instead, it varies from zero to some maximum value. This maximum value is reached at the instant the object starts to move.

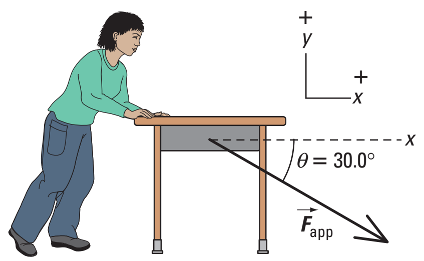
If you push on a table with a force of ever-increasing magnitude, you will notice that the table remains at rest until you exceed a critical value. Because of Newton's second law, the magnitude of the force of static friction must increase as the applied force on the table increases, if the forces are to remain balanced.

### *Static Friction on a Horizontal Surface*

Suppose the applied force acting on the desk in Figure 3.70 on page 171 is given. Example 3.14 demonstrates how to calculate the force of static friction by using a free-body diagram to help write the equation for the net force on the desk. Since $\vec{F}_{\text{app}}$ acts at an angle to the surface of the desk, it is convenient to use Cartesian axes to solve this problem.

## Example 3.14

The magnitude of the applied force in Figure 3.71 is 165 N and $\theta = 30.0°$. If the desk remains stationary, calculate the force of static friction acting on the desk.




▲ Figure 3.71

***Given***

magnitude of $\vec{F}_{\text{app}}$ = 165 N

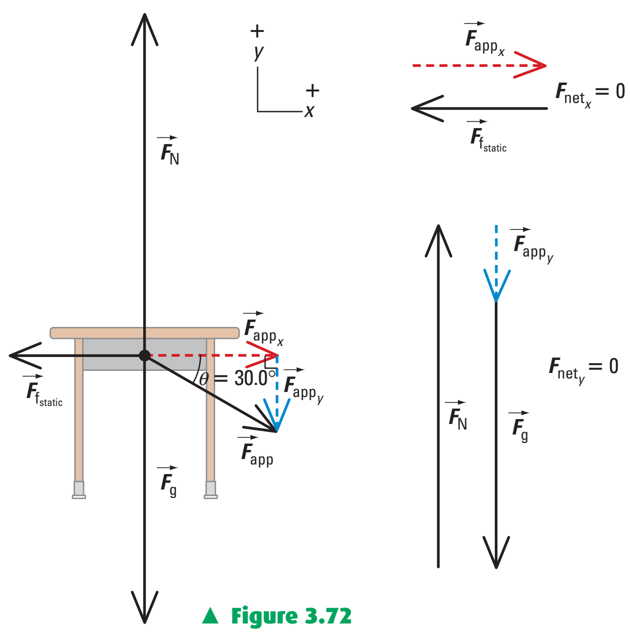
$\theta$ = 30.0°

***Required***

force of static friction ($\vec{F}_{\text{f}_{\text{static}}}$)

***Analysis and Solution***

Draw a free-body diagram for the desk (Figure 3.72).




▲ Figure 3.72

## Practice Problem

1. A mountain climber stops during the ascent of a mountain (Figure 3.73). Sketch all the forces acting on the climber, and *where* those forces are acting.

▲ Figure 3.73

Since the desk is not accelerating, $\vec{F}_{\text{net}} = 0$ N in both the $x$ and $y$ directions.
Write equations for the net force on the desk in both directions.

$x$ direction

$$\vec{F}_{\text{net}_x} = \vec{F}_{\text{app}_x} + \vec{F}_{\text{f}_{\text{static}}}$$
$$F_{\text{net}_x} = F_{\text{app}_x} + F_{\text{f}_{\text{static}}}$$
$$0 = F_{\text{app}_x} + F_{\text{f}_{\text{static}}}$$

$y$ direction

$$\vec{F}_{\text{net}_y} = \vec{F}_{\text{N}} + \vec{F}_{\text{app}_y} + \vec{F}_{\text{g}}$$
$$F_{\text{net}_y} = 0$$

Calculations in the $y$ direction are not required in this problem.

$$\begin{aligned} F_{\text{f}_{\text{static}}} &= -F_{\text{app}_x} \\ &= -(165 \text{ N})(\cos\theta) \\ &= -(165 \text{ N})(\cos 30.0°) \\ &= -143 \text{ N} \end{aligned}$$

$\vec{F}_{\text{f}_{\text{static}}}$ prevents the desk from sliding in the $x$ direction. The negative value for $F_{\text{f}_{\text{static}}}$ indicates that the direction of $\vec{F}_{\text{f}_{\text{static}}}$ is along the negative $x$-axis or [180°].

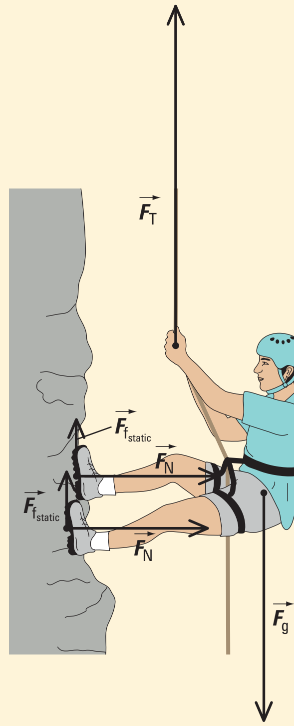
$$\vec{F}_{\text{f}_{\text{static}}} = 143 \text{ N } [180°]$$

***Paraphrase***

The force of static friction acting on the desk is 143 N [180°].

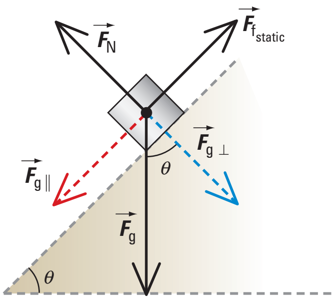
**Answer**

1.




***Static Friction on an Incline***

If an object is at rest on an incline, the net force acting on the object is zero, $\vec{F}_{\text{net}} = 0$ N. Let's first examine the forces acting on the object (Figure 3.74).




◀ **Figure 3.74** (left) Free-body diagram for an object at rest on an incline; (below) vector addition diagrams for the ∥ and ⊥ forces

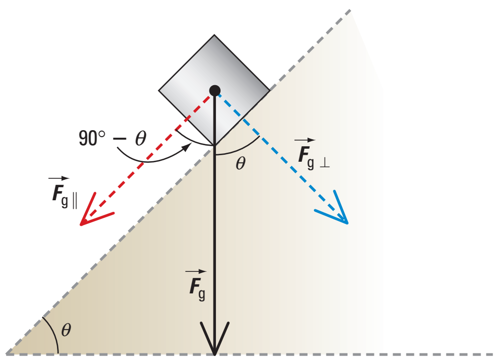
When working with inclines, it is easier to rotate the reference coordinates so that motion along the incline is described as either uphill or downhill. This means that only the gravitational force needs to be resolved into components, one parallel to the incline $\vec{F}_{g\parallel}$ and one perpendicular to the incline $\vec{F}_{g\perp}$. Usually, uphill is chosen to be positive unless the object is accelerating downhill.

In Figure 3.74 on page 173, if there were no friction, the component $\vec{F}_{g\parallel}$ would cause the object to accelerate down the incline. So for the object to remain at rest, a balancing force ($\vec{F}_{f_{static}}$) must be acting *up* the incline.

The equation for the net force acting on the object parallel to the incline would then be

$$\begin{aligned} \vec{F}_{net\parallel} &= \vec{F}_{g\parallel} + \vec{F}_{f_{static}} \\ F_{net\parallel} &= F_{g\parallel} + F_{f_{static}} \\ 0 &= F_{g\parallel} + F_{f_{static}} \\ F_{f_{static}} &= -F_{g\parallel} \end{aligned}$$

To determine the expression for $\vec{F}_{g\parallel}$ requires using the geometry of a triangle. In Figure 3.75, the angle between $\vec{F}_{g\parallel}$ and $\vec{F}_g$ is $90.0° - \theta$. Since the angle between $\vec{F}_{g\parallel}$ and $\vec{F}_{g\perp}$ is 90.0°, the angle between $\vec{F}_g$ and $\vec{F}_{g\perp}$ is $\theta$.




◀ **Figure 3.75** Diagram for an object at rest on an incline showing only the force of gravity vector resolved into components

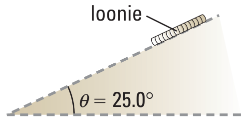
Since the object is not accelerating perpendicular to the incline, the equation for the net force acting on the object in this direction is

$$\begin{aligned} \vec{F}_{net\perp} &= \vec{F}_N + \vec{F}_{g\perp} \\ F_{net\perp} &= F_N + F_{g\perp} \\ 0 &= F_N + F_{g\perp} \\ F_N &= -F_{g\perp} \end{aligned}$$

In 3-10 QuickLab, the sandpaper exerted a force of static friction on the loonie, preventing the coin from sliding down the incline. Example 3.15 demonstrates how to calculate the force of static friction acting on a loonie at rest on an incline of 25.0°.

## Example 3.15

A loonie with a mass of 7.0 g is at rest on an incline of 25.0° (Figure 3.76). Calculate the force of static friction acting on the loonie.




▲ **Figure 3.76**

***Given***

$m = 7.0\text{ g} = 7.0 \times 10^{-3}\text{ kg}$ $\qquad \theta = 25.0°$

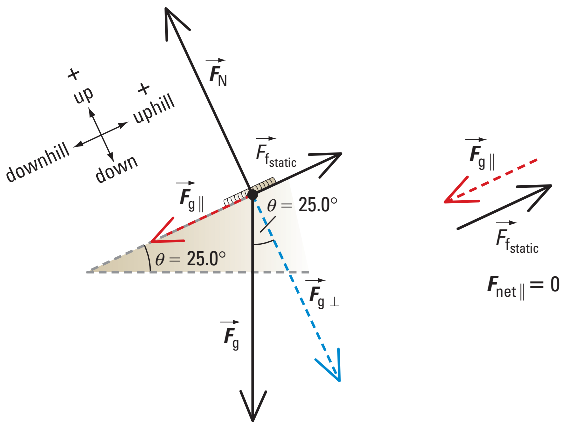
$g = 9.81\text{ m/s}^2$

***Required***

force of static friction ($\vec{F}_{f_{static}}$)

***Analysis and Solution***

Draw a free-body diagram for the loonie (Figure 3.77).




▲ **Figure 3.77**

Since the loonie is not accelerating, $\vec{F}_{net} = 0$ N both parallel and perpendicular to the incline.
Write equations to find the net force on the loonie in both directions.

$\perp$ direction

$$\vec{F}_{net\perp} = \vec{F}_N + \vec{F}_{g\perp}$$

$$F_{net\perp} = 0$$

Calculations in the $\perp$ direction are not required in this problem.

$\parallel$ direction

$$\begin{aligned}
\vec{F}_{net\parallel} &= \vec{F}_{g\parallel} + \vec{F}_{f_{static}} \\
F_{net\parallel} &= F_{g\parallel} + F_{f_{static}} \\
F_{f_{static}} &= F_{net\parallel} - F_{g\parallel} \\
\text{Now, } F_{g\parallel} &= -mg \sin \theta \\
\text{So, } F_{f_{static}} &= 0 - (-mg \sin \theta) \\
&= mg \sin \theta \\
&= (7.0 \times 10^{-3}\text{ kg})(9.81\text{ m/s}^2)(\sin 25.0°) \\
&= 2.9 \times 10^{-2}\text{ N}
\end{aligned}$$

$\vec{F}_{f_{static}}$ prevents the loonie from sliding downhill. The positive value for $F_{f_{static}}$ indicates that the direction of $\vec{F}_{f_{static}}$ is uphill.

$$\vec{F}_{f_{static}} = 2.9 \times 10^{-2}\text{ N [uphill]}$$

***Paraphrase***

The force of static friction acting on the loonie is $2.9 \times 10^{-2}$ N [uphill].

### Practice Problems

1. A loonie of mass 7.0 g is taped on top of a toonie of mass 7.3 g and the combination stays at rest on an incline of 30.0°. Calculate the force of static friction acting on the face of the toonie in contact with the incline.
2. A loonie of mass 7.00 g is placed on the surface of a rough book. A force of static friction of magnitude $4.40 \times 10^{-2}$ N acts on the coin. Calculate the maximum angle at which the book can be inclined before the loonie begins to slide.

**Answers**

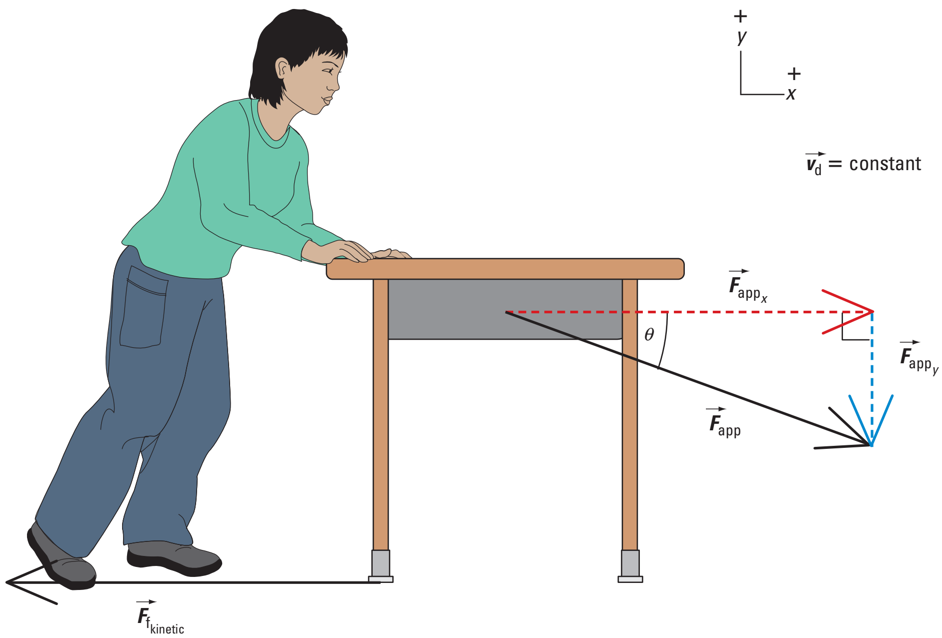
1. $7.0 \times 10^{-2}$ N [uphill]
2. 39.8°

## Kinetic Friction

Suppose you apply a force to the desk in Figure 3.78 and the desk starts to slide across the floor at constant velocity. In this situation, the force of static friction is not able to balance the applied force, so motion occurs. Now the floor will exert a force of friction on the desk that opposes the direction of motion of the desk. This force is the **force of kinetic friction**, $\vec{F}_{f_{\text{kinetic}}}$.

**kinetic friction:** force exerted on an object in motion that opposes the motion of the object as it slides on another object

Kinetic friction is present any time an object is sliding on another, whether or not another force acts on the sliding object. If you stop pushing the desk once it is in motion, the desk will coast and eventually stop. While the desk is sliding, the floor exerts a force of kinetic friction on the desk. This frictional force is directed backward, and causes the desk to eventually come to a stop.



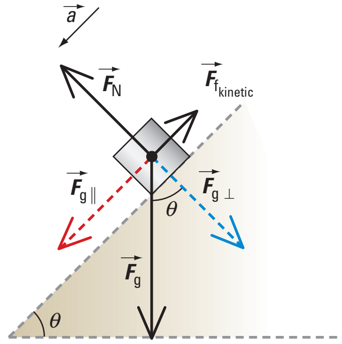

▲ **Figure 3.78** The applied force $\vec{F}_{app}$ overcomes the force of static friction acting on the desk, causing the desk to slide. While the desk is in motion, the floor exerts a force of kinetic friction that opposes the motion of the desk.

### The Direction of Kinetic Friction on an Incline

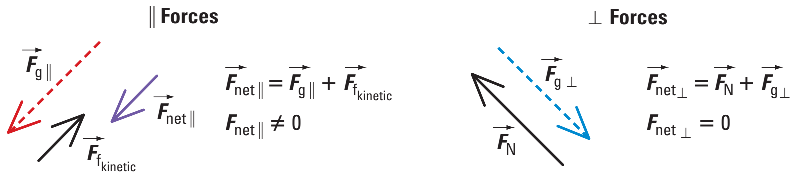
If an object is on an incline and the object begins to slide, the surface of the incline exerts a force of kinetic friction on the object that opposes its motion. Whether the object is accelerating uphill or downhill, $\vec{F}_{\text{net}} \neq 0$ N parallel to the incline.

### *Accelerating Down an Incline*

Let's first consider the case where an object accelerates downhill (Figure 3.79). In this situation, $\vec{F}_{g\parallel}$ causes the object to accelerate downhill. The force of kinetic friction acts to oppose the motion of the object. So $\vec{F}_{f_{kinetic}}$ is uphill as shown below.




◀ **Figure 3.79** (left) Free-body diagram for an object accelerating downhill; (below) vector addition diagrams for the $\parallel$ and $\perp$ forces




The equation for the net force acting on the object parallel to the incline is

$$\vec{F}_{net\parallel} = \vec{F}_{g\parallel} + \vec{F}_{f_{kinetic}}$$

If you apply Newton's second law, the equation for $\vec{F}_{net\parallel}$ becomes

$$m\vec{a} = \vec{F}_{g\parallel} + \vec{F}_{f_{kinetic}}$$

$$ma = F_{g\parallel} + F_{f_{kinetic}}$$

In Figure 3.79, $\vec{F}_{g\parallel}$ acts downhill and $\vec{F}_{f_{kinetic}}$ acts uphill. For the object to accelerate downhill, the net force on the object, $\vec{F}_{net\parallel}$, is directed downhill. So the magnitude of $\vec{F}_{g\parallel}$ must be greater than the magnitude of $\vec{F}_{f_{kinetic}}$.

Since the object is not accelerating perpendicular to the incline, the net force acting on the object in this direction is zero. The equation for the net force on the object in the perpendicular direction is

$$\vec{F}_{net\perp} = \vec{F}_N + \vec{F}_{g\perp}$$

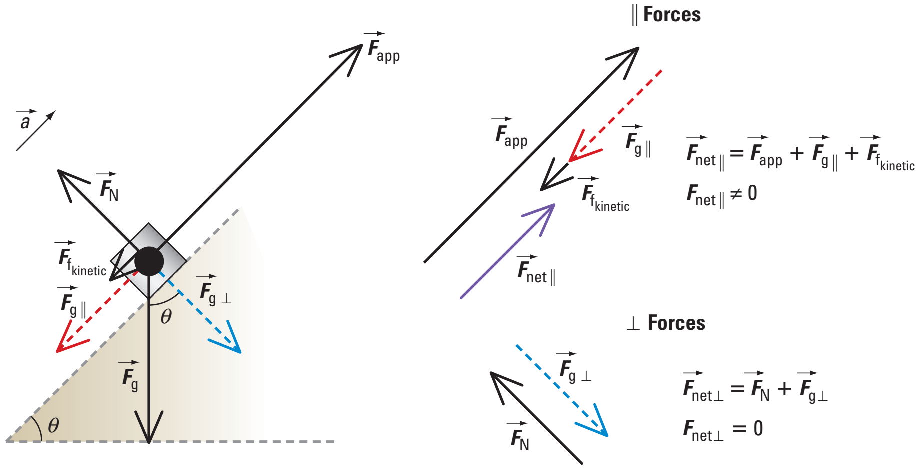
$$F_{net\perp} = F_N + F_{g\perp}$$

$$0 = F_N + F_{g\perp}$$

$$F_N = -F_{g\perp}$$

### *Accelerating Up an Incline*

If an object is accelerating uphill, the force of kinetic friction acts downhill to oppose the motion. $\vec{F}_{g\parallel}$ also acts downhill. A force, $\vec{F}_{app}$, must act uphill on the object that is great enough to overcome both $\vec{F}_{f_{kinetic}}$ and $\vec{F}_{g\parallel}$ (Figure 3.80).




▲ **Figure 3.80** (left) Free-body diagram for an object accelerating uphill; (right) vector addition diagrams for the ∥ and ⊥ forces

The equation for the net force acting on the object parallel to the incline is

$$\vec{F}_{net\parallel} = \vec{F}_{app} + \vec{F}_{g\parallel} + \vec{F}_{f_{kinetic}}$$

If you apply Newton's second law, the equation for $\vec{F}_{net\parallel}$ becomes

$$m\vec{a} = \vec{F}_{app} + \vec{F}_{g\parallel} + \vec{F}_{f_{kinetic}}$$

$$ma = F_{app} + F_{g\parallel} + F_{f_{kinetic}}$$

In Figure 3.80, both $\vec{F}_{g\parallel}$ and $\vec{F}_{f_{kinetic}}$ act downhill and $\vec{F}_{app}$ acts uphill. For the object to accelerate uphill, $\vec{F}_{net\parallel}$ is directed uphill. So the magnitude of $\vec{F}_{app}$ must be greater than the sum of the magnitudes of $\vec{F}_{g\parallel}$ and $\vec{F}_{f_{kinetic}}$.

Since the object is not accelerating perpendicular to the incline, the net force acting on the object in this direction is zero. The equation for the net force on the object in the perpendicular direction is

$$\vec{F}_{net\perp} = \vec{F}_N + \vec{F}_{g\perp}$$

$$F_{net\perp} = F_N + F_{g\perp}$$

$$0 = F_N + F_{g\perp}$$

$$F_N = -F_{g\perp}$$

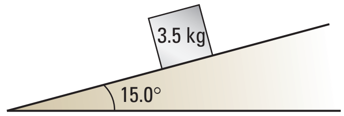
**Concept Check**

What is the angle between the normal force and the force of friction? Is this angle always the same size? Explain your reasoning.

Example 3.16 demonstrates how to calculate the acceleration of a block sliding down an incline. Since the direction of motion of the block is downhill, it is convenient to choose *downhill* to be positive.

## Example 3.16

A 3.5-kg block is sliding down an incline of 15.0° (Figure 3.81). The surface of the incline exerts a force of kinetic friction of magnitude 3.9 N on the block. Calculate the acceleration of the block.




▲ **Figure 3.81**

### *Given*

$m = 3.5\ \text{kg}$ $\qquad \theta = 15.0°$

magnitude of $\vec{F}_{\text{f}_{\text{kinetic}}} = 3.9\ \text{N}$ $\qquad g = 9.81\ \text{m/s}^2$

### *Required*

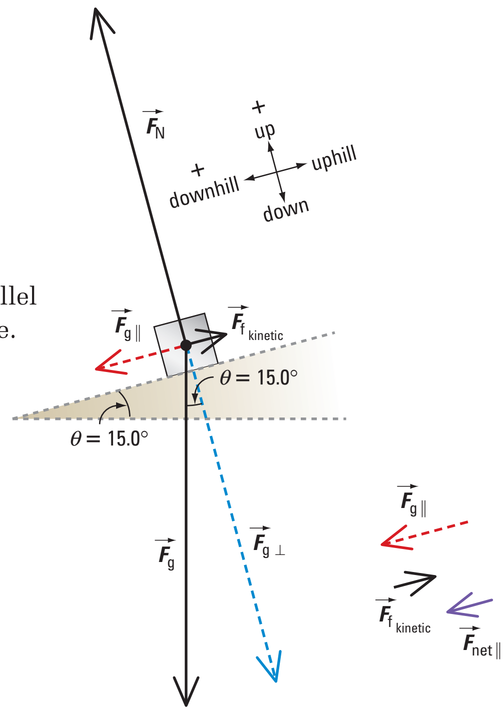
acceleration of block ($\vec{a}$)

### *Analysis and Solution*

Draw a free-body diagram for the block (Figure 3.82).

Since the block is accelerating downhill, $\vec{F}_{\text{net}} \neq 0$ N parallel to the incline, but $\vec{F}_{\text{net}} = 0$ N perpendicular to the incline.

Write equations to find the net force on the block in both directions.




▲ **Figure 3.82**

$\perp$ direction

$$\vec{F}_{\text{net}\perp} = \vec{F}_{\text{N}} + \vec{F}_{\text{g}\perp}$$

$$F_{\text{net}\perp} = 0$$

Calculations in the $\perp$ direction are not required in this problem.

$\parallel$ direction

$$\begin{aligned}
\vec{F}_{\text{net}\parallel} &= \vec{F}_{\text{g}\parallel} + \vec{F}_{\text{f}_{\text{kinetic}}} \\
F_{\text{net}\parallel} &= F_{\text{g}\parallel} + F_{\text{f}_{\text{kinetic}}} \\
ma &= F_{\text{g}\parallel} + F_{\text{f}_{\text{kinetic}}} \\
\text{Now, } F_{\text{g}\parallel} &= mg \sin\theta \\
\text{So, } ma &= mg\sin\theta + (-3.9\ \text{N}) \\
&= mg\sin\theta - 3.9\ \text{N} \\
a &= g\sin\theta - \frac{3.9\ \text{N}}{m} \\
&= (9.81\ \text{m/s}^2)(\sin 15.0°) - \frac{3.9\ \text{N}}{3.5\ \text{kg}} \\
&= 1.4\ \text{m/s}^2
\end{aligned}$$

The positive value for $a$ indicates that the direction of $\vec{a}$ is downhill.

$\vec{a} = 1.4\ \text{m/s}^2$ [downhill]

### *Paraphrase*

The acceleration of the block is 1.4 m/s² [downhill].

## Practice Problems

1. Determine the acceleration of the block in Example 3.16 if friction is not present.
2. A 55.0-kg skier is accelerating down a 35.0° slope. The magnitude of the skier's acceleration is 4.41 m/s². Calculate the force of kinetic friction that the snowy surface exerts on the skis.

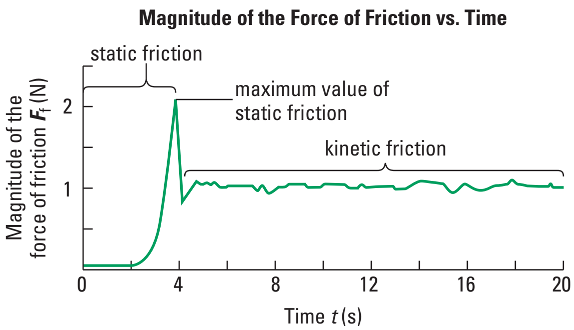
### Answers

1. 2.5 m/s² [downhill]
2. 66.9 N [uphill]

## Comparing the Magnitudes of Static and Kinetic Friction

The magnitude of the force of kinetic friction is *never* greater than the maximum magnitude of the force of static friction. Often, the magnitude of $\vec{F}_{f_{kinetic}}$ is *less* than the magnitude of $\vec{F}_{f_{static}}$.

Figure 3.83 shows a graph of a situation where a person is applying very little force to an object during the first 2 s. Then the person begins to push harder, and at $t = 4$ s, the object starts to move. The graph does not provide any information about the applied force after 4 s.




◀ **Figure 3.83** The force of static friction increases up to a maximum value.

**Concept Check**

Explain why it makes sense that the magnitude of the force of kinetic friction does not exceed the maximum magnitude of the force of static friction.

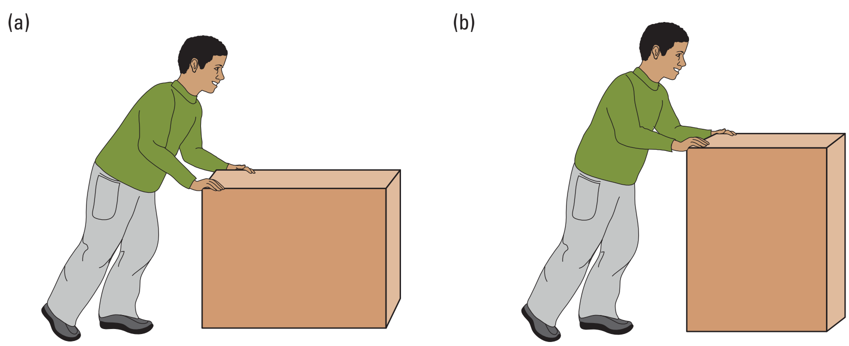
## Determining the Magnitude of Frictional Forces

Leonardo da Vinci (1452–1519) was one of the first people to experimentally determine two important relationships about friction. He discovered that for hard contact surfaces, the force of friction does *not* depend on the contact surface area. If you push a heavy box across the floor, the force of friction acting on the box is the same whether you push it on its bottom or on its side [Figure 3.84 (a) and (b)].

Da Vinci also discovered that the force of friction acting on an object depends on the normal force acting on that object. Find out what this relationship is by doing 3-11 Inquiry Lab.

**e WEB**

Leonardo da Vinci was as creative in science as he was in art. Research some of da Vinci's scientific ideas. Write a brief report of your findings, including diagrams where appropriate. Begin your search at www.pearsoned.ca/school/physicssource.




▲ **Figure 3.84** The force of friction acting on the box in each of these pictures is the same. For hard contact surfaces, the force of friction does not depend on contact surface area.

3-11 Inquiry Lab

# Relating Static Friction and the Normal Force

**Required Skills**
- Initiating and Planning
- Performing and Recording
- Analyzing and Interpreting
- Communication and Teamwork

## Question

What is the relationship between the maximum magnitude of the force of static friction and the magnitude of the normal force acting on an object?

## Hypothesis

State a hypothesis relating the magnitude of $\vec{F}_{f_{static}}$ and the magnitude of $\vec{F}_N$. Write an "if/then" statement.

## Variables

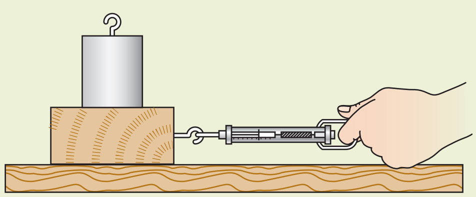
Read the procedure and identify the controlled, manipulated, and responding variable(s).

## Materials and Equipment

balance
wooden block with different face areas and a hook
horizontal board
spring scale, calibrated in newtons
set of standard masses

## Procedure

1. Read the steps of the procedure and design a chart to record your results.
2. Measure the mass of the block using the balance.
3. Place the largest face of the block on the horizontal board. Attach the spring scale to the block. Pull with an ever-increasing horizontal force until the block just starts to move. Record this force, which is the maximum magnitude of the force of static friction.
4. Increase the mass of the block system by placing a standard mass on the upper surface. Record the total mass of the block with the standard mass. Use the spring scale to determine the maximum magnitude of the force of static friction for this system (Figure 3.85).



▲ **Figure 3.85**

5. Repeat step 4 three more times, increasing the added mass each time until you have five different masses and five corresponding maximum magnitudes of static friction.
6. Calculate the magnitude of the weight corresponding to each mass system. Record the magnitude of the normal force.
7. (a) Graph the maximum magnitude of the force of static friction as a function of the magnitude of the normal force.
   (b) Draw the line of best fit and calculate the slope of the graph.

## Analysis

1. Describe the graph you drew in step 7.
2. As the magnitude of the normal force acting on the mass system increased, what happened to the maximum magnitude of the force of static friction?
3. What is the relationship between the maximum magnitude of the force of static friction and the magnitude of the normal force? Write this as a proportionality statement. Does this relationship agree with your hypothesis?
4. On a level surface, how does the magnitude of the weight of an object affect the magnitude of the normal force and the maximum magnitude of the force of static friction?
5. Explain why adding a bag of sand to the trunk of a rear-wheel-drive car increases its traction.
6. Design and conduct an experiment to verify that contact surface area does not affect the maximum magnitude of the force of static friction for a sliding object. Identify the controlled, manipulated, and responding variables. Analyze your data and form conclusions.

*e*LAB
For a probeware activity, go to www.pearsoned.ca/school/physicssource.

*Project* **LINK**

How will the force of static friction acting on each vehicle in the Unit II Project on page 232 affect the stopping distance?

How will the types of treads of the tires affect the force of static friction?

**coefficient of static friction:** proportionality constant relating $(F_{f_{static}})_{max}$ and $F_N$

## Coefficient of Static Friction

In 3-11 Inquiry Lab, you found that the maximum magnitude of the force of static friction is directly proportional to the magnitude of the normal force. This proportionality can be written mathematically:

$$(F_{f_{static}})_{max} \propto F_N$$

As an equation, the relationship is

$$(F_{f_{static}})_{max} = \mu_s F_N$$

where $\mu_s$ is a proportionality constant called the **coefficient of static friction**. Since the magnitude of the force of static friction can be anywhere from zero to some maximum value just before motion occurs, the general equation for the magnitude of the force of static friction must have an inequality sign.

$$F_{f_{static}} \leq \mu_s F_N \text{ for static friction}$$

## Coefficient of Kinetic Friction

Find out how the force of kinetic friction acting on an object is related to the normal force on that object by doing 3-12 Design a Lab.

## 3-12 Design a Lab

# Relating Kinetic Friction and the Normal Force

In this lab, you will investigate the relationship between the force of kinetic friction acting on an object and the normal force acting on that object.

### The Question

What is the relationship between the magnitude of the force of kinetic friction and the magnitude of the normal force acting on an object?

### Design and Conduct Your Investigation

- State a hypothesis relating the magnitudes of $\vec{F}_{f_{kinetic}}$ and $\vec{F}_N$.
- Then use the set-up in Figure 3.85 on page 181 to design an experiment. List the materials you will use as well as a detailed procedure. You will need to place objects of different mass on the block for each trial.
- For each trial, measure the force that must be applied to keep the block system moving at constant velocity. Then calculate the magnitude of the normal force.
- Plot a graph of $F_{f_{kinetic}}$ as a function of $F_N$.
- Analyze your data and form conclusions. How well did your results agree with your hypothesis?

*e* **LAB**

For a probeware activity, go to www.pearsoned.ca/school/physicssource.

From 3-12 Design a Lab, just as with static friction, the magnitude of kinetic friction is directly proportional to the magnitude of the normal force. This proportionality can be written mathematically:

$$F_{f_{kinetic}} \propto F_N$$

As an equation, the relationship is

$$F_{f_{kinetic}} = \mu_k F_N \text{ for kinetic friction}$$

where $\mu_k$ is a proportionality constant called the **coefficient of kinetic friction**. The force of kinetic friction has only one value, unlike the force of static friction which varies from zero to some maximum value. So the equation for the force of kinetic friction has an equal sign, not an inequality as does the equation for the force of static friction.

**coefficient of kinetic friction:** proportionality constant relating $F_{f_{kinetic}}$ and $F_N$

## Characteristics of Frictional Forces and Coefficients of Friction

There are a few important points to keep in mind about the force of friction and the variables that affect its magnitude:

- The equations for static friction and kinetic friction are not fundamental laws. Instead, they are approximations of experimental results.
- The equations $(F_{f_{static}})_{max} = \mu_s F_N$ and $F_{f_{kinetic}} = \mu_k F_N$ cannot be written as vector equations because the vectors $\vec{F}_f$ and $\vec{F}_N$ are perpendicular to each other.
- Both $\mu_s$ and $\mu_k$ are proportionality constants that have no units.
- For a given pair of surfaces, the coefficient of static friction is usually *greater* than the coefficient of kinetic friction.
- The coefficients of friction depend on the materials forming the contact surface, how smooth or rough a surface is, whether the surface is wet or dry, the temperature of the two contact surfaces, and other factors.

Table 3.4 lists coefficients of friction between pairs of materials.

**▼ Table 3.4** Approximate Coefficients of Friction for Some Materials

| Material | Coefficient of Static Friction $\mu_s$ | Coefficient of Kinetic Friction $\mu_k$ |
|---|---|---|
| Copper on copper | 1.6 | 1.0 |
| Steel on dry steel | 0.41 | 0.38 |
| Steel on greased steel | 0.15 | 0.09 |
| Dry oak on dry oak | 0.5 | 0.3 |
| Rubber tire on dry asphalt | 1.2 | 0.8 |
| Rubber tire on wet asphalt | 0.6 | 0.5 |
| Rubber tire on dry concrete | 1.0 | 0.7 |
| Rubber tire on wet concrete | 0.7 | 0.5 |
| Rubber tire on ice | 0.006 | 0.005 |
| Curling stone on ice | 0.003 | 0.002 |
| Teflon™ on Teflon™ | 0.04 | 0.04 |
| Waxed hickory skis on dry snow | 0.06 | 0.04 |
| Waxed hickory skis on wet snow | 0.20 | 0.14 |
| Synovial fluid on joint | 0.01 | 0.01 |

▲ **Figure 3.86** The amount of synovial fluid present depends on the need for a joint to move in a particular direction.

## How Friction Affects Motion

Movable joints in the human body, such as elbows, knees, and hips, have membranes that produce a lubricating fluid called synovial fluid. Among other factors, the amount of synovial fluid and the smoothness of adjacent bone surfaces affect the coefficients of friction in synovial joints (Figure 3.86).

The movement of synovial joints is very complicated because various biological processes are involved. In diseases such as arthritis, physical changes in joints and/or the presence of too much or too little synovial fluid affect the coefficients of friction. This, in turn, results in limited and painful movement.

The effect of temperature on the coefficients of friction plays a role in drag racing. Drag racers often warm the tires on their cars by driving for a while. Tires that are warm stick to a racing track better than cooler tires. This increased coefficient of static friction increases traction and improves the acceleration of the car.

The amount of moisture on a road surface, the temperature of the road surface and tires, and the type of tire treads are some factors that determine if a vehicle will skid. For a given tire, the coefficients of static and kinetic friction are greater on a dry road than if the same road is wet. The result is that vehicles are less likely to skid on a dry road than on a wet road.

Tire treads and road surfaces also affect the force of friction acting on a vehicle (Figure 3.87). A ribbed tire increases friction acting sideways which helps a driver steer better. A lug tread provides more traction than a ribbed tire. Slicks, the tires on drag racing cars, have no treads at all to increase the surface area of the tire in contact with the racing track to better dissipate heat.

*info* **BIT**

Cars with wide tires experience no more friction than if the cars had narrow tires. Wider tires simply spread the weight of a vehicle over a greater surface area. This reduced pressure on the road reduces heating and tire wear.

(a)

(b)

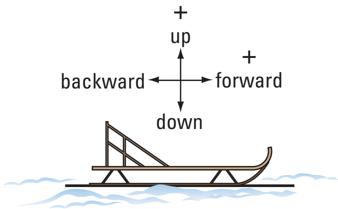

(c)

▲ **Figure 3.87** Different types of tires: (a) a ribbed tire with chains on it for better traction on snowy and icy surfaces, (b) a lug tread, and (c) slicks on a racing car

Example 3.17 demonstrates how to use the coefficients of friction in Table 3.4 on page 183 to calculate the mass of a sled. Since the sled is at rest, the snowy surface exerts a force of static friction on the sled.

## Example 3.17

A sled with waxed hickory runners rests on a horizontal, dry snowy surface (Figure 3.88). Calculate the mass of the sled if the maximum force that can be applied to the sled before it starts moving is 46 N [forward]. Refer to Table 3.4 on page 183.




▲ **Figure 3.88**

### *Given*

$\vec{F}_{app} = 46$ N [forward] $\qquad \vec{g} = 9.81$ m/s$^2$ [down]

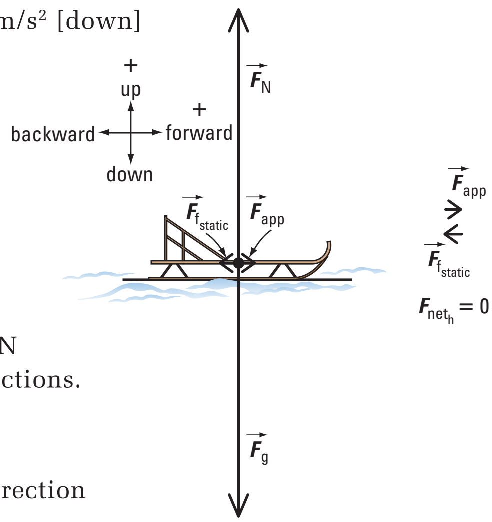
$\mu_s = 0.06$ from Table 3.4
(waxed hickory skis on dry snow)

### *Required*

mass of sled ($m$)

### *Analysis and Solution*

Draw a free-body diagram for the sled (Figure 3.89).




▲ **Figure 3.89**

Since the sled is not accelerating, $\vec{F}_{net} = 0$ N in both the horizontal and vertical directions.
Write equations to find the net force on the sled in both directions.

horizontal direction

$$\begin{aligned}
\vec{F}_{net_h} &= \vec{F}_{app} + \vec{F}_{f_{static}} \\
F_{net_h} &= F_{app} + F_{f_{static}} \\
0 &= F_{app} + F_{f_{static}} \\
&= F_{app} + (-\mu_s F_N) \\
&= F_{app} - \mu_s F_N \\
F_{app} &= \mu_s F_N
\end{aligned}$$

vertical direction

$$\begin{aligned}
\vec{F}_{net_v} &= \vec{F}_N + \vec{F}_g \\
F_{net_v} &= F_N + F_g \\
0 &= F_N + (-mg) \\
&= F_N - mg \\
F_N &= mg
\end{aligned}$$

Substitute $F_N = mg$ into the equation for $F_{app}$.

$$\begin{aligned}
F_{app} &= \mu_s mg \\
m &= \frac{F_{app}}{\mu_s g} \\
&= \frac{46 \text{ N}}{(0.06)\left(9.81 \frac{\text{m}}{\text{s}^2}\right)} \\
&= \frac{46 \text{ kg} \cdot \cancel{\frac{\text{m}}{\text{s}^2}}}{(0.06)\left(9.81 \cancel{\frac{\text{m}}{\text{s}^2}}\right)} \\
&= 8 \times 10^1 \text{ kg}
\end{aligned}$$

### *Paraphrase*

The mass of the sled is $8 \times 10^1$ kg.

## Practice Problems

1. An applied force of 24 N [forward] causes a steel block to start moving across a horizontal, greased steel surface. Calculate the mass of the block. Refer to Table 3.4 on page 183.
2. Suppose the sled in Example 3.17 is resting on a horizontal, wet snowy surface. Would the sled move if the applied force is 125 N? Explain. Refer to Table 3.4 on page 183.

### Answers

1. 16 kg
2. no, $\vec{F}_{f_{static}} > \vec{F}_{app}$

In Example 3.18, a toboggan is initially at rest on a snowy hill. By knowing only the angle of the incline, it is possible to determine the coefficient of static friction for the toboggan on the hill.

## Practice Problems

1. Calculate the coefficient of static friction if the toboggan in Example 3.18 is 20 kg and the hill forms an angle of 30.0° with the horizontal.
2. An 80-kg skier on a slushy surface starts moving down a hill forming an angle of at least 25.0° with the horizontal.
   (a) Determine the coefficient of static friction.
   (b) Calculate the maximum force of static friction on the skier.

### Answers

1. 0.58
2. (a) 0.47
   (b) $3.3 \times 10^2$ N [uphill]

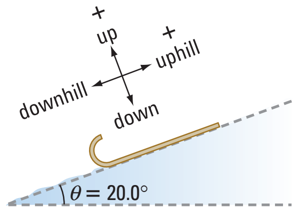
## *info* BIT

The trigonometric function tan $\theta$ can be expressed in terms of sin $\theta$ and cos $\theta$.

$$\tan\theta = \frac{\sin\theta}{\cos\theta}$$

## Example 3.18

A 50-kg toboggan is on a snowy hill. If the hill forms an angle of at least 20.0° with the horizontal, the toboggan just begins to slide downhill (Figure 3.90). Calculate the coefficient of static friction for the toboggan on the snow.




▲ **Figure 3.90**

***Given***

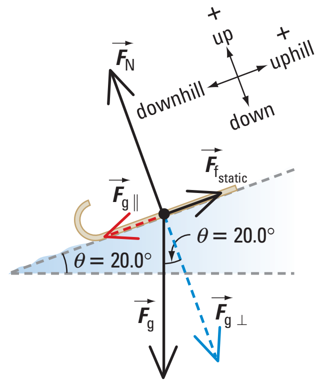
$m = 50$ kg $\quad \theta = 20.0°\quad g = 9.81$ m/s$^2$

***Required***

coefficient of static friction ($\mu_s$)

***Analysis and Solution***

Draw a free-body diagram for the toboggan [Figure 3.91 (a)]. When the angle of the incline is just enough for the toboggan to start moving, the surface of the incline is exerting the maximum magnitude of the force of static friction on the toboggan.




▲ **Figure 3.91 (a)**

Just before the toboggan begins to slide, $\vec{F}_{net} = 0$ N in both the parallel and perpendicular directions to the incline.

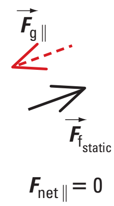
Write equations to find the net force on the toboggan in both directions [Figure 3.91 (b)].

$\perp$ direction

$$\begin{aligned}
\vec{F}_{net\perp} &= \vec{F}_N + \vec{F}_{g\perp}\\
F_{net\perp} &= F_N + F_{g\perp}\\
0 &= F_N + F_{g\perp}\\
F_N &= -F_{g\perp}\\
\text{Now, } F_{g\perp} &= -mg\cos\theta\\
\text{So, } F_N &= -(-mg\cos\theta)\\
&= mg\cos\theta
\end{aligned}$$

$\parallel$ direction

$$\begin{aligned}
\vec{F}_{net\parallel} &= \vec{F}_{g\parallel} + \vec{F}_{f_{static}}\\
F_{net\parallel} &= F_{g\parallel} + F_{f_{static}}\\
0 &= F_{g\parallel} + F_{f_{static}}\\
F_{f_{static}} &= -F_{g\parallel}\\
F_{g\parallel} &= -mg\sin\theta\\
F_{f_{static}} &= -(-mg\sin\theta)\\
&= mg\sin\theta\\
\mu_s F_N &= mg\sin\theta
\end{aligned}$$




▲ **Figure 3.91 (b)**

Substitute $F_N = mg\cos\theta$ into the last equation for the $\parallel$ direction.

$$\begin{aligned}
\mu_s(\cancel{mg}\cos\theta) &= \cancel{mg}\sin\theta\\
\mu_s\cos\theta &= \sin\theta\\
\mu_s &= \frac{\sin\theta}{\cos\theta}\\
&= \tan\theta\\
&= \tan 20.0°\\
&= 0.36
\end{aligned}$$

***Paraphrase***

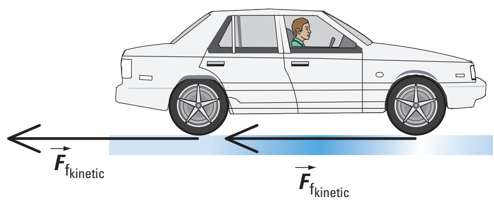
The coefficient of static friction for the toboggan on the snow is 0.36. Note that $\mu_s$ does *not* depend on the mass of the toboggan, only on the angle of the hill.

## Kinetic Friction Applies to Skidding Tires

When the tires of a vehicle lock or if the tires skid on a road surface, the tires no longer rotate. Instead, the tires slide along the road surface. At the area where the tire and the road are in contact, the road surface exerts a force of kinetic friction directed backward on the tire (Figure 3.92).

**e TECH**

Explore how the initial velocity of a skidding car and its mass affect the braking distance. Follow the eTech links at www.pearsoned.ca/school/physicssource.




▲ **Figure 3.92** Diagram showing the force of kinetic friction acting on the tires of a skidding car

Safety features on vehicles such as anti-lock braking systems are designed to prevent the wheels of a vehicle from locking when a driver steps on the brakes. If the wheels lock, the tires no longer rotate on the road surface and the vehicle ends up skidding. As long as the wheels continue to turn, the road surface exerts a force of static friction on the tires. Anti-lock braking systems maximize the force of static friction acting on the tires, allowing the driver of a vehicle to come to a more controlled stop.

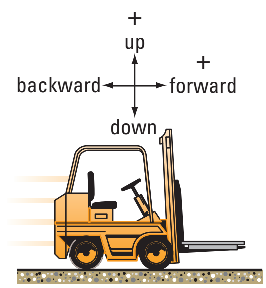
In Example 3.19, a lift truck is skidding on a concrete surface. Since the wheels are not rotating, the concrete surface is exerting a force of kinetic friction on the tires.

**e WEB**

Research how anti-lock braking systems work, and identify the strengths and weaknesses. Interview a car salesperson and/or an owner. Write a brief report of your findings, including diagrams where appropriate. Begin your search at www.pearsoned.ca/school/physicssource.

### Example 3.19

A 1640-kg lift truck with rubber tires is skidding on wet concrete with all four wheels locked (Figure 3.93). Calculate the acceleration of the truck. Refer to Table 3.4 on page 183.




▲ **Figure 3.93**

***Given***

$m = 1640$ kg $\qquad \vec{g} = 9.81$ m/s² [down]

$\mu_k = 0.5$ from Table 3.4 (rubber on wet concrete)

***Required***

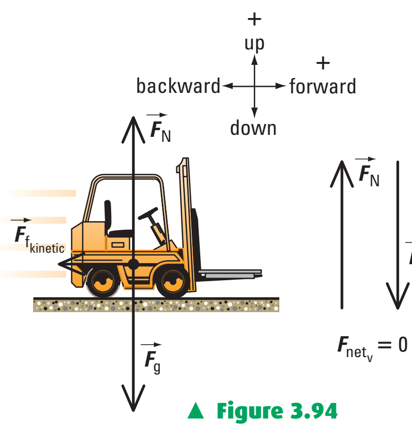
acceleration of lift truck ($\vec{a}$)

***Analysis and Solution***

Draw a free-body diagram for the lift truck (Figure 3.94).

Since the lift truck is accelerating forward, $\vec{F}_{\text{net}} \neq 0$ N in the horizontal direction, but $\vec{F}_{\text{net}} = 0$ N in the vertical direction.

Write equations to find the net force on the lift truck in both directions.




▲ **Figure 3.94**

## Practice Problems

1. An applied force of 450 N [forward] is needed to drag a 1000-kg crate at constant speed across a horizontal, rough floor. Calculate the coefficient of kinetic friction for the crate on the floor.
2. Calculate the force of kinetic friction if the truck in Example 3.19 is skidding downhill at constant speed on a hill forming an angle of 15.0° with the horizontal.

### Answers

1. $4.59 \times 10^{-2}$
2. $4.16 \times 10^{3}$ N [uphill]

horizontal direction

$$\begin{aligned}\vec{F}_{\text{net}_\text{h}} &= \vec{F}_{\text{f}_\text{kinetic}}\\ F_{\text{net}_\text{h}} &= F_{\text{f}_\text{kinetic}}\\ ma &= F_{\text{f}_\text{kinetic}}\\ &= -\mu_\text{k}F_\text{N}\end{aligned}$$

vertical direction

$$\begin{aligned}\vec{F}_{\text{net}_\text{v}} &= \vec{F}_\text{N} + \vec{F}_\text{g}\\ F_{\text{net}_\text{v}} &= F_\text{N} + F_\text{g}\\ 0 &= F_\text{N} + (-mg)\\ &= F_\text{N} - mg\\ F_\text{N} &= mg\end{aligned}$$

Substitute $F_\text{N} = mg$ into the equation for $F_{\text{f}_\text{kinetic}}$.

$$\begin{aligned}\cancel{m}a &= -\mu_\text{k}\cancel{m}g\\ a &= -\mu_\text{k}g\\ &= -(0.5)\left(9.81\ \frac{\text{m}}{\text{s}^2}\right)\\ &= -5\ \text{m/s}^2\end{aligned}$$

The negative value for $a$ indicates that the direction of $\vec{a}$ is backward.

$$\vec{a} = 5\ \text{m/s}^2\ [\text{backward}]$$

***Paraphrase***

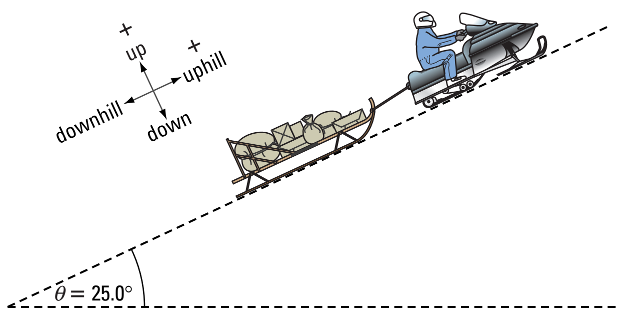
The acceleration of the truck is 5 m/s² [backward].

Example 3.20 involves a snowmobile accelerating uphill while towing a sled. Since the motion of the sled is uphill, it is convenient to choose uphill to be positive.

## Example 3.20

A person wants to drag a 40-kg sled with a snowmobile up a snowy hill forming an angle of 25.0° (Figure 3.95). The coefficient of kinetic friction for the sled on the snow is 0.04. Calculate the force of the snowmobile on the sled if the sled accelerates at 2.5 m/s² [uphill].

▼ **Figure 3.95**




***Given***

$m = 40$ kg  $\theta = 25.0°$  $\mu_\text{k} = 0.04$

$g = 9.81\ \text{m/s}^2$  $\vec{a} = 2.5\ \text{m/s}^2$ [uphill]

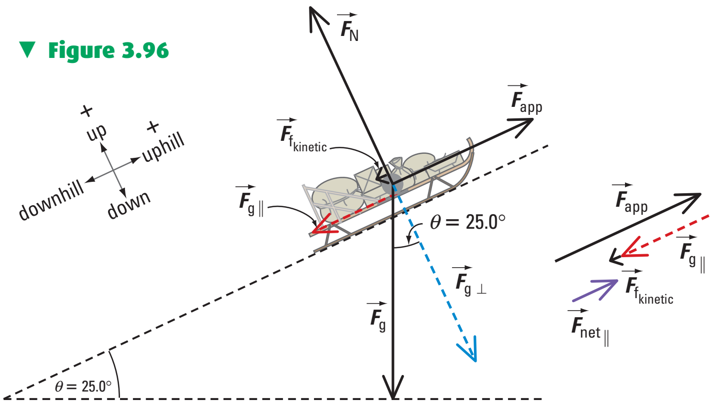
***Required***

applied force on sled ($\vec{F}_\text{app}$)

### *Analysis and Solution*

Draw a free-body diagram for the sled (Figure 3.96).

▼ **Figure 3.96**




Since the sled is accelerating uphill, $\vec{F}_{net} \neq 0$ N parallel to the incline, but $\vec{F}_{net} = 0$ N perpendicular to the incline.

Write equations to find the net force on the sled in both directions.

$\perp$ direction

$$\begin{aligned}
\vec{F}_{net\perp} &= \vec{F}_N + \vec{F}_{g\perp} \\
F_{net\perp} &= F_N + F_{g\perp} \\
0 &= F_N + F_{g\perp} \\
F_N &= -F_{g\perp}
\end{aligned}$$

Now, $F_{g\perp} = -mg\cos\theta$

So, $F_N = -(-mg\cos\theta)$

$= mg\cos\theta$

$\parallel$ direction

$$\begin{aligned}
\vec{F}_{net\parallel} &= \vec{F}_{app} + \vec{F}_{g\parallel} + \vec{F}_{f_{kinetic}} \\
F_{net\parallel} &= F_{app} + F_{g\parallel} + F_{f_{kinetic}} \\
ma &= F_{app} + F_{g\parallel} + F_{f_{kinetic}} \\
F_{app} &= ma - F_{g\parallel} - F_{f_{kinetic}}
\end{aligned}$$

Also, $F_{g\parallel} = -mg\sin\theta$ and

$F_{f_{kinetic}} = -\mu_k F_N$

$$\begin{aligned}
F_{app} &= ma - (-mg\sin\theta) - (-\mu_k F_N) \\
&= ma + mg\sin\theta + \mu_k F_N
\end{aligned}$$

Substitute $F_N = mg\cos\theta$ into the equation for $F_{app}$.

$$\begin{aligned}
F_{app} &= ma + mg\sin\theta + \mu_k mg\cos\theta \\
&= ma + mg(\sin\theta + \mu_k\cos\theta) \\
&= (40\text{ kg})(2.5\text{ m/s}^2) + (40\text{ kg})(9.81\text{ m/s}^2)\,[(\sin 25.0°) + (0.04)(\cos 25.0°)] \\
&= 3 \times 10^2\text{ N}
\end{aligned}$$

The positive value for $F_{app}$ indicates that the direction of $\vec{F}_{app}$ is uphill.

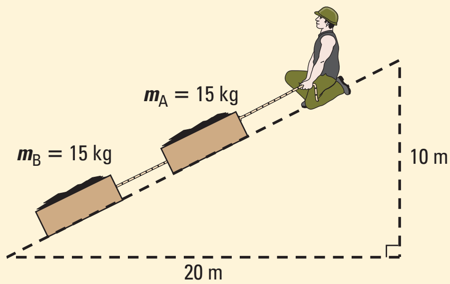
$$\vec{F}_{app} = 3 \times 10^2\text{ N [uphill]}$$

### *Paraphrase*

The snowmobile must apply a force of $3 \times 10^2$ N [uphill].

## Practice Problems

1. A roofer is shingling a roof that rises 1.0 m vertically for every 2.0 m horizontally. The roofer is pulling one bundle of shingles (A) with a rope up the roof. Another rope connects bundle A to bundle B farther down the roof (Figure 3.97).




▲ **Figure 3.97**

Each of the two bundles of shingles has a mass of 15 kg. The coefficient of kinetic friction for the bundles on plywood sheeting is 0.50.

(a) What force must the roofer exert up the roof to drag the bundles at constant speed?

(b) Calculate the force exerted by bundle A on bundle B.

(c) What total force would the roofer have to exert to accelerate both bundles at 2.0 m/s² [up roof]?

### Answers

1. (a) $2.6 \times 10^2$ N [up roof]
   (b) $1.3 \times 10^2$ N [up roof]
   (c) $3.2 \times 10^2$ N [up roof]

## 3.5 Check and Reflect

### Knowledge

1. In your own words, define friction.
2. What are some situations where friction is so small that it could be neglected?
3. Distinguish between static friction and kinetic friction.

### Applications

4. A pair of skis weigh 15 N [down]. Calculate the difference in the maximum force of static friction for the skis on a wet and dry snowy, horizontal surface. Refer to Table 3.4 on page 183.
5. A force of 31 N [forward] is needed to start an 8.0-kg steel slider moving along a horizontal steel rail. What is the coefficient of static friction?
6. A biker and his motorcycle have a weight of 2350 N [down]. Calculate the force of kinetic friction for the rubber tires and dry concrete if the motorcycle skids. Refer to Table 3.4 on page 183.
7. A 15-kg box is resting on a hill forming an angle with the horizontal. The coefficient of static friction for the box on the surface is 0.45. Calculate the maximum angle of the incline just before the box starts to move.
8. The coefficient of static friction for a wheelchair with its brakes engaged on a conveyor-type ramp is 0.10. The average mass of a person including the wheelchair is 85 kg. Determine if a ramp of 8.0° with the horizontal will prevent motion.
9. A truck loaded with a crate of mass $m$ is at rest on an incline forming an angle of 10.0° with the horizontal. The coefficient of static friction for the crate on the truck bed is 0.30. Find the maximum possible acceleration uphill for the truck before the crate begins to slip backward.
10. A loaded dogsled has a mass of 400 kg and is being pulled across a horizontal, packed snow surface at a velocity of 4.0 m/s [N]. Suddenly, the harness separates from the sled. If the coefficient of kinetic friction for the sled on the snow is 0.0500, how far will the sled coast before stopping?

### Extensions

11. A warehouse employee applies a force of 120 N [12.0°] to accelerate a 35-kg wooden crate from rest across a wooden floor. The coefficient of kinetic friction for the crate on the floor is 0.30. How much time elapses from the time the employee starts to move the crate until it is moving at 1.2 m/s [0°]?
12. Make a Venn diagram to summarize the similarities and differences between static and kinetic friction. See Student References 4: Using Graphic Organizers on page 869 for an example.
13. Research how the type of tread on a tire affects the coefficients of static friction and kinetic friction given the same road surface. Find out what hydroplaning is and how tires are designed to minimize this problem. Write a brief report of your findings, including diagrams where appropriate. Begin your search at www.pearsoned.ca/school/physicssource.
14. Design an experiment to determine the coefficients of static and kinetic friction for a curling stone on an icy surface. Perform the experiment at a local arena or club. Ask the icemaker to change the temperature of the ice, and repeat the experiment to determine if there is a difference in your values. Write a brief report of your findings.

**e TEST**

To check your understanding of friction and inclines, follow the eTest links at www.pearsoned.ca/school/physicssource.

## Key Terms and Concepts

dynamics
force
free-body diagram
normal force
net force
inertia
inertial mass
action force
reaction force
friction
static friction
kinetic friction
coefficient of static friction
coefficient of kinetic friction

## Key Equations

Newton's first law: $\vec{F}_{\text{net}} = 0$ when $\Delta\vec{v} = 0$

Newton's second law: $\vec{F}_{\text{net}} = m\vec{a}$

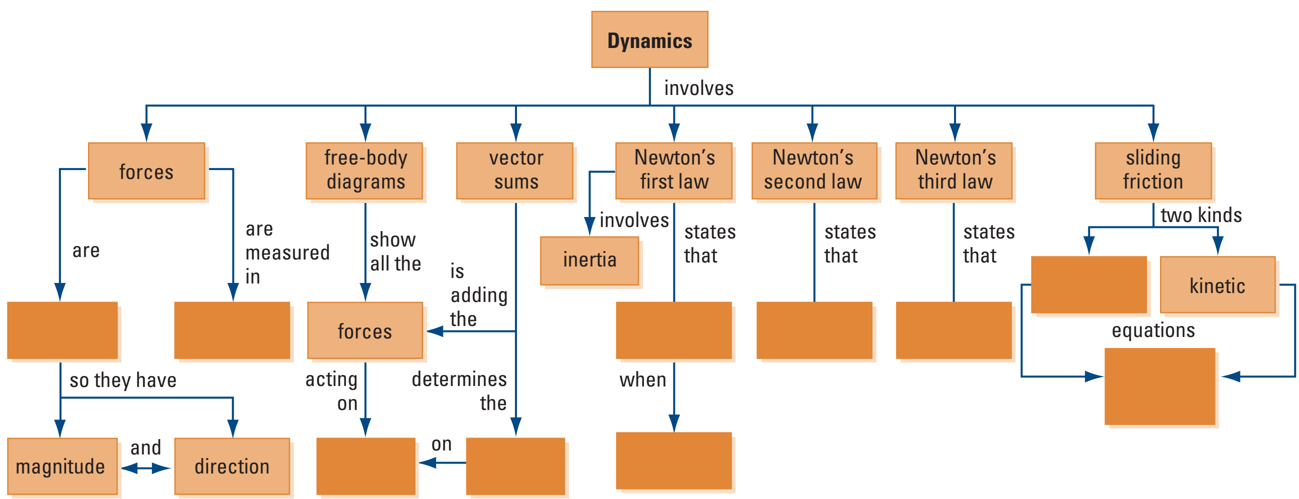
Newton's third law: $\vec{F}_{\text{A on B}} = -\vec{F}_{\text{B on A}}$

Static friction: $F_{\text{f}_{\text{static}}} \leq \mu_{\text{s}}F_{\text{N}}$

Kinetic friction: $F_{\text{f}_{\text{kinetic}}} = \mu_{\text{k}}F_{\text{N}}$

## Conceptual Overview

The concept map below summarizes many of the concepts and equations in this chapter. Copy and complete the map to have a full summary of the chapter.




▲ **Figure 3.98**

## Knowledge

**1.** (3.1, 3.3) Two people, A and B, are pushing a stalled 2000-kg truck along a level road. Person A exerts a force of 300 N [E]. Person B exerts a force of 350 N [E]. The magnitude of the force of friction on the truck is 550 N. Calculate the acceleration of the truck.

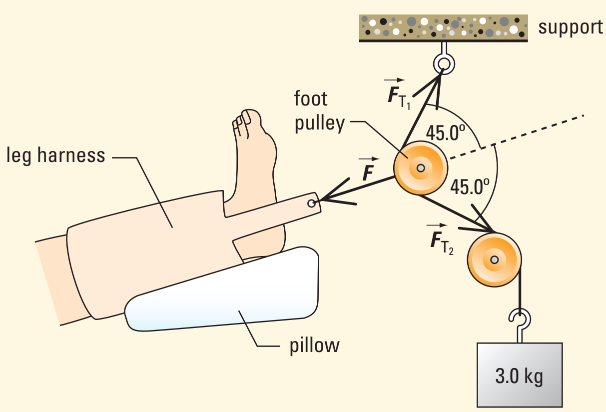
**2.** (3.2) Use a free-body diagram and Newton's first law to explain the motion of
(a) a figure skater during a glide, and
(b) a hockey puck during a cross-ice pass.
Assume ice is frictionless.

**3.** (3.4) A transport truck pulls a trailer with a force of 1850 N [E]. What force does the trailer exert on the transport truck?

**4.** (3.5) An inexperienced driver, stuck in snow, tends to spin the car tires to increase the force of friction exerted by the snow on the tires. What advice would you give to the driver? Why?

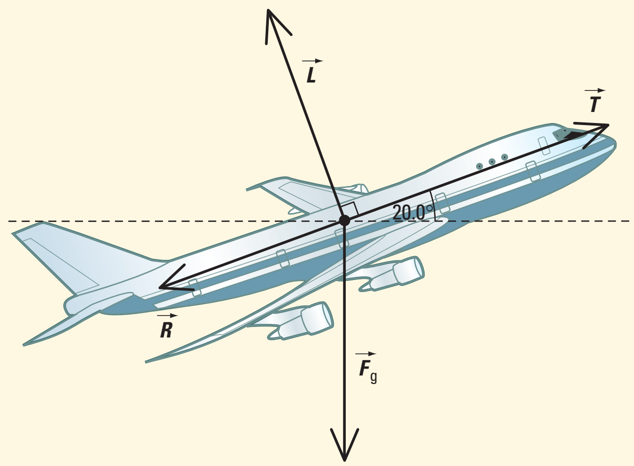
## Applications

**5.** A device used to treat a leg injury is shown below. The pulley is attached to the foot, and the weight of the 3.0-kg object provides a tension force to each side of the pulley. The pulley is at rest because the foot applies a force $\vec{F}$ to the pulley, which is balanced by the forces $\vec{F}_{T_1}$ and $\vec{F}_{T_2}$ in the rope. The weight of the leg and foot is supported by the pillow.
(a) Using a free-body diagram for the pulley, determine the force $\vec{F}$.
(b) What will happen to the magnitude of $\vec{F}$ if the angle between $\vec{F}_{T_1}$ and $\vec{F}_{T_2}$ decreases? Why?




**6.** Refer to Example 3.6 Practice Problem 1 on page 150. In a second practice run, the initial acceleration of the bobsled, pilot, and brakeman is 4.4 m/s² [forward]. Rider A exerts an average force of magnitude 1200 N on the bobsled, and the force of friction decreases to 400 N. What average force does rider B exert?

**7.** During its ascent, a loaded jet of mass $4.0 \times 10^5$ kg is flying at constant velocity 20.0° above the horizontal. The engines of the plane provide a thrust $\vec{T}$ of $4.60 \times 10^6$ N [forward] to provide the lift force $\vec{L}$ [perpendicular to wings]. The air resistance $\vec{R}$ opposes the motion of the jet. Determine the magnitudes of $\vec{L}$ and $\vec{R}$.




**8.** Suppose the force of kinetic friction on a sliding block of mass $m$ is 2.5 N [backward]. What is the force of kinetic friction on the block if another block of mass $2m$ is placed on its upper surface?

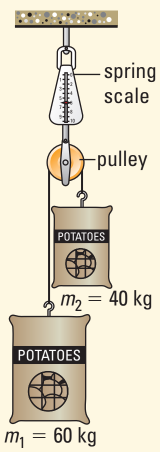
**9.** A 1385-kg pickup truck hitched to a 453-kg trailer accelerates along a level road from a stoplight at 0.75 m/s² [forward]. Ignore friction and air resistance. Calculate
(a) the tension in the hitch,
(b) the force of friction exerted by the road on the pickup truck to propel it forward, and
(c) the force the trailer exerts on the pickup truck.

**10.** Two curlers, A and B, have masses of 50 kg and 80 kg respectively. Both players are standing on a carpet with shoes having Teflon™ sliders. The carpet exerts a force of friction of 24.5 N [E] on player A and a force of friction of 39.2 N [W] on player B. Player A pushes player B with a force of 60 N [E].
(a) Calculate the net force acting on each player.
(b) Calculate the acceleration of each player.

11. A force of 15 N [S] moves a case of soft drinks weighing 40 N [down] across a level counter at constant velocity. Calculate the coefficient of kinetic friction for the case on the counter.

12. A 1450-kg car is towing a trailer of mass 454 kg. The force of air resistance on both vehicles is 7471 N [backward]. If the acceleration of both vehicles is 0.225 m/s$^2$, what is the coefficient of static friction for the wheels on the ground?

13. Two bags of potatoes, $m_1 = 60$ kg and $m_2 = 40$ kg, are connected by a light rope that passes over a light, frictionless pulley. The pulley is suspended from the ceiling using a light spring scale.
   (a) What is the reading on the scale if the pulley is prevented from turning?
   (b) Draw a free-body diagram for each bag when the pulley is released.
      (i) Calculate the acceleration of the system.
      (ii) Calculate the tension in the rope.
   (c) What is the reading on the scale when the bags are accelerating?
   (d) Explain the difference between your answers in parts (a) and (c).




14. A drag racing car initially at rest can reach a speed of 320 km/h in 6.50 s. The wheels of the car can exert an average horizontal force of $1.52 \times 10^4$ N [backward] on the pavement. If the force of air resistance on the car is $5.2 \times 10^3$ N [backward], what is the mass of the car?

15. A tractor and tow truck have rubber tires on wet concrete. The tow truck drags the tractor at constant velocity while its brakes are locked. If the tow truck exerts a horizontal force of $1.0 \times 10^4$ N on the tractor, determine the mass of the tractor. Refer to Table 3.4 on page 183.

16. Create a problem involving an object of mass $m$ on an incline of angle $\theta$. Write a complete solution, including an explanation of how to resolve the gravitational force vector into components.

17. The table below shows some coefficients of static and kinetic friction ($\mu_s$ and $\mu_k$) for rubber tires in contact with various road surfaces.

| Coefficient | Dry Concrete | Wet Concrete | Dry Asphalt | Wet Asphalt |
|---|---|---|---|---|
| $\mu_s$ | 1.0 | 0.7 | 1.2 | 0.6 |
| $\mu_k$ | 0.7 | 0.5 | 0.6 | 0.5 |

   (a) Which road surface exerts more static friction on a rubber tire, dry concrete or dry asphalt? Explain.
   (b) On which surface does a car slide more easily, on wet concrete or on wet asphalt? Why?
   (c) On which surface will a moving car begin to slide more easily, on dry concrete or on dry asphalt? Why?
   (d) On which surface will a car with locked brakes slide a shorter distance, on dry concrete or on dry asphalt? Explain.

## Extensions

18. An 80-kg baseball player slides onto third base. The coefficient of kinetic friction for the player on the ground is 0.70. His speed at the start of the slide is 8.23 m/s.
   (a) Calculate his acceleration during the slide.
   (b) For how long does he slide until he stops?
   (c) Show that the time it takes the player to come to a stop is given by the equation $\Delta t = \dfrac{v_i}{\mu_k g}$.

## Consolidate Your Understanding

19. Write a paragraph explaining the similarities and differences among Newton's three laws. Include an example that involves all three laws and explain how each law applies. Use the example to teach the laws to a student who has not studied dynamics.

20. Write a paragraph describing the differences between static and kinetic friction, and between the coefficients of static and kinetic friction. Include an example with a free-body diagram for each type of friction.

### Think About It

Review your answers to the Think About It questions on page 125. How would you answer each question now?

### e TEST

To check your understanding of forces and Newton's laws of motion, follow the eTest links at www.pearsoned.ca/school/physicssource.