Lecture 7, 8

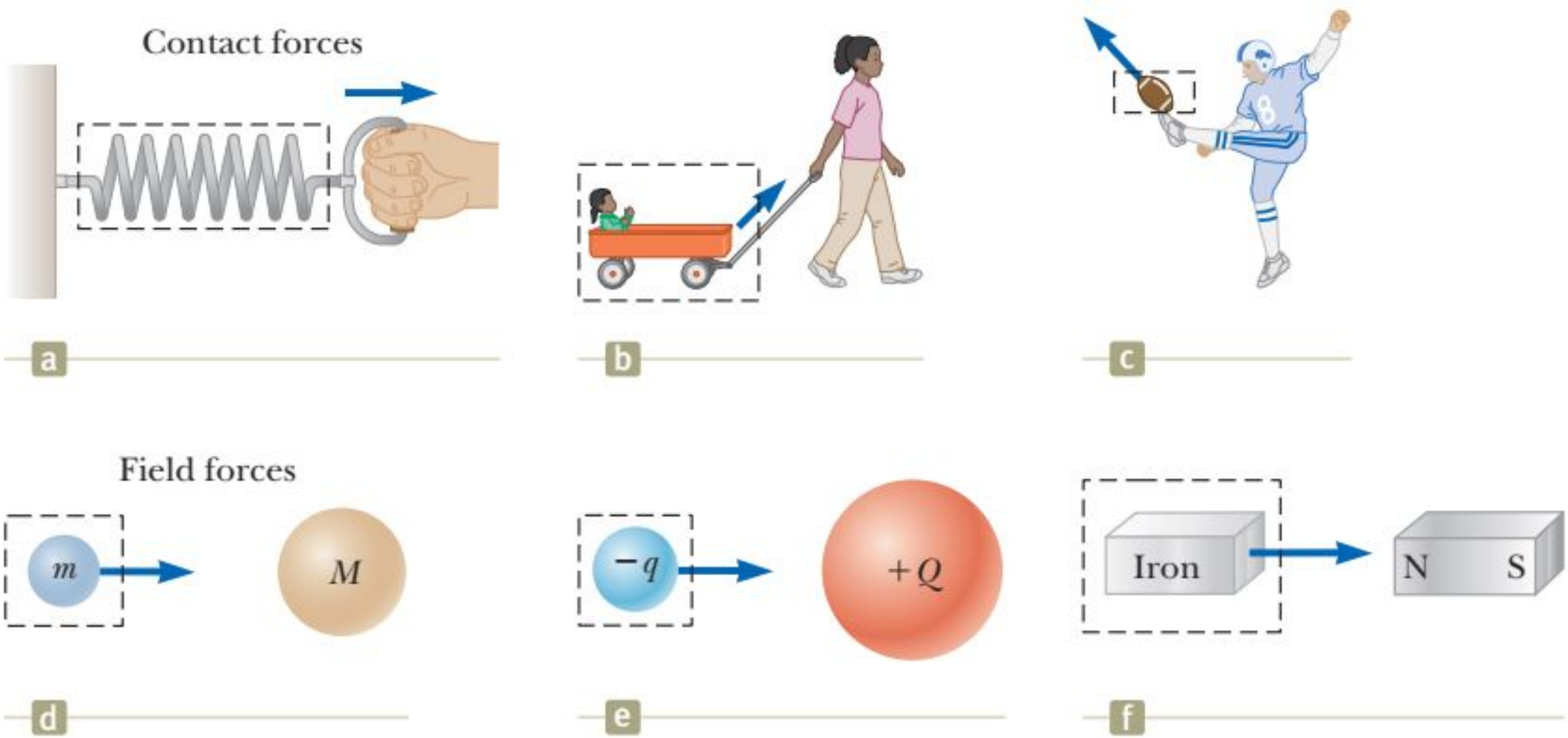
The Laws of Motion

CHAPTER 5

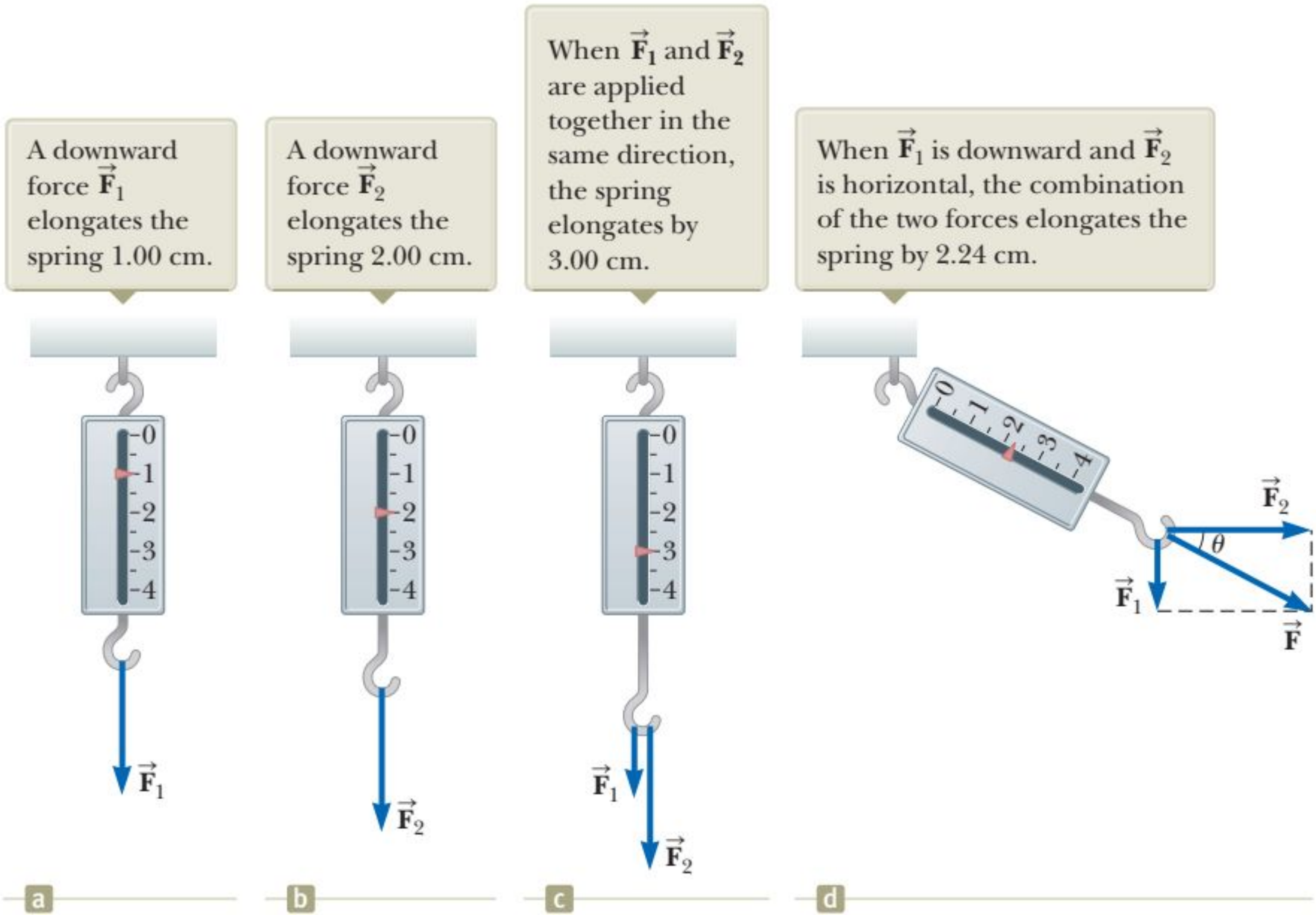
Lecture-7
Outline

- Concept of Force
- Newton Laws
- Type of Forces
- Examples

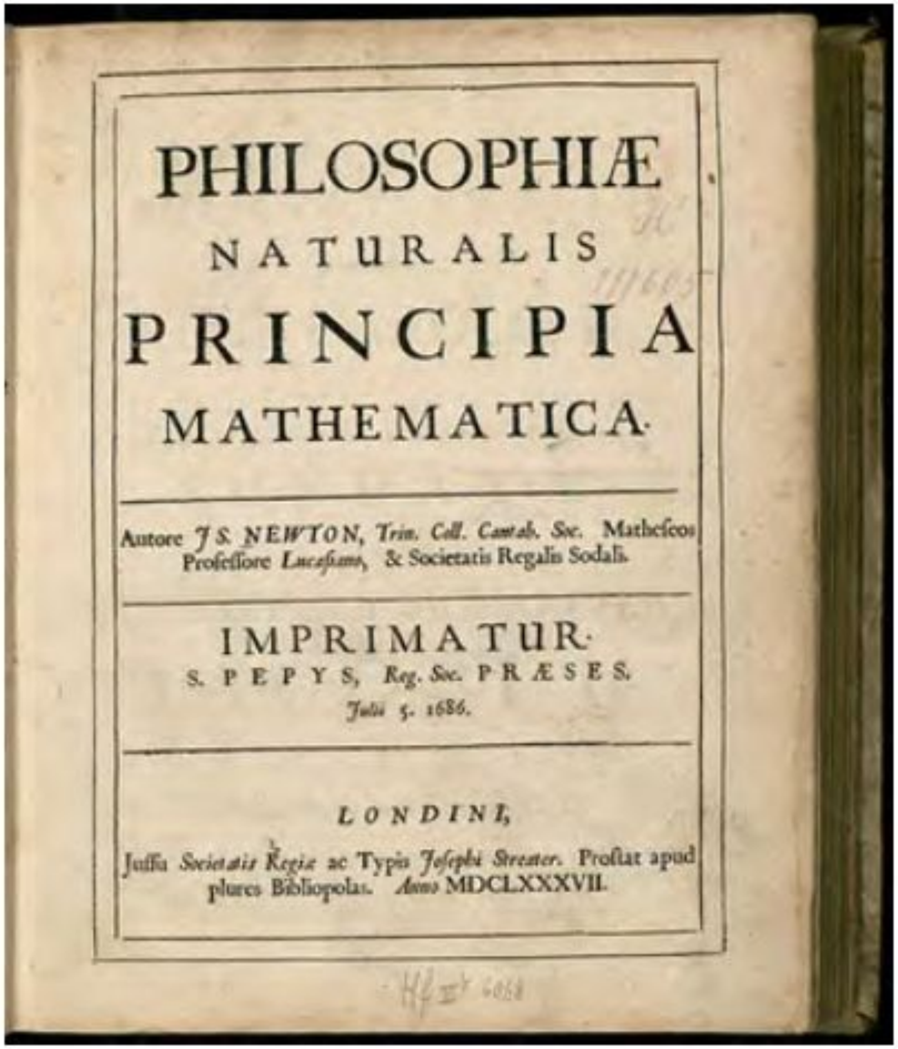
5.1 The Concept of Force



The Vector Nature of Force



Introduction to Dynamics: Newton's Laws of Motion



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Autore J S. NEWTON, *Trin. Coll. Cantab. Soc.* Matheseos Professore *Lucasiano*, & Societatis Regalis Sodali.

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S. PEPYS, *Reg. Soc.* PRÆSES.
Julii 5. 1686.

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Jussu *Societatis Regiæ* ac Typis *Josephi Streater*. Prostat apud plures Bibliopolas. *Anno* MDCLXXXVII.

Isaac Newton

English physicist and mathematician
(1642–1727)

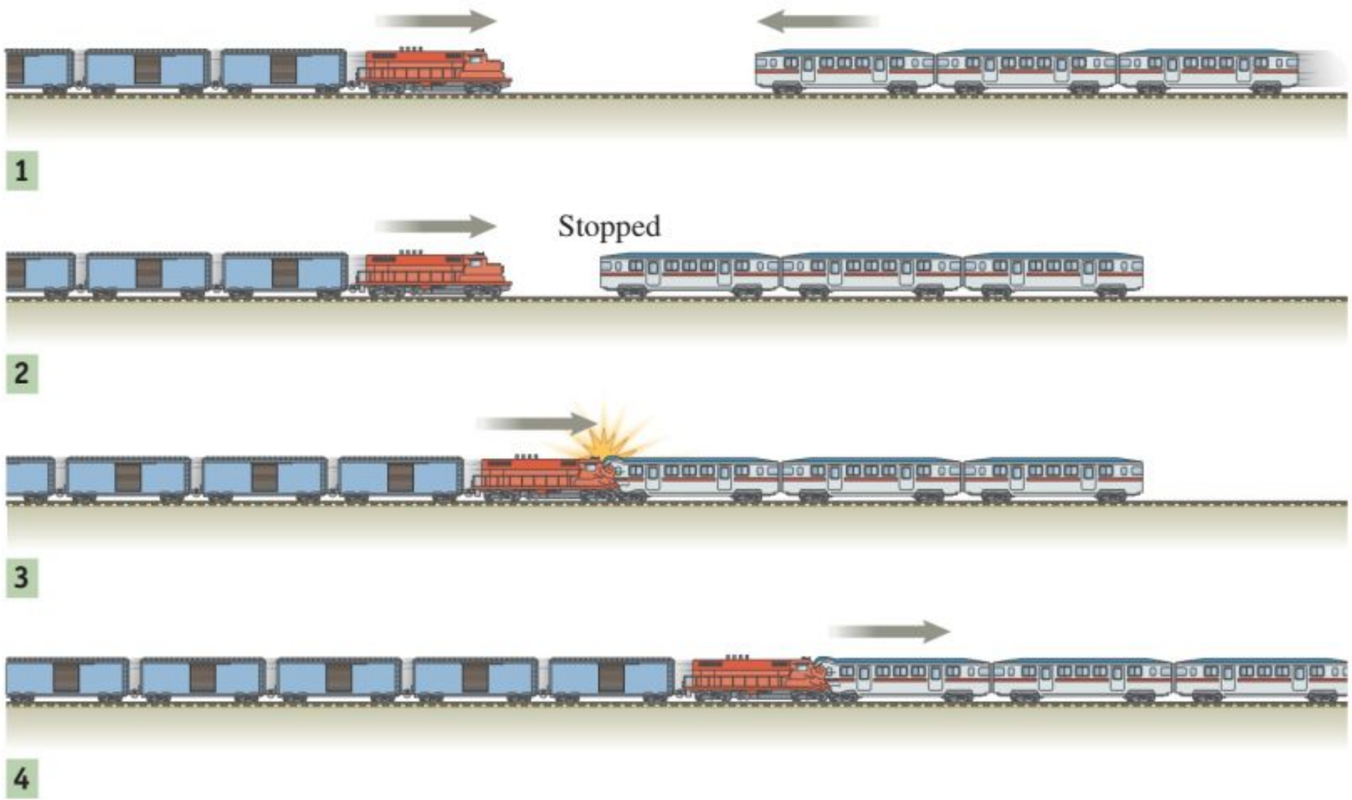
Isaac Newton was one of the most brilliant scientists in history. Before the age of 30, he formulated the basic concepts and laws of mechanics, discovered the law of universal gravitation, and invented the mathematical methods of calculus. As a consequence of his theories, Newton was able to explain the motions of the planets, the ebb and flow of the tides, and many special features of the motions of the Moon and the Earth. He also interpreted many fundamental observations concerning the nature of light. His contributions to physical theories dominated scientific thought for two centuries and remain important today.

5.2 Newton's First Law and Inertial Frames

FIGURE 5.1 Aerial view of emergency workers helping the injured from a train crash near Los Angeles (April 23, 2002).

CASE STUDY Train Collision

On April 23, 2002, a passenger train about 35 miles outside of Los Angeles was hit by a freight train (Fig. 5.1). The accident killed two people and injured more than 260, with all the injured being on the passenger train. Witnesses reported that those people who were seated facing backward suffered little or no injury. News reports said that the passenger train came to a quick stop before the collision and that the impact with the freight train pushed the passenger train 370 ft backward (Fig. 5.2).



1. Why did passengers seated facing backward fare better than those who were either standing or seated facing forward?
2. The passenger train was at rest before the collision and was pushed backward. What do those facts tell us about how hard the freight train pushed on the passenger train? Did the passenger train push on the freight train? If so, how hard did it push?

Newton's First Law of Motion

A body at rest remains at rest, or, if in motion, remains in motion at a constant velocity unless acted on by a net external force.

If no force acts on an object, then the object cannot accelerate.

Internal Versus External Forces

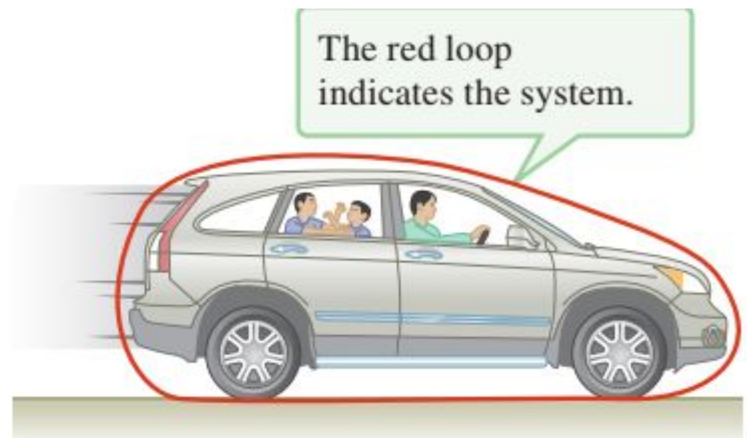
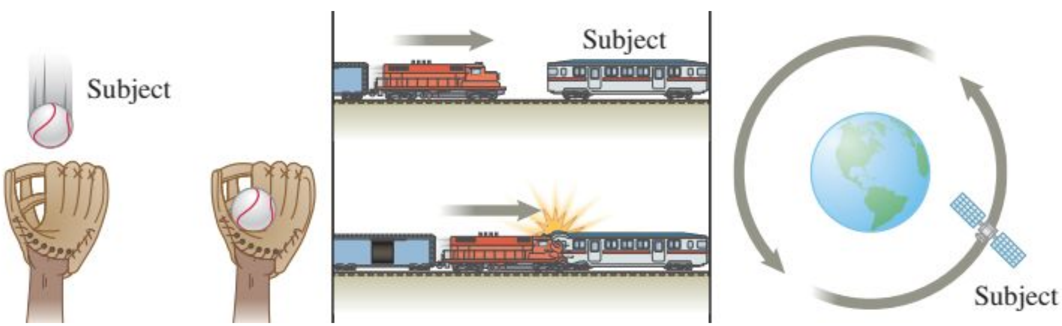


FIGURE 5.3 The people and the car have been chosen as the system (encircled in red). External forces due to the road or the Earth can accelerate the system. Internal forces such as the two children pushing on each other cannot.

Contact Versus Field Forces



Inertial Mass

Not all objects have the same inertia. It is, for instance, difficult to stop a runaway truck but easy to flip a quarter into the air. It is difficult to change the truck's velocity because the truck has a lot of inertia. The quarter, on the other hand, has little inertia, and it is therefore easy to change its velocity with just your thumb. The truck and quarter are different from each other in many ways—shape, size, and composition, to name just a few—but their difference in mass is what counts when we try to accelerate them. **Mass,** also known as **inertial mass,** is an intrinsic scalar property of any object. Mass measures the object's inertia. In SI units, mass is measured in kilograms. In the U.S. customary system, the unit of mass is the slug, a term we almost never use in everyday conversation.

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

Inertial Reference Frames

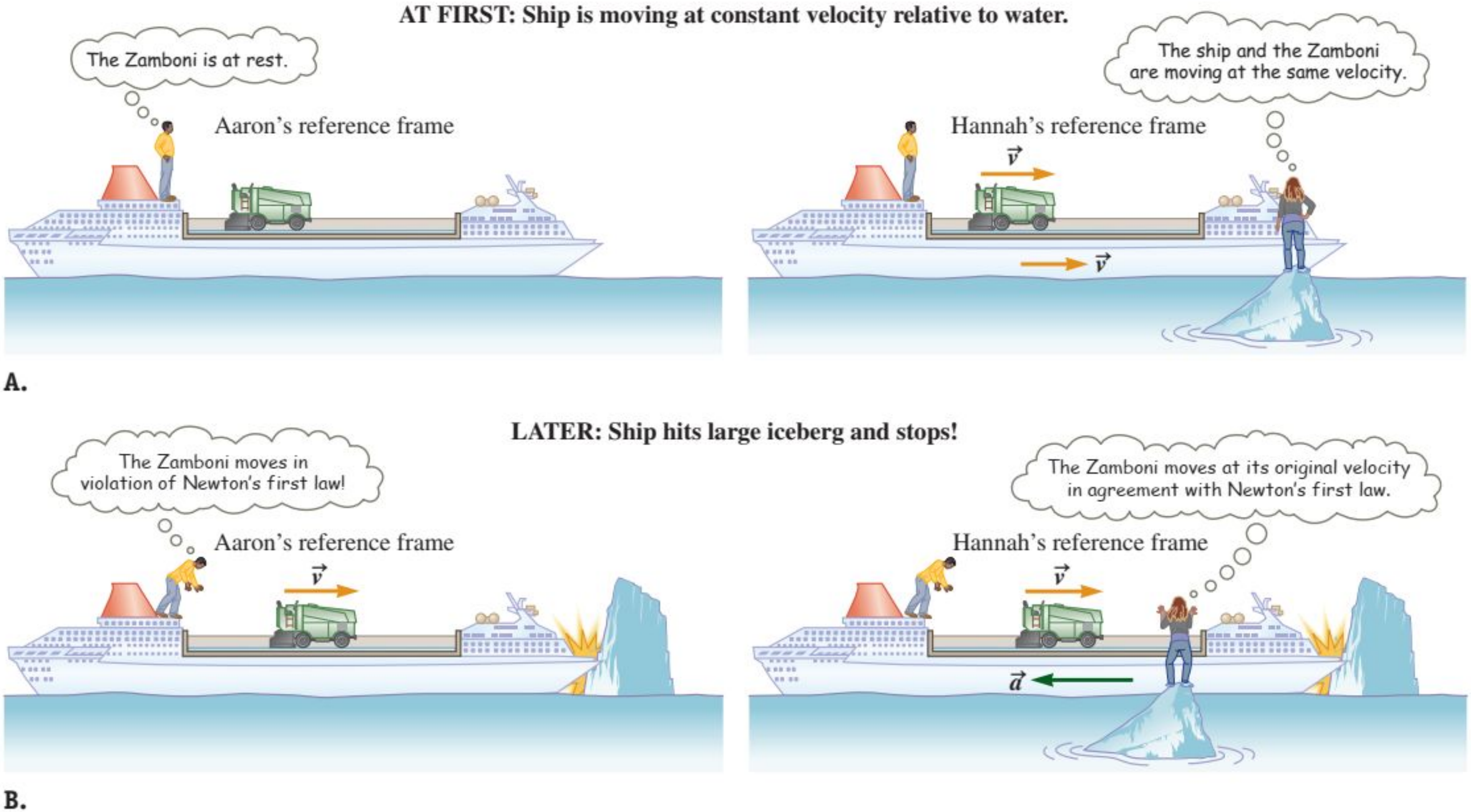
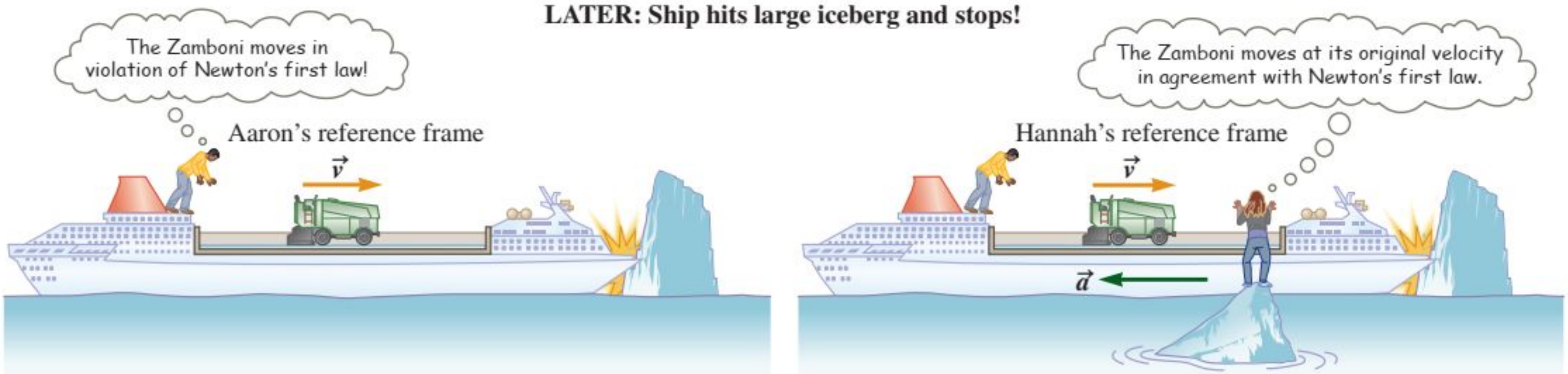


FIGURE 5.6 Two observers see a Zamboni machine on an ice rink aboard a cruise ship. **A.** At first, Aaron on the ship sees the Zamboni at rest. Hannah is on an iceberg, and she sees the Zamboni moving at the same velocity $\vec{v}$ as the ship. **B.** When the ship suddenly stops, Aaron sees the Zamboni move across the ice, and he cannot identify a force that caused the Zamboni's acceleration. Hannah on the iceberg notices that as the ship stops (accelerates to the left), the Zamboni continues moving rightward at its original velocity $\vec{v}$ until it reaches the wall (consistent with Newton's first law).



To Aaron, the Zamboni starts with zero velocity but then accelerates toward the rink wall. He cannot identify any force that could cause this acceleration. To him, the Zamboni moves in violation of Newton's first law. According to this law, the Zamboni should remain at rest unless acted upon by a force.

Reference frames in which Newton's first law is valid are called **inertial reference frames.** Inertial reference frames may move with constant velocity, but they do not accelerate. Accelerating frames are known as **noninertial reference frames,** and Newton's first law is not valid in them. In our example, the shipboard observer is in a noninertial reference frame once the ship starts slowing down.

As long as no external force acts on an object, it is always possible to find an inertial reference frame in which the velocity of the object is zero. In other words, there is nothing special or "natural" about a state of rest.

5.4 Newton's Second Law

1. Rest is not a particularly special state; it is merely a special case of constant velocity.
2. A force is required to change an object's velocity.
3. Inertia is the tendency of an object to maintain its constant velocity. An object's inertia is determined by its mass. The more mass (inertia) an object has, the more difficult it is to accelerate that object.

The net force on an object is zero if and only if the acceleration of the object is also zero.

$$\vec{\mathbf{F}} = F_x\hat{\mathbf{i}} + F_y\hat{\mathbf{j}} + F_z\hat{\mathbf{k}}.$$

$$\vec{\mathbf{a}} \propto \frac{\sum \vec{\mathbf{F}}}{m} \qquad \sum \vec{\mathbf{F}} = m\vec{\mathbf{a}} \qquad \sum F_x = ma_x \qquad \sum F_y = ma_y \qquad \sum F_z = ma_z$$

Newton's second law is used to define a unit of force. If a single force is applied to a standard mass of 1 kg such that the mass accelerates at 1 m/s^2, the applied force is defined to be 1 newton (1 N):

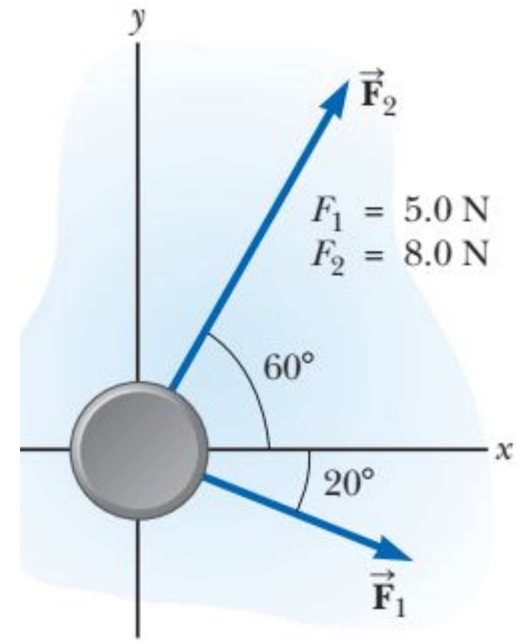
$$1\text{ N} \equiv (1\text{ kg})(1\text{ m/s}^2) = 1\text{ kg}\cdot\text{m/s}^2 \tag{5.3}$$

In U.S. customary units, force is measured in pounds:

$$1\text{ lb} \equiv (1\text{ slug})(1\text{ ft/s}^2) = 4.45\text{ N}$$

Example 5.1 An Accelerating Hockey Puck AM

A hockey puck having a mass of 0.30 kg slides on the frictionless, horizontal surface of an ice rink. Two hockey sticks strike the puck simultaneously, exerting the forces on the puck shown in Figure 5.4. The force $\vec{\mathbf{F}}_1$ has a magnitude of 5.0 N, and is directed at $\theta = 20°$ below the x axis. The force $\vec{\mathbf{F}}_2$ has a magnitude of 8.0 N and its direction is $\phi = 60°$ above the x axis. Determine both the magnitude and the direction of the puck's acceleration.



Find the component of the net force acting on the puck in the y direction:

$$\sum F_y = F_{1y} + F_{2y} = F_1 \sin\theta + F_2 \sin\phi$$

Use Newton's second law in component form (Eq. 5.3) to find the x and y components of the puck's acceleration:

$$a_x = \frac{\sum F_x}{m} = \frac{F_1 \cos\theta + F_2 \cos\phi}{m}$$

$$a_y = \frac{\sum F_y}{m} = \frac{F_1 \sin\theta + F_2 \sin\phi}{m}$$

Substitute numerical values:

$$a_x = \frac{(5.0\text{ N})\cos(-20°) + (8.0\text{ N})\cos(60°)}{0.30\text{ kg}} = 29\text{ m/s}^2$$

$$a_y = \frac{(5.0\text{ N})\sin(-20°) + (8.0\text{ N})\sin(60°)}{0.30\text{ kg}} = 17\text{ m/s}^2$$

Find the magnitude of the acceleration:

$$a = \sqrt{(29\text{ m/s}^2)^2 + (17\text{ m/s}^2)^2} = \boxed{34\text{ m/s}^2}$$

Find the direction of the acceleration relative to the positive x axis:

$$\theta = \tan^{-1}\left(\frac{a_y}{a_x}\right) = \tan^{-1}\left(\frac{17}{29}\right) = \boxed{31°}$$

Finalize The vectors in Figure 5.4 can be added graphically to check the reasonableness of our answer. Because the acceleration vector is along the direction of the resultant force, a drawing showing the resultant force vector helps us check the validity of the answer. (Try it!)

WHAT IF? Suppose three hockey sticks strike the puck simultaneously, with two of them exerting the forces shown in Figure 5.4. The result of the three forces is that the hockey puck shows *no* acceleration. What must be the components of the third force?

Answer If there is zero acceleration, the net force acting on the puck must be zero. Therefore, the three forces must cancel. The components of the third force must be of equal magnitude and opposite sign compared to the components of the net force applied by the first two forces so that all the components add to zero. Therefore, $F_{3x} = -\sum F_x = -(0.30\text{ kg})(29\text{ m/s}^2) = -8.7\text{ N}$ and $F_{3y} = -\sum F_y = -(0.30\text{ kg})(17\text{ m/s}^2) = -5.2\text{ N}$.

Some Specific Forces

5.5 The Gravitational Force and Weight

Gravity Near the Earth's Surface

Gravity, or the **gravitational force** (the two terms are synonymous), is the field force that keeps us on the surface of the Earth and keeps the planets in orbit around the Sun. In general, any two objects that have mass exert an attractive gravitational force on each other. The closer the objects are together, the stronger their gravitational attraction. The general gravitational force between any two bodies is described in Chapter 7. For now, let's focus on the gravitational force exerted by the Earth on objects located near its surface.

$$\vec{F}_{\text{tot}} = \vec{F}_g = m\vec{a} \qquad \vec{a} = -g\hat{j}$$

$$w \equiv F_g = mg$$

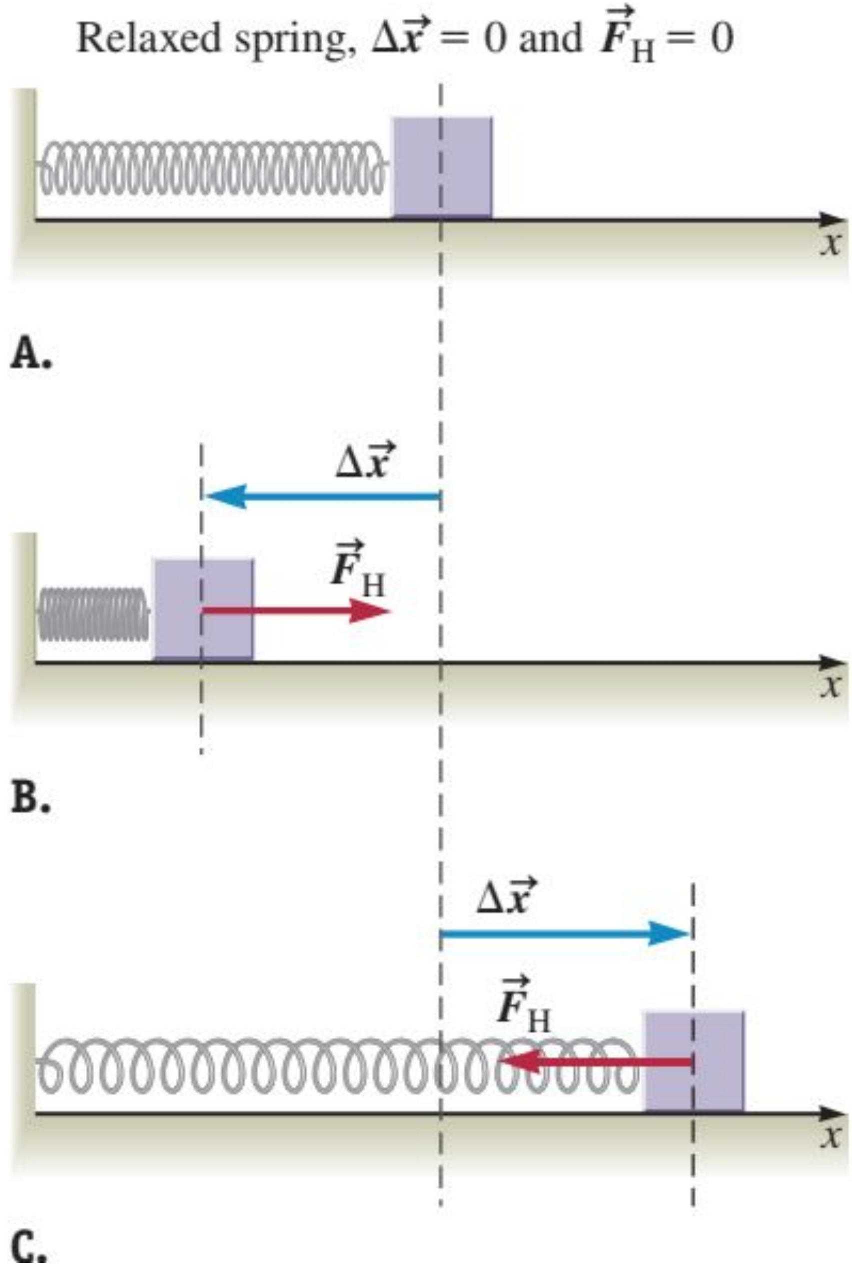
Weight

This is the equation for *weight*—the gravitational force on a mass m:

$$w = mg.$$

The free-fall acceleration near the surface of the Moon is $g_M = 0.16g$.

Spring Force



The force due to the spring is a **restoring force**; that is, it is directed so as to return ("restore") the spring to its relaxed state. The farther the spring is from being in its relaxed state, the stronger the restoring force. For many springs, the force exerted is proportional to how far the attached block is displaced from the relaxed position. These springs are said to obey **Hooke's law**. For a spring lying along the x axis, Hooke's law is mathematically expressed as

$$\vec{F}_{\mathrm{H}} = -k\,\Delta\vec{x} \tag{5.8}$$

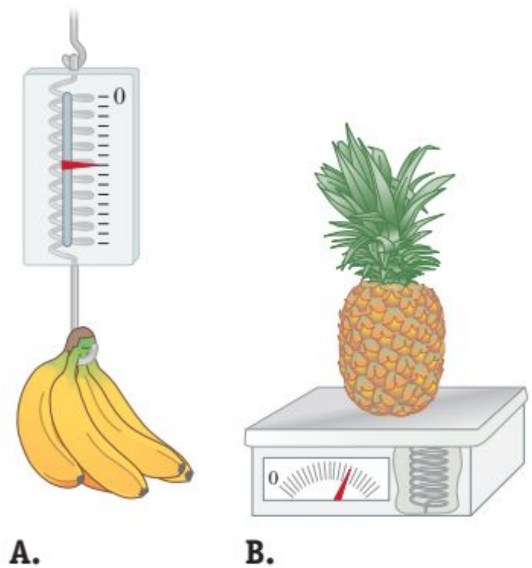
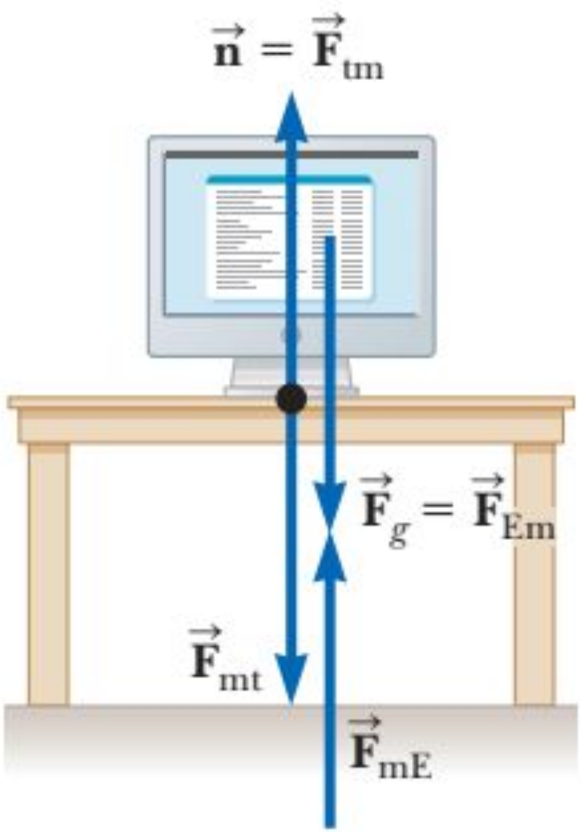
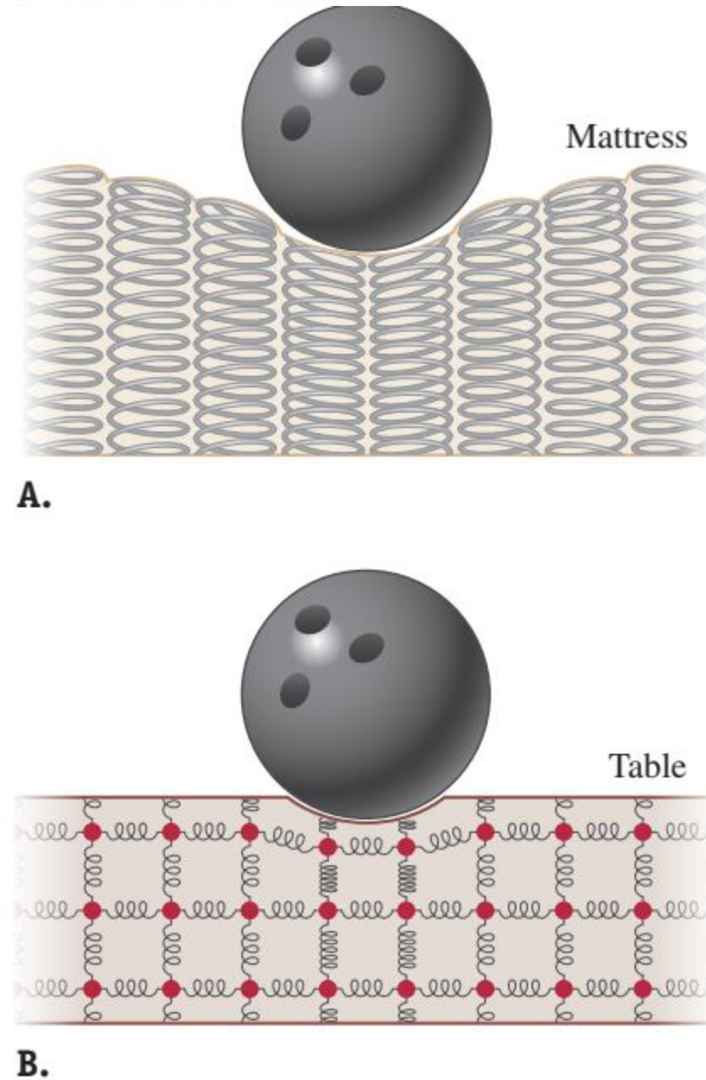


FIGURE 5.14 Spring scales are used to measure the apparent weight of an object. **A.** An object may hang from the spring. **B.** A pan scale employs a main spring (cutaway) connected to a system of levers (not shown).

Normal Force

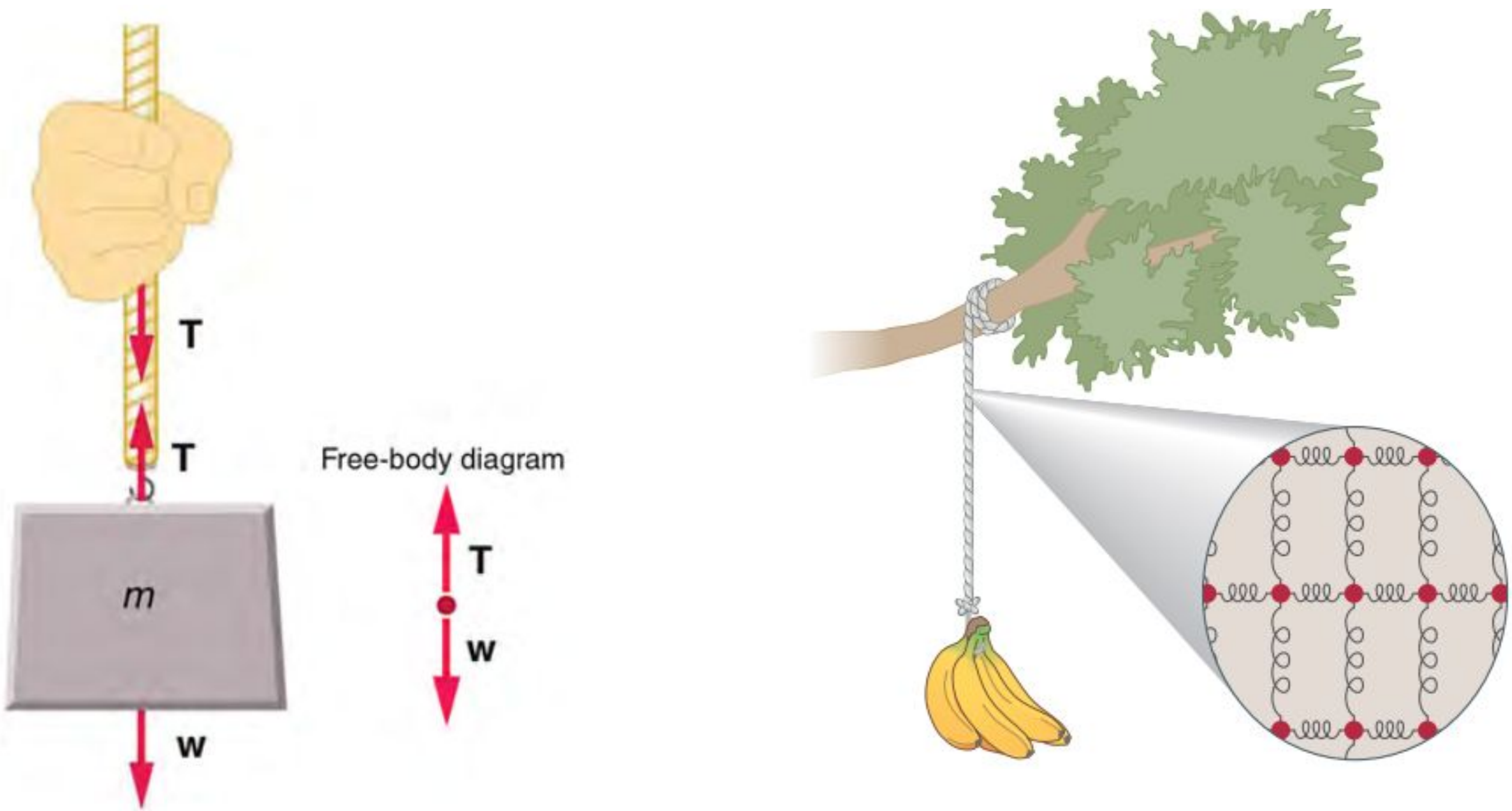
Whenever any object is in contact with a surface, the surface exerts a contact force on the object. The component of this contact force that is perpendicular to the surface is called the **normal force**. (*Normal* is another word for *perpendicular*.) The normal force gets its name because its direction is always perpendicular to the surface.





Tension Force

A **tension force** $\vec{F}_T$ is exerted by a taut rope, cable, or similar cord such as the rope pulling on the bananas in Figure 5.16. The rope must be in contact with the object to exert a tension force. Because the rope pulls on the object, the tension force is directed along the rope. In Figure 5.16, the rope pulls upward on the bananas. The magnitude of the tension force is called the **tension**.



Free-Body Diagrams

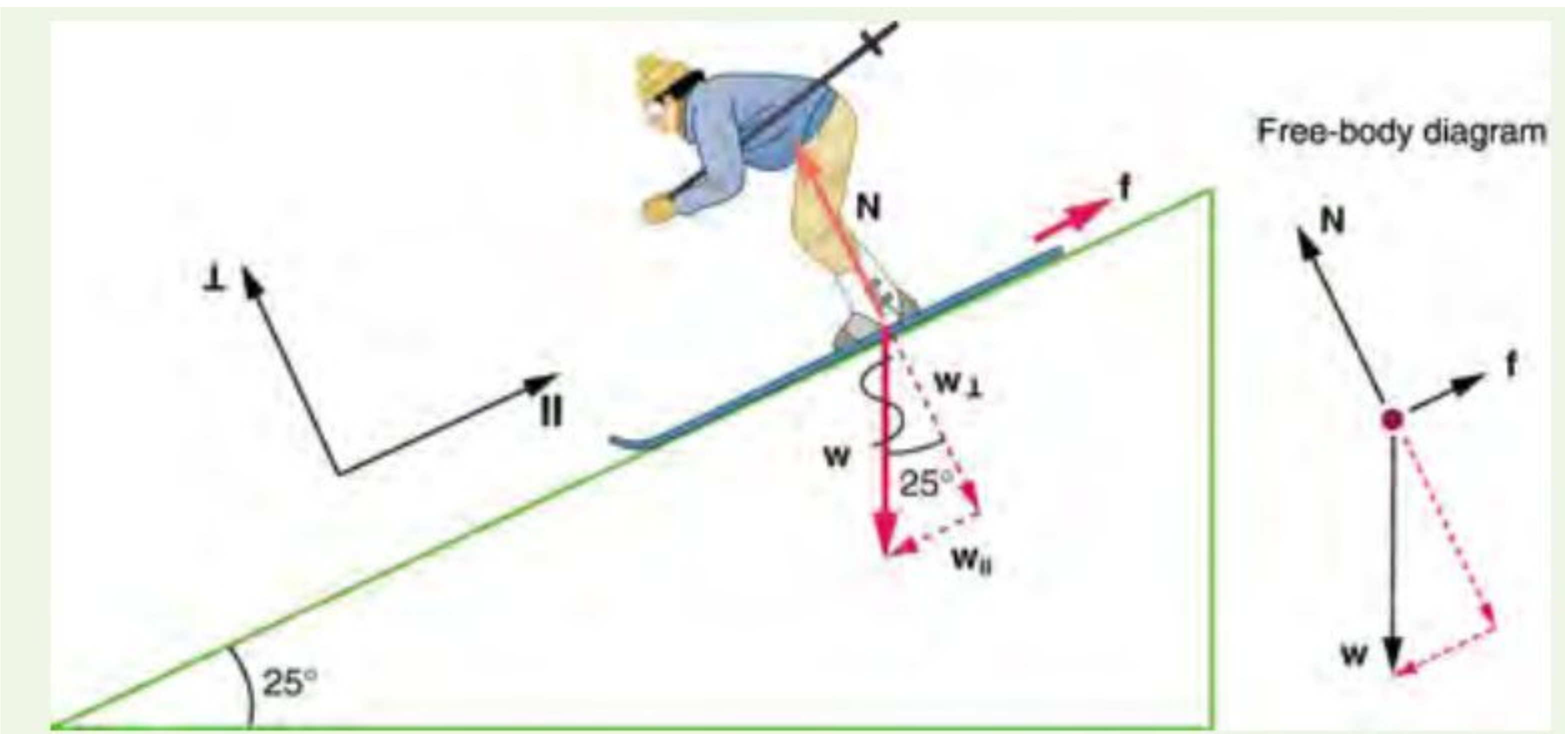
Element 1. **A simple representation of a subject.** We will continue to use the particle model for all objects until Chapter 13. Until then, represent any object (or system) by a dot.

Element 2. **Clearly labeled vector representations** of all the external forces exerted on the subject. In most cases, the tails of the vectors should be on the subject. To make sure that you don't miss any force exerted on the subject, consult Table 5.1 and decide which of the five forces are present. Make your decision based on whether or not the source of a particular force is present in the situation.

Element 3. A clearly labeled **coordinate system.** Picking a good coordinate system comes with practice. One helpful tip is to choose one axis to be parallel to the subject's acceleration.

Element 4. **An indication of the acceleration.** If relevant, draw a vector arrow indicating the direction of the subject's acceleration, but visually different from the arrows representing the force vectors. For example, you might use a dashed line or a different color. If the subject's acceleration is zero, note that on the diagram.

Free-Body Diagrams



5.6 Newton's Third Law

Unlike Newton's first two laws, which deal with forces acting on a single subject, Newton's third law is concerned with the forces between two objects that interact with each other. Conceptually, Newton's third law states that if two objects A and B interact, the force exerted by A on B is equal in magnitude to the force exerted by B on A but in the opposite direction.

NEWTON'S THIRD LAW OF MOTION If object *A* exerts a force on object *B* (an "action"), then object *B* exerts a force on object *A* (a "reaction"). These two forces have the same magnitude but are opposite in direction. These two forces act on *different* objects.

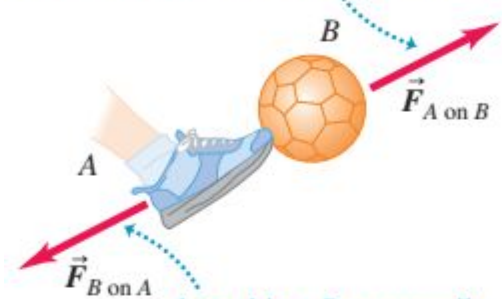
Newton's third law: When two objects *A* and *B* exert forces on each other ...

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

... the two forces have the same magnitude but opposite directions.

Note: The two forces act on *different* objects.

If object *A* exerts force $\vec{F}_{A \text{ on } B}$ on object *B* (for example, a foot kicks a ball) ...

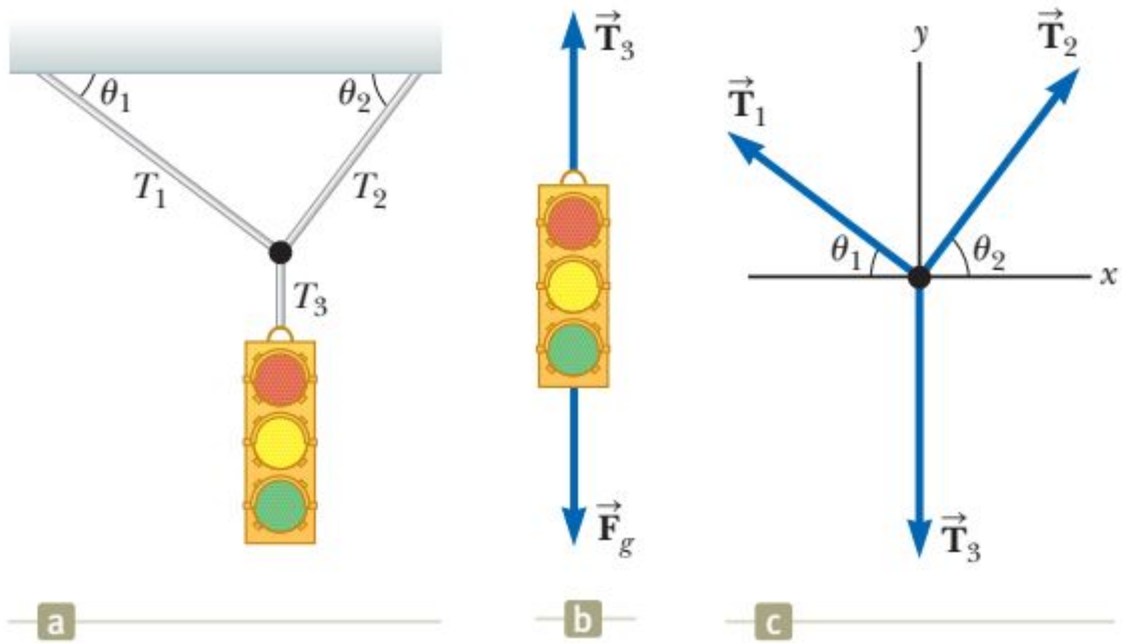


... then object *B* necessarily exerts force $\vec{F}_{B \text{ on } A}$ on object *A* (ball kicks back on foot).

The two forces have the same magnitude but opposite directions: $\vec{F}_{A \text{ on } B} = -\vec{F}_{B \text{ on } A}$.

Example 5.4 A Traffic Light at Rest AM

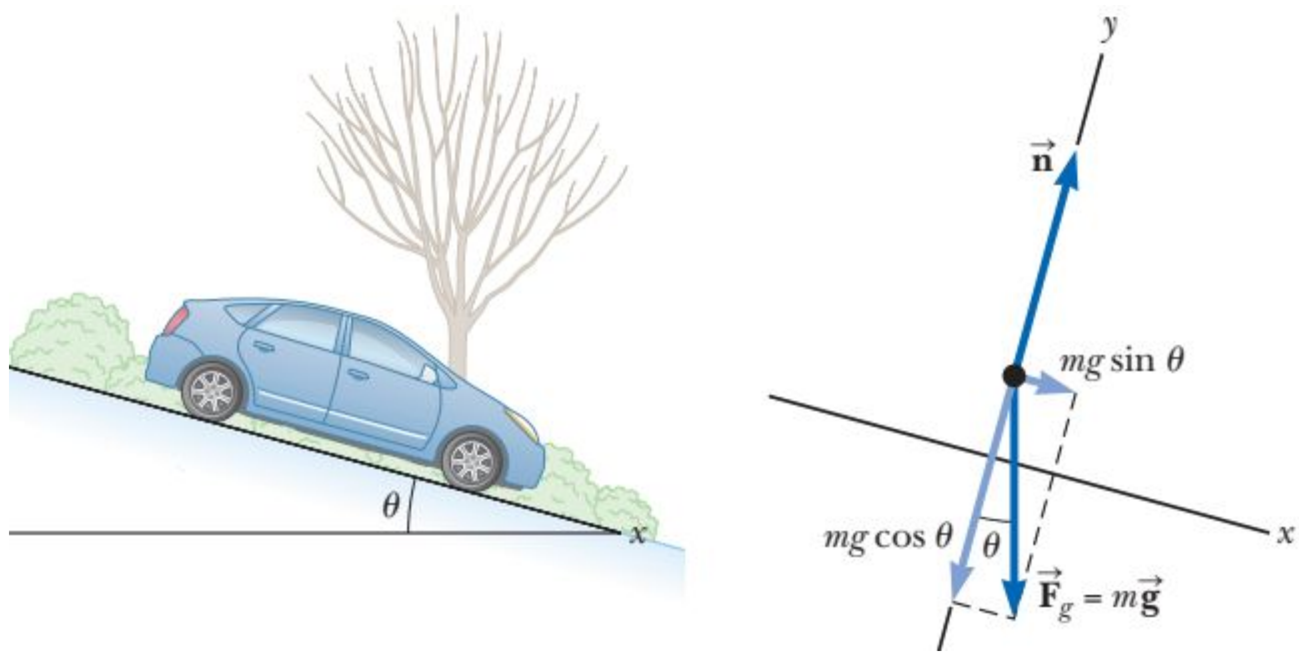
A traffic light weighing 122 N hangs from a cable tied to two other cables fastened to a support as in Figure 5.10a. The upper cables make angles of $\theta_1 = 37.0°$ and $\theta_2 = 53.0°$ with the horizontal. These upper cables are not as strong as the vertical cable and will break if the tension in them exceeds 100 N. Does the traffic light remain hanging in this situation, or will one of the cables break?



Example 5.6 The Runaway Car AM

A car of mass m is on an icy driveway inclined at an angle θ as in Figure 5.11a.

(A) Find the acceleration of the car, assuming the driveway is frictionless.

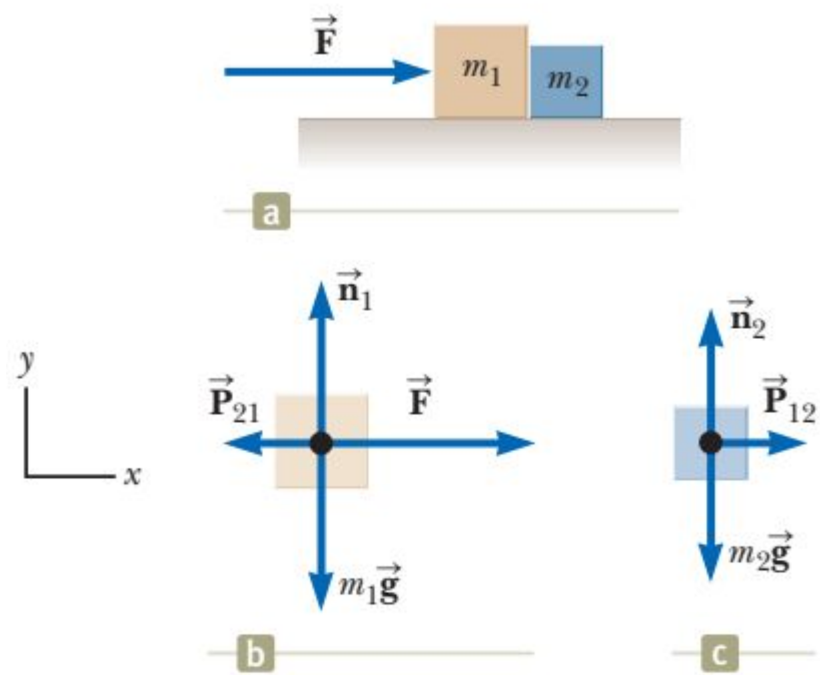


(B) Suppose the car is released from rest at the top of the incline and the distance from the car's front bumper to the bottom of the incline is d. How long does it take the front bumper to reach the bottom of the hill, and what is the car's speed as it arrives there?

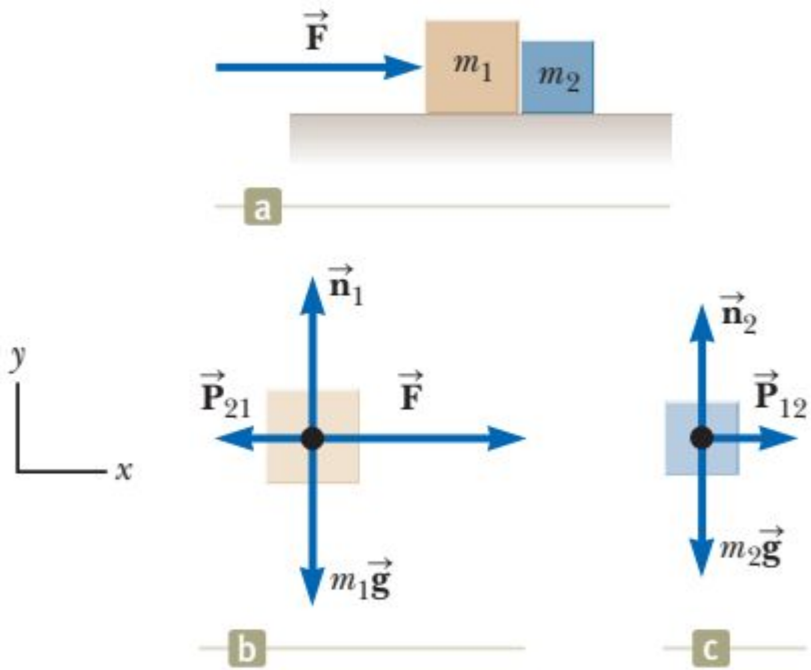
Example 5.7 One Block Pushes Another AM

Two blocks of masses m_1 and m_2, with $m_1 > m_2$, are placed in contact with each other on a frictionless, horizontal surface as in Figure 5.12a. A constant horizontal force $\vec{\mathbf{F}}$ is applied to m_1 as shown.

(A) Find the magnitude of the acceleration of the system.



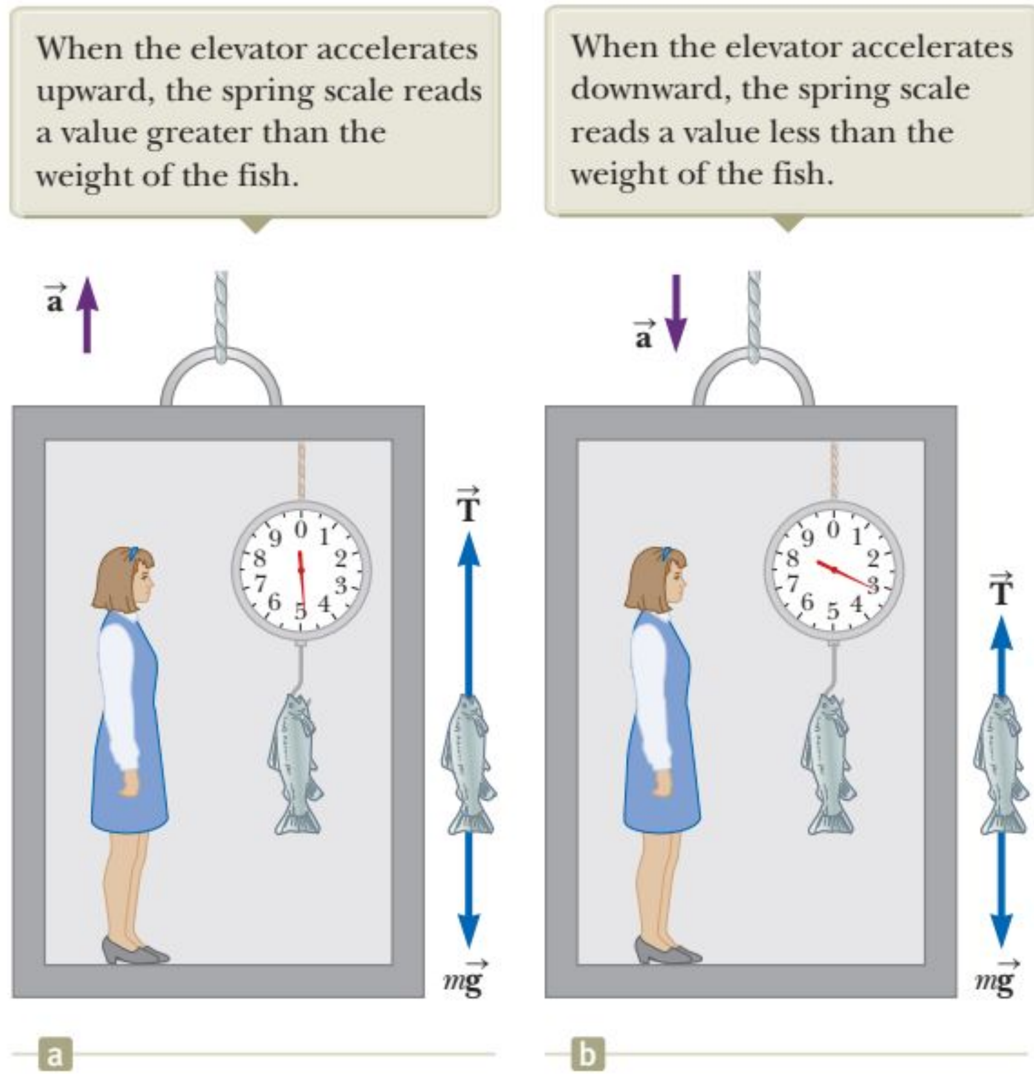
(B) Determine the magnitude of the contact force between the two blocks.



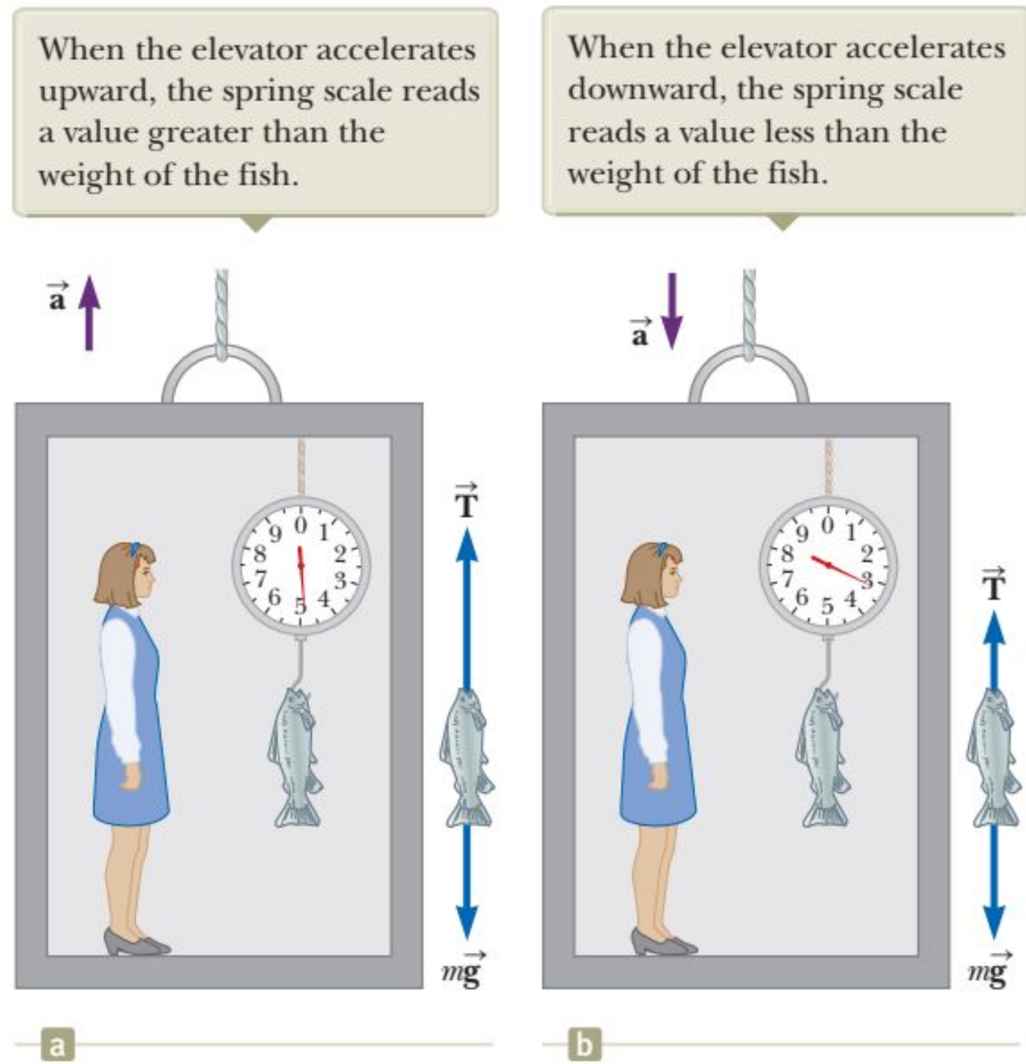
Example 5.8 Weighing a Fish in an Elevator AM

A person weighs a fish of mass m on a spring scale attached to the ceiling of an elevator as illustrated in Figure 5.13.

(A) Show that if the elevator accelerates either upward or downward, the spring scale gives a reading that is different from the weight of the fish.

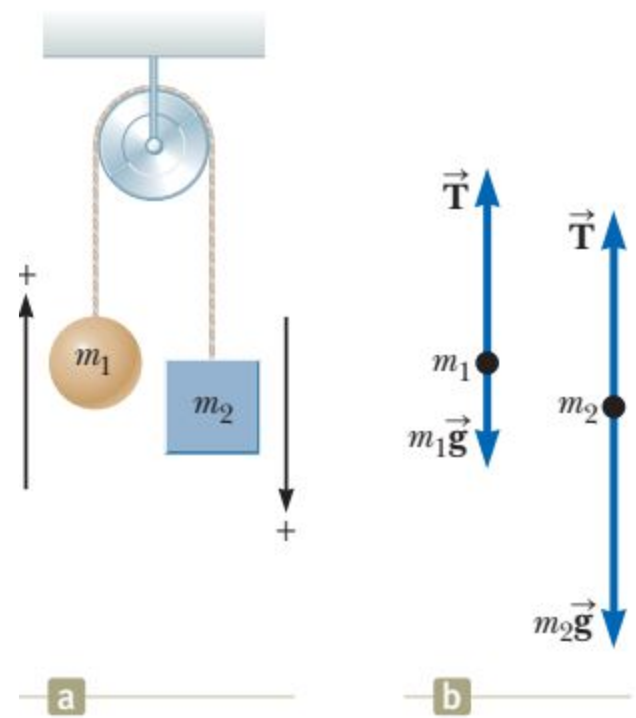


(B) Evaluate the scale readings for a 40.0-N fish if the elevator moves with an acceleration $a_y = \pm 2.00\ \mathrm{m/s^2}$



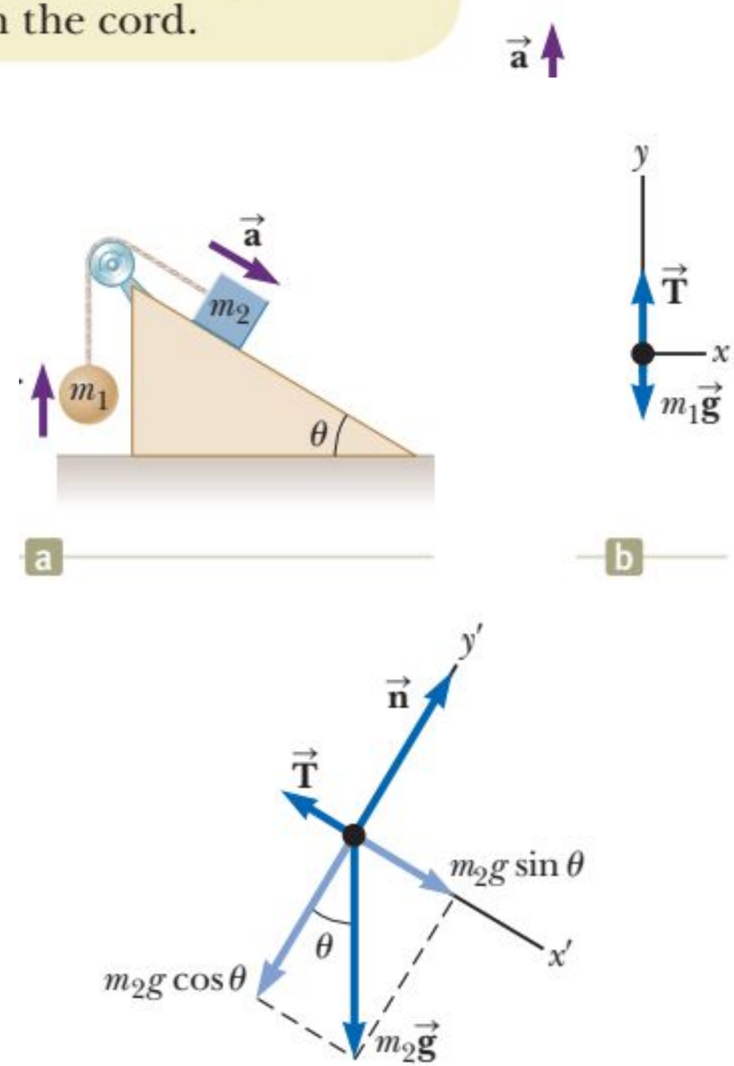
Example 5.9 The Atwood Machine AM

When two objects of unequal mass are hung vertically over a frictionless pulley of negligible mass as in Figure 5.14a, the arrangement is called an *Atwood machine*. The device is sometimes used in the laboratory to determine the value of g. Determine the magnitude of the acceleration of the two objects and the tension in the lightweight string.

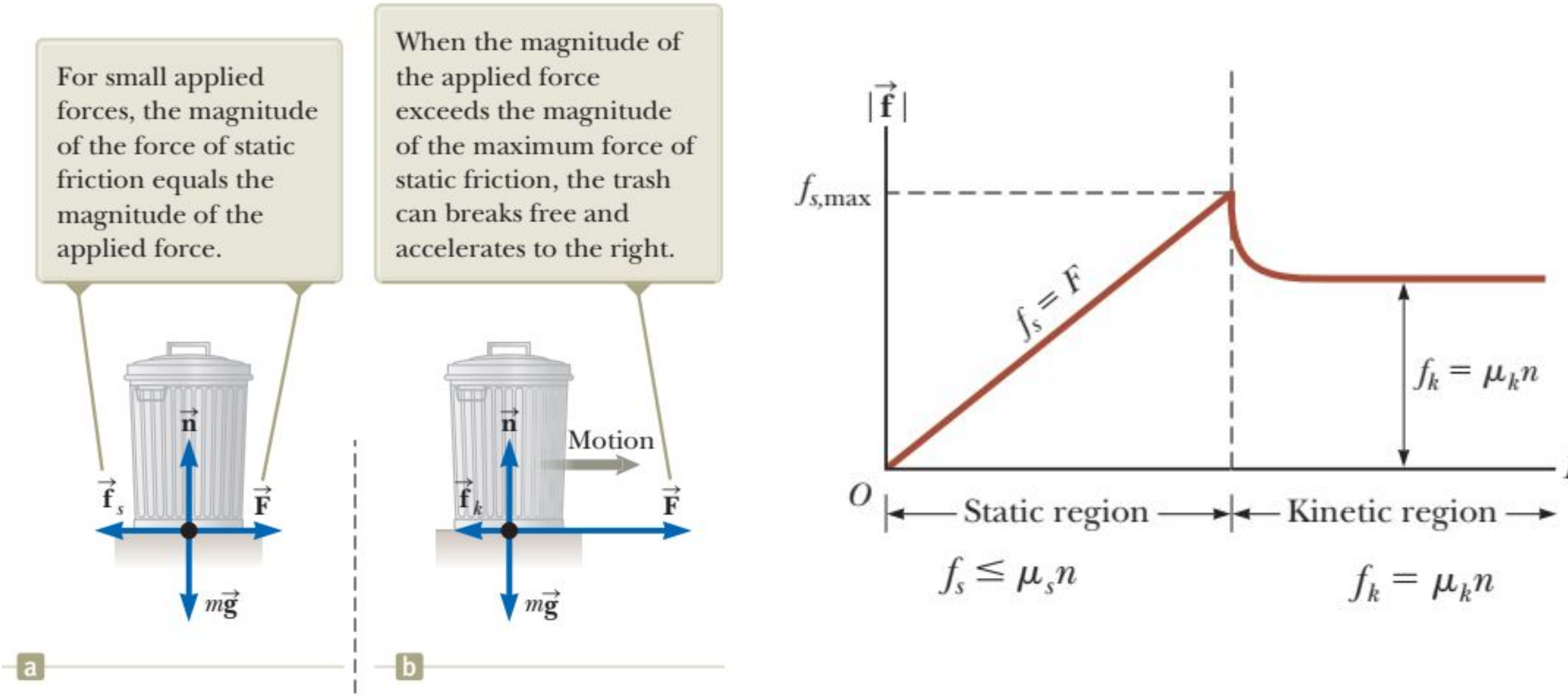


Example 5.10 Acceleration of Two Objects Connected by a Cord

A ball of mass m_1 and a block of mass m_2 are attached by a lightweight cord that passes over a frictionless pulley of negligible mass as in Figure 5.15a. The block lies on a frictionless incline of angle θ. Find the magnitude of the acceleration of the two objects and the tension in the cord.

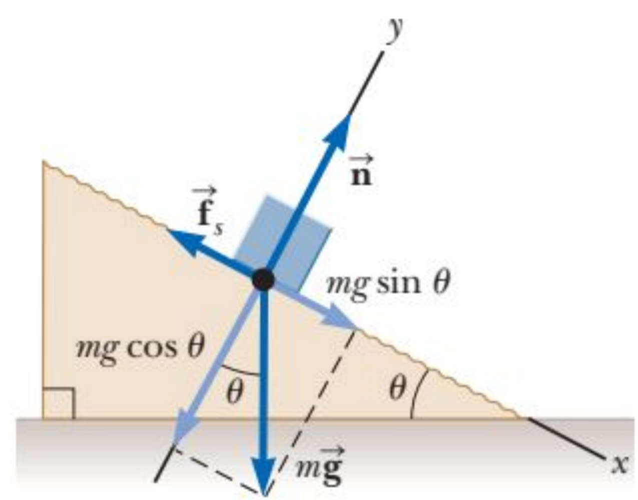


5.8 Forces of Friction



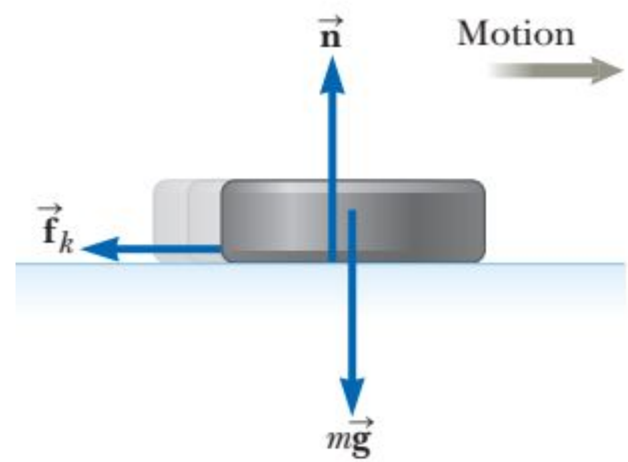
Example 5.11 Experimental Determination of μ_s and μ_k AM

The following is a simple method of measuring coefficients of friction. Suppose a block is placed on a rough surface inclined relative to the horizontal as shown in Figure 5.18. The incline angle is increased until the block starts to move. Show that you can obtain μ_s by measuring the critical angle θ_c at which this slipping just occurs.



Example 5.12 The Sliding Hockey Puck AM

A hockey puck on a frozen pond is given an initial speed of 20.0 m/s. If the puck always remains on the ice and slides 115 m before coming to rest, determine the coefficient of kinetic friction between the puck and ice.



Example 5.13 Acceleration of Two Connected Objects When Friction Is Present

A block of mass m_2 on a rough, horizontal surface is connected to a ball of mass m_1 by a lightweight cord over a lightweight, frictionless pulley as shown in Figure 5.20a. A force of magnitude F at an angle θ with the horizontal is applied to the block as shown, and the block slides to the right. The coefficient of kinetic friction between the block and surface is μ_k. Determine the magnitude of the acceleration of the two objects.