Slide 1

THIRD EDITION

college physics
a strategic approach

knight · jones · field

Lecture Presentation

Chapter 4

Forces and Newton's Laws of Motion

Slide 2

Chapter 4 Forces and Newton's Laws of Motion

Chapter Goal: To establish a connection between force and motion.

Slide 3

Chapter 4 Preview
Looking Ahead

Forces

A force is a push or a pull. It is an interaction between two objects, the **agent** (the woman) and the **object** (the car).

In this chapter, you'll learn how to identify different forces, and you'll learn their properties.

Forces and Motion

Acceleration is caused by forces. A forward acceleration of the sled requires a forward force.

A larger acceleration requires a larger force. You'll learn this connection between force and motion, part of Newton's second law.

Reaction Forces

The hammer exerts a downward force on the nail. Surprisingly, the nail exerts an equal force on the hammer, directed upward.

You'll learn how to identify and reason with **action/reaction pairs** of forces.

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Slide 4

Reading Question 4.1

If you are not wearing a seat belt and the car you are driving hits a fixed barrier, you will hit the steering wheel with some force. This is because

- A. The force of the collision has thrown you forward.
- B. The steering wheel has been pushed back toward you.
- C. You continue moving even after the car has stopped.

Reading Question 4.1

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- A. The force of the collision has thrown you forward.
- B. The steering wheel has been pushed back toward you.
- ✔C. You continue moving even after the car has stopped.

Reading Question 4.2

If you stand on a trampoline, it depresses under your weight. When you stand on a hard stone floor,

- A. The floor does not deform under your weight; it is too stiff.
- B. The floor deforms—very slightly—under your weight.
- C. The floor deforms a slight amount if you are heavy enough.

Reading Question 4.2

If you stand on a trampoline, it depresses under your weight. When you stand on a hard stone floor,

- A. The floor does not deform under your weight; it is too stiff.
- ✔B. The floor deforms—very slightly—under your weight.
- C. The floor deforms a slight amount if you are heavy enough.

Reading Question 4.4

If you are standing on the floor, motionless, what are the forces that act on you?

- A. Weight force
- B. Weight force and normal force
- C. Normal force and friction force
- D. Weight force and tension force

Reading Question 4.4

If you are standing on the floor, motionless, what are the forces that act on you?

    A. Weight force
✔B. Weight force and normal force
    C. Normal force and friction force
    D. Weight force and tension force

Reading Question 4.5

A skydiver has reached terminal velocity—she now falls at a constant speed, so her acceleration is zero. Is there a net force on her? If so, what is the direction?

    A. There is a net force directed upward.
    B. There is no net force.
    C. There is a net force directed downward.

Reading Question 4.5

A skydiver has reached terminal velocity—she now falls at a constant speed, so her acceleration is zero. Is there a net force on her? If so, what is the direction?

    A. There is a net force directed upward.
✔B. There is no net force.
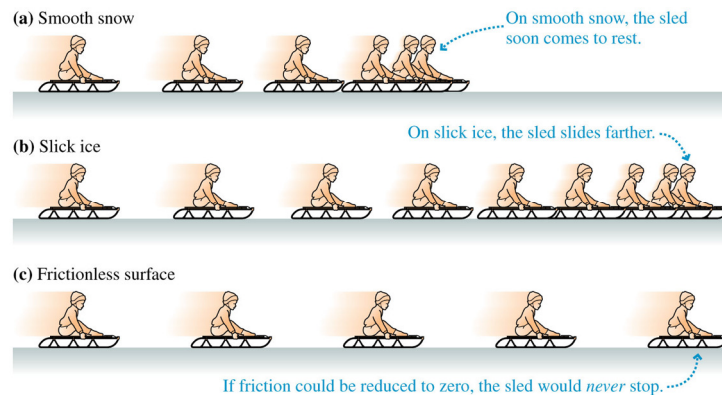   C. There is a net force directed downward.

Reading Question 4.6

An action/reaction pair of forces

    A. Points in the same direction.
    B. Acts on the same object.
    C. Are always long-range forces.
    D. Acts on two different objects.

Reading Question 4.6

An action/reaction pair of forces

A. Points in the same direction.
B. Acts on the same object.
C. Are always long-range forces.
✔ D. Acts on two different objects.

Section 4.1 Motion and Forces

What Causes Motion?

(a) Smooth snow — On smooth snow, the sled soon comes to rest.

(b) Slick ice — On slick ice, the sled slides farther.

(c) Frictionless surface — If friction could be reduced to zero, the sled would *never* stop.

- In the absence of friction, **if the sled is moving, it will stay in motion.**

What Causes Motion?

Newton's first law An object has no forces acting on it. If it is at rest, it will remain at rest. If it is moving, it will continue to move in a straight line at a constant speed.

What Is a Force?

- A **force** is a *push* or a *pull*.

- **A force acts on an object.**

- Every force has an **agent**, something that acts or pushes or pulls.

What Is a Force?

- A **force** is a *vector*. The general symbol for a force is the vector symbol $\vec{F}$. The size or strength of such a force is its magnitude F.

- **Contact forces** are forces that act on an object by touching it at a point of contact.

- **Long-range forces** are forces that act on an object without physical contact.
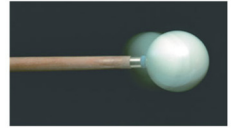
Force Vectors

TACTICS BOX 4.1 Drawing force vectors

❶ Represent the object as a particle.

❷ Place the *tail* of the force vector on the particle.

❸ Draw the force vector as an arrow pointing in the direction that the force acts, and with a length proportional to the size of the force.

❹ Give the vector an appropriate label.

$\vec{F}$

Exercise 1

Text: p. 100

Force Vectors

Pictorial representation of box

The rope is the agent.

Particle representation of box

Box

Pulling force of rope $\vec{T}$

Box

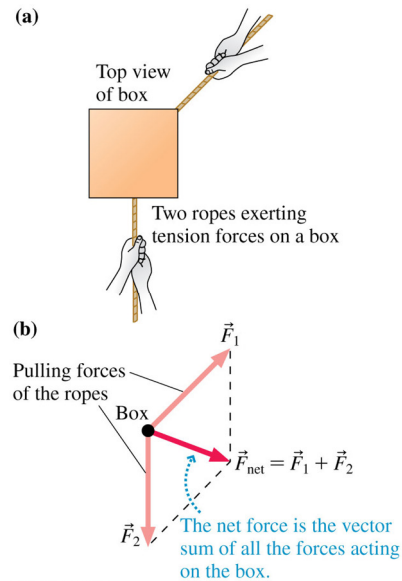Long-range force of gravity $\vec{w}$

Earth is the agent.
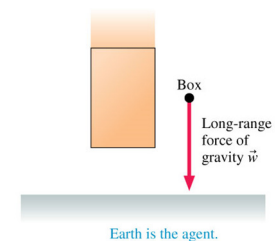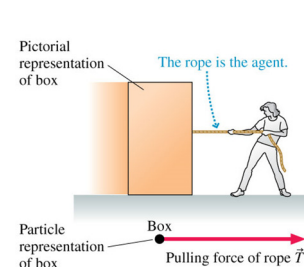
Combining Forces

- Experiments show that when several forces $\vec{F}_1$, $\vec{F}_2$, $\vec{F}_3$,… are exerted on an object, the combine to form a **net force** that is the *vector sum* of all the forces:
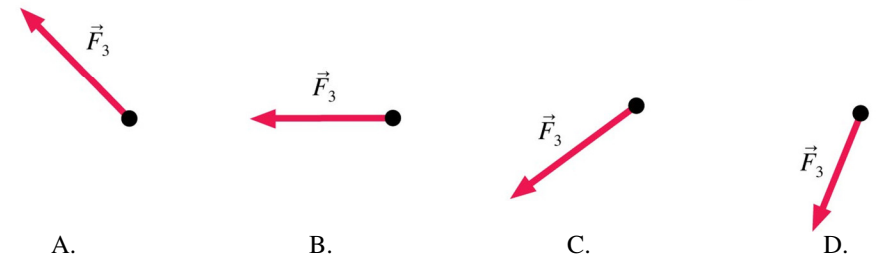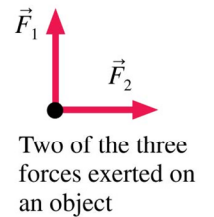
$$\vec{F}_{\text{net}} = \vec{F}_1 + \vec{F}_2 + \vec{F}_3 + \cdots$$

- The net force is sometimes called the resultant force. It is not a new force. Instead, we should think of the original forces being *replaced* by $\vec{F}_{\text{net}}$.
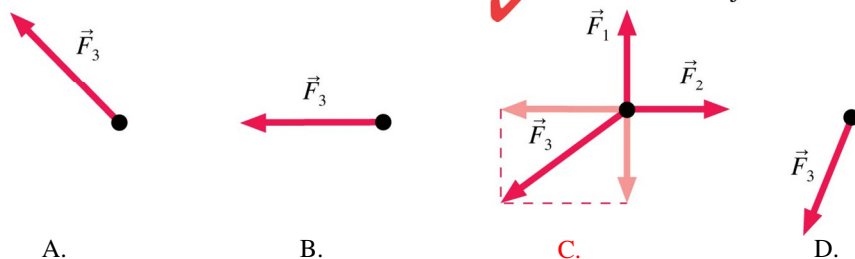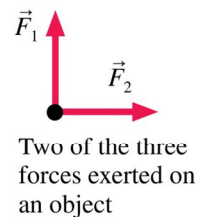
(a)

Top view of box

Two ropes exerting tension forces on a box

(b)

$\vec{F}_1$

Pulling forces of the ropes

Box

$\vec{F}_{\text{net}} = \vec{F}_1 + \vec{F}_2$

$\vec{F}_2$

The net force is the vector sum of all the forces acting on the box.

QuickCheck 4.1

The net force on an object points to the left. Two of three forces are shown. Which is the missing third force?

$\vec{F}_1$

$\vec{F}_2$

Two of the three forces exerted on an object

$\vec{F}_3$

$\vec{F}_3$

$\vec{F}_3$

$\vec{F}_3$

A.   B.   C.   D.

QuickCheck 4.1

The net force on an object points to the left. Two of three forces are shown. Which is the missing third force?

$\vec{F}_1$

$\vec{F}_2$

Two of the three forces exerted on an object

✔

$\vec{F}_3$

$\vec{F}_3$

$\vec{F}_1$

$\vec{F}_2$

$\vec{F}_3$

$\vec{F}_3$

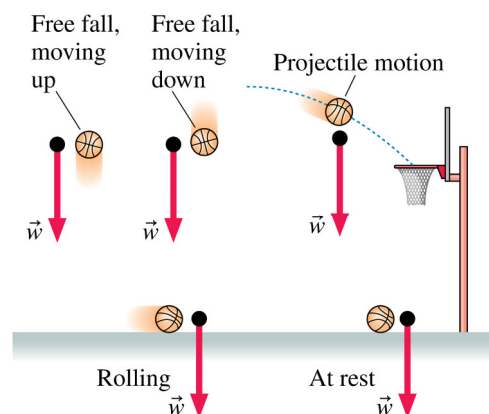A.   B.   C.   D.

Vertical components cancel

Section 4.2 A Short Catalog of Forces

Weight

- The gravitational pull of the earth on an object on or near the surface of the earth is called **weight**.

- The agent for the weight forces is the *entire earth* pulling on an object.

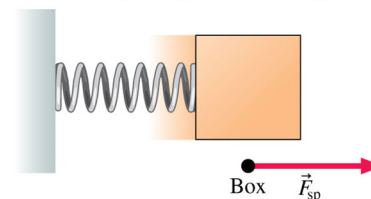- **An object's weight vector always points vertically downward,** no matter how the object is moving**.**

Free fall, moving up   Free fall, moving down   Projectile motion

$\vec{w}$ $\vec{w}$ $\vec{w}$

Rolling   At rest

$\vec{w}$ $\vec{w}$

Spring Force

(a) A compressed spring exerts a pushing force on an object.

(b) A stretched spring exerts a pulling force on an object.

Box $\vec{F}_{sp}$

$\vec{F}_{sp}$ Box
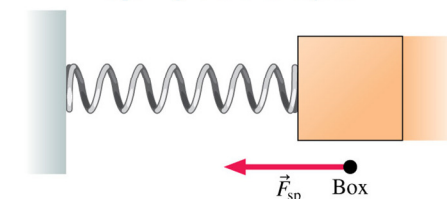
- Springs come in in many forms. When deflected, they push or pull with a spring force.

Tension Force

The rope exerts a tension force on the sled.
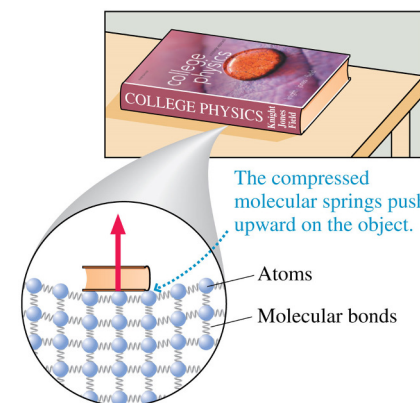
Sled $\vec{T}$
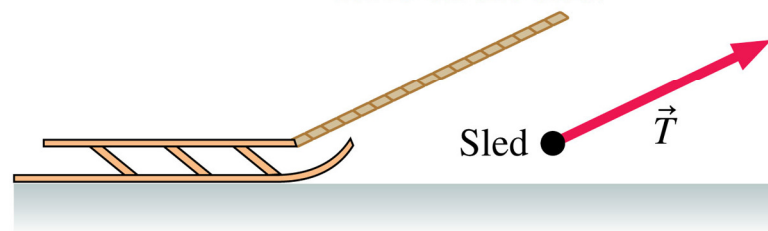
- When a string or rope or wire pulls on an object, it exerts a contact force that we call the **tension force**.

- **The direction of the tension force is always in the direction of the string or rope**.

Normal Force

- The force exerted on an object that is pressing against a surface is in a direction *perpendicular* to the surface.

- The **normal force** is the force exerted by a surface (the agent) against an object that is pressing against the surface.
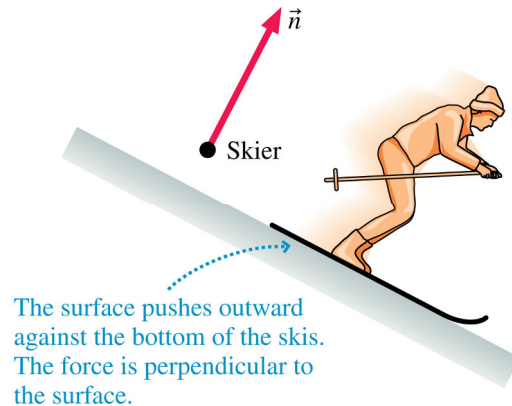
COLLEGE PHYSICS

The compressed molecular springs push upward on the object.

Atoms

Molecular bonds

Normal Force

- The normal force is responsible for the "solidness" of solids.
- The symbol for the normal force is $\vec{n}$.

The surface pushes outward against the bottom of the skis. The force is perpendicular to the surface.
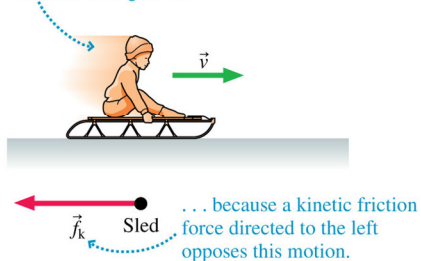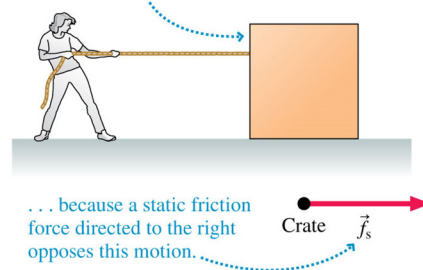
Friction

- Friction, like the normal force, is exerted by a surface.
- The frictional force is always parallel to the surface.
- *Kinetic friction,* denoted by $\vec{f}_k$, acts as an object slides across a surface. Kinetic friction is a force that always "opposes the motion."
- *Static friction,* denoted by $\vec{f}_s$, is the force that keeps an object "stuck" on a surface and prevents its motion relative to the surface. Static friction points in the direction necessary to *prevent* motion.

Friction

The sled is moving to the right but it is slowing down . . .

. . . because a kinetic friction force directed to the left opposes this motion.

The woman is pulling to the left, but the crate doesn't move . . .

. . . because a static friction force directed to the right opposes this motion.

Drag

- The force of a fluid (like air or water) on a moving object is called **drag**.
- Like kinetic friction, drag points opposite the direction of motion.
- **You can neglect air resistance in all problems unless a problem explicitly asks you to include it.**
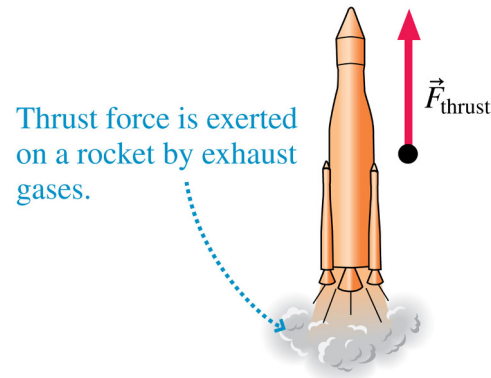
Air resistance is a significant force on falling leaves. It points opposite the direction of motion.
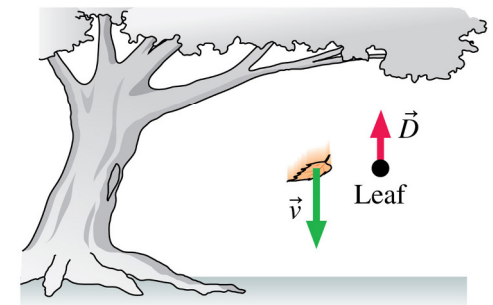
Thrust

- **Thrust** is a force that occurs when a jet or rocket engine expels gas molecules at high speed.
- **Thrust is a force opposite the direction in which the exhaust gas is expelled.**

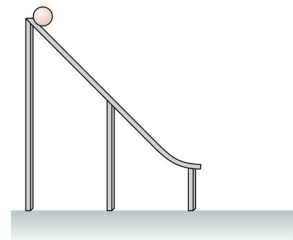Thrust force is exerted on a rocket by exhaust gases.

$\vec{F}_{\text{thrust}}$

Electric and Magnetic Forces

- Electricity and magnetism, like gravity, exert long-range forces.
- The forces of electricity and magnetism act on charged particles.
- These forces—and the forces inside the nucleus—won't be important for the dynamics problems we consider in the next several chapters.
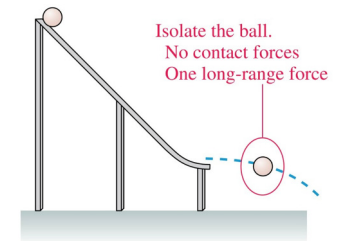
QuickCheck 4.2

A ball rolls down an incline and off a horizontal ramp. Ignoring air resistance, what force or forces act on the ball as it moves through the air just after leaving the horizontal ramp?

- A. The weight of the ball acting vertically down.
- B. A horizontal force that maintains the motion.
- C. A force whose direction changes as the direction of motion changes.
- D. The weight of the ball and a horizontal force.
- E. The weight of the ball and a force in the direction of motion.

QuickCheck 4.2

A ball rolls down an incline and off a horizontal ramp. Ignoring air resistance, what force or forces act on the ball as it moves through the air just after leaving the horizontal ramp?

Isolate the ball.
No contact forces
One long-range force

- ✔ A. The weight of the ball acting vertically down.
- B. A horizontal force that maintains the motion.
- C. A force whose direction changes as the direction of motion changes.
- D. The weight of the ball and a horizontal force.
- E. The weight of the ball and a force in the direction of motion.

QuickCheck 4.3

A steel beam hangs from a cable as a crane lifts the beam. What forces act on the beam?

- A. Gravity
- B. Gravity and tension in the cable
- C. Gravity and a force of motion
- D. Gravity and tension and a force of motion

QuickCheck 4.3

A steel beam hangs from a cable as a crane lifts the beam. What forces act on the beam?

- A. Gravity
- ✔ B. Gravity and tension in the cable
- C. Gravity and a force of motion
- D. Gravity and tension and a force of motion

QuickCheck 4.4

A bobsledder pushes her sled across horizontal snow to get it going, then jumps in. After she jumps in, the sled gradually slows to a halt. What forces act on the sled just after she's jumped in?

- A. Gravity and kinetic friction
- B. Gravity and a normal force
- C. Gravity and the force of the push
- D. Gravity, a normal force, and kinetic friction
- E. Gravity, a normal force, kinetic friction, and the force of the push

QuickCheck 4.4

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- A. Gravity and kinetic friction
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- C. Gravity and the force of the push
- ✔ D. Gravity, a normal force, and kinetic friction
- E. Gravity, a normal force, kinetic friction, and the force of the push

Section 4.3 Identifying Forces

Identifying Forces

Text: p. 105

Identifying Forces

TABLE 4.1 Common forces and their notation

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

Section 4.4 What Do Forces Do?

What Do Forces Do?

The experimental findings of the motion of objects acted on by constant forces are:

- **An object pulled with a constant force moves with a constant acceleration.**
- **Acceleration is directly proportional to force.**
- **Acceleration is *inversely proportional* to an object's mass.**

Example 4.4 Finding the mass of an unknown block

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

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

Example 4.4 Finding the mass of an unknown block (cont.)

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

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

or

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

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

Section 4.5 Newton's Second Law

Newton's Second Law

- **A force causes an object to accelerate.**

- **The acceleration a is directly proportional to the force F and inversely proportional to the mass m:**

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

- The direction of the acceleration is the same as the direction of the force:

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

Newton's Second Law

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

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

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

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

QuickCheck 4.9

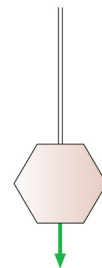An object on a rope is lowered at constant speed. Which is true?

Constant velocity
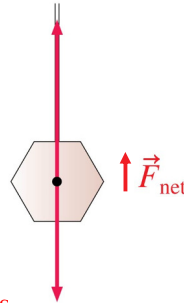Zero acceleration
$\vec{F}_{net} = \vec{0}$
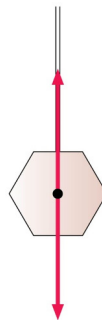
- A. The rope tension is greater than the object's weight.
- ✔ B. The rope tension equals the object's weight.
- C. The rope tension is less than the object's weight.
- D. The rope tension can't be compared to the object's weight.

QuickCheck 4.10

An object on a rope is lowered at a steadily decreasing speed. Which is true?

- A. The rope tension is greater than the object's weight.
- B. The rope tension equals the object's weight.
- C. The rope tension is less than the object's weight.
- D. The rope tension can't be compared to the object's weight.

QuickCheck 4.10

An object on a rope is lowered at a steadily decreasing speed. Which is true?

Decreasing downward velocity
Acceleration vector points up
$\vec{F}_{net}$ points up

$\uparrow \vec{F}_{net}$

✔ A. The rope tension is greater than the object's weight.
B. The rope tension equals the object's weight.
C. The rope tension is less than the object's weight.
D. The rope tension can't be compared to the object's weight.

Units of Force

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

The basic unit of force is called a *newton*. One **newton** is the force that causes a 1 kg mass to accelerate at 1 m/s^2.

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

Example 4.6 Racing down the runway

A Boeing 737—a small, short-range jet with a mass of 51,000 kg—sits at rest. The pilot turns the pair of jet engines to full throttle, and the thrust accelerates the plane down the runway. After traveling 940 m, the plane reaches its takeoff speed of 70 m/s and leaves the ground. What is the thrust of each engine?

Known
$x_i = 0$ m, $(v_x)_i = 0$ m/s
$x_f = 940$ m, $(v_x)_f = 70$ m/s
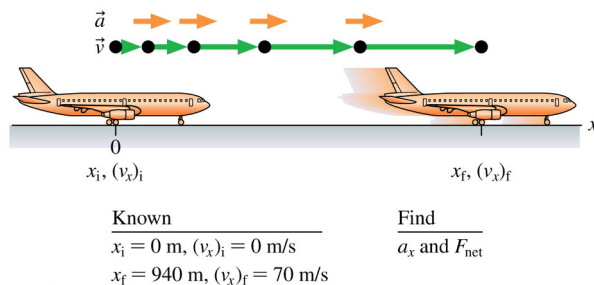
Find
a_x and F_{net}

Example 4.6 Racing down the runway (cont.)

PREPARE If we assume that the plane undergoes a constant acceleration (a reasonable assumption), we can use kinematics to find the magnitude of that acceleration. Then we can use Newton's second law to find the force—the thrust—that produced this acceleration. FIGURE 4.23 is a visual overview of the airplane's motion.

Known
$x_i = 0$ m, $(v_x)_i = 0$ m/s
$x_f = 940$ m, $(v_x)_f = 70$ m/s

Find
a_x and F_{net}
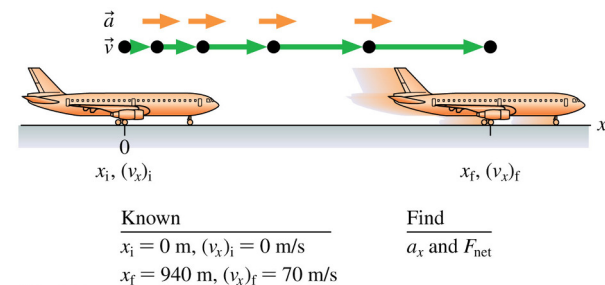
Example 4.6 Racing down the runway (cont.)

SOLVE We don't know how much time it took the plane to reach its takeoff speed, but we do know that it traveled a distance of 940 m. We can solve for the acceleration by using the third constant-acceleration equation in Synthesis 2.1:

$$(v_x)_f^2 = (v_x)_i^2 + 2a_x \Delta x$$

The displacement is $\Delta x = x_f - x_i = 940$ m, and the initial velocity is 0. We can rearrange the equation to solve for the acceleration:

$$a_x = \frac{(v_x)_f^2}{2 \Delta x} = \frac{(70 \text{ m/s})^2}{2(940 \text{ m})} = 2.61 \text{ m/s}^2$$

Example 4.6 Racing down the runway (cont.)

We've kept an extra significant figure because this isn't our final result—we are asked to solve for the thrust. We complete the solution by using Newton's second law:

$$F = ma_x = (51,000 \text{ kg})(2.61 \text{ m/s}^2) = 133,000 \text{ N}$$

The thrust of each engine is half of this total force:

Thrust of one engine = 67,000 N = 67 kN

Section 4.6 Free-Body Diagrams

Free-Body Diagrams

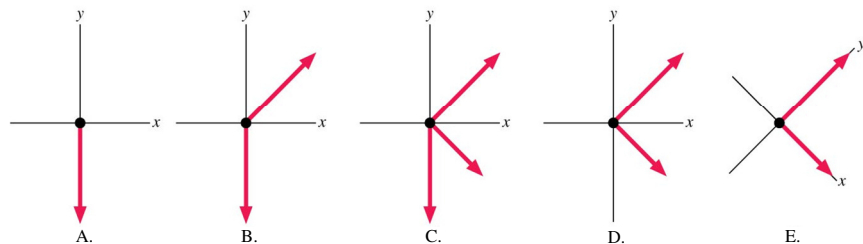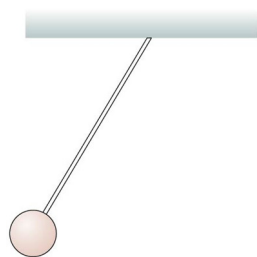**TACTICS BOX 4.3 Drawing a free-body diagram** (MP)

❶ **Identify all forces acting on the object.** This step was described in Tactics Box 4.2.

❷ **Draw a coordinate system.** Use the axes defined in your pictorial representation (Tactics Box 2.2). If those axes are tilted, for motion along an incline, then the axes of the free-body diagram should be similarly tilted.

❸ **Represent the object as a dot at the origin of the coordinate axes.** This is the particle model.

❹ **Draw vectors representing each of the identified forces.** This was described in Tactics Box 4.1. Be sure to label each force vector.

❺ **Draw and label the *net force* vector $\vec{F}_{net}$.** Draw this vector beside the diagram, not on the particle. Then check that $\vec{F}_{net}$ points in the same direction as the acceleration vector $\vec{a}$ on your motion diagram. Or, if appropriate, write $\vec{F}_{net} = \vec{0}$.

Exercises 17–22

Text: p. 112

QuickCheck 4.13

A ball, hanging from the ceiling by a string, is pulled back and released. Which is the correct free-body diagram just after its release?
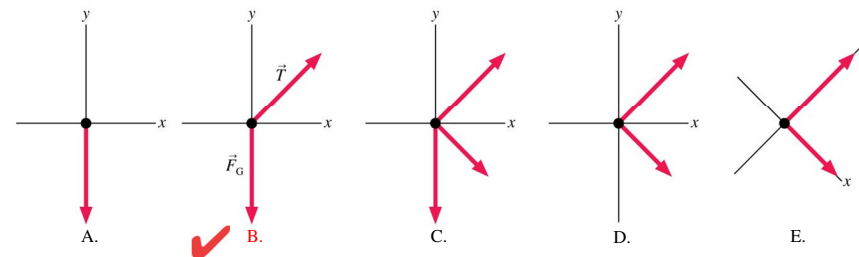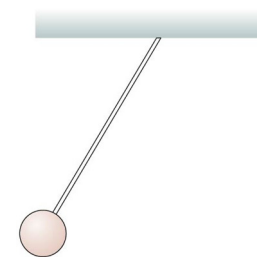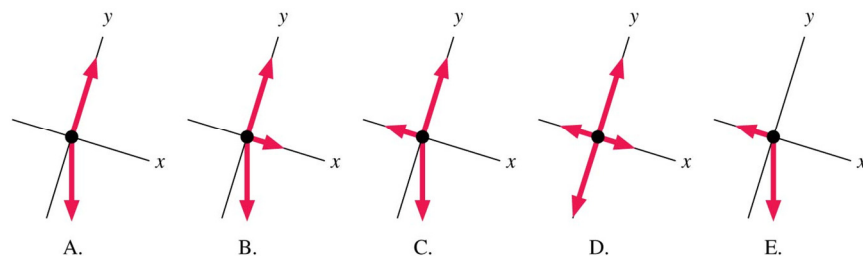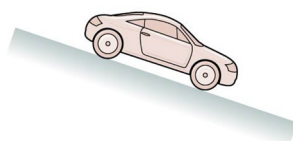

A.   B.   C.   D.   E.

QuickCheck 4.13

A ball, hanging from the ceiling by a string, is pulled back and released. Which is the correct free-body diagram just after its release?

A.   ✔ B.   C.   D.   E.

QuickCheck 4.14

A car is parked on a hill. Which is the correct free-body diagram?

A.   B.   C.   D.   E.

QuickCheck 4.14

A car is parked on a hill. Which is the correct free-body diagram?

A.   B.   C.   ✔   D.   E.
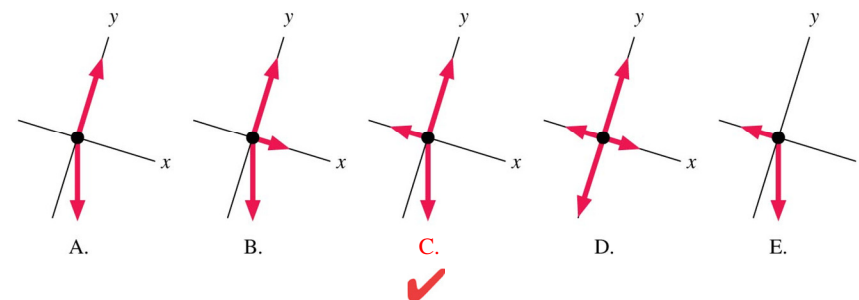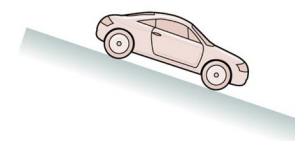
QuickCheck 4.15

A car is towed to the right at constant speed. Which is the correct free-body diagram?

A. B. C. D. E.

A. B. C. D. ✔ E.
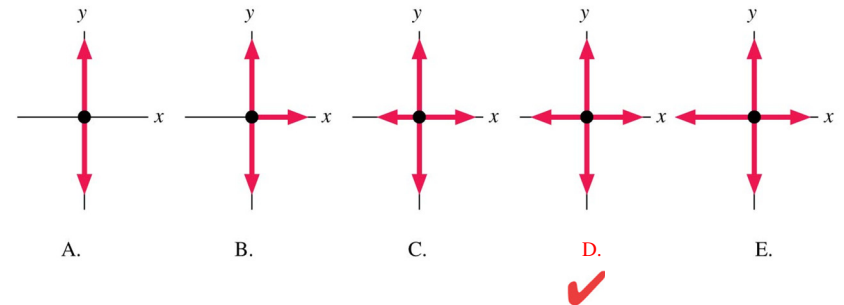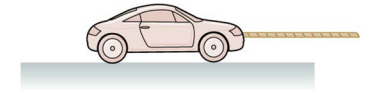
Section 4.7 Newton's Third Law

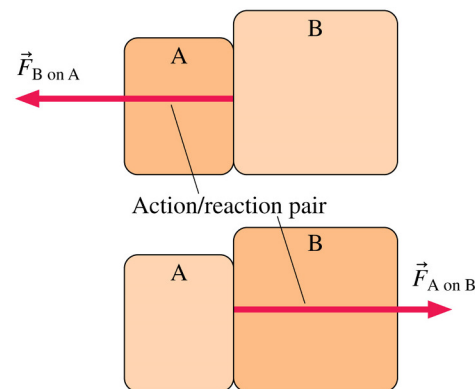
Newton's Third Law

- Motion often involves two or more objects *interacting* with each other.

- As the hammer hits the nail, the nail pushes back on the hammer.

- A bat and a ball, your foot and a soccer ball, and the earth-moon system are other examples of interacting objects.

The hammer exerts a force on the nail . . .

. . . but the *nail* also exerts a force on the *hammer*.
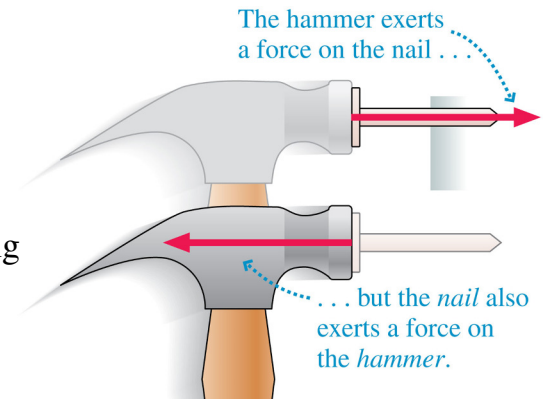
Interacting Objects

- An **interaction** is the mutual influence of two objects on each other.
- The pair of forces shown in the figure is called an **action/reaction pair**.
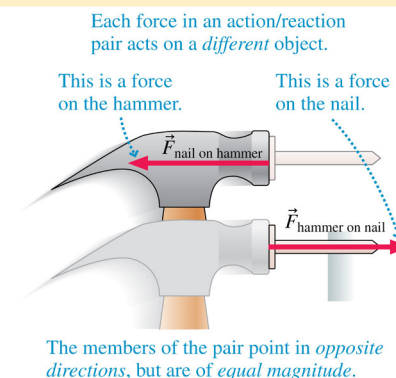- **An action/reaction pair of forces exists as a pair, or not at all.**

Action/reaction pair

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

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

Reasoning with Newton's Third Law

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

- The two members of an action/reaction pair act on two *different* objects.
- The two members of an action/reaction pair point in *opposite* directions and are *equal in magnitude*.
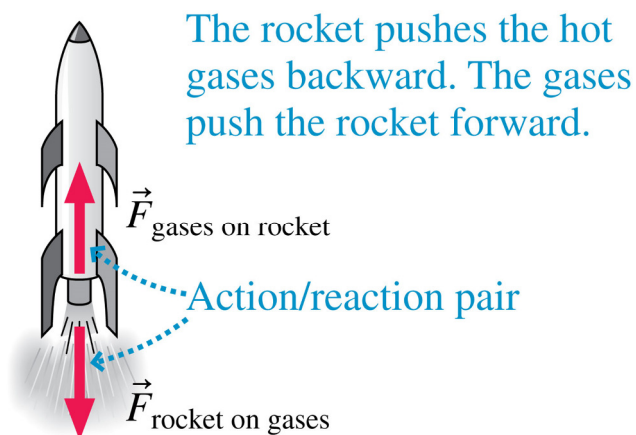
Each force in an action/reaction pair acts on a *different* object.

This is a force on the hammer.

This is a force on the nail.

$\vec{F}_{\text{nail on hammer}}$

$\vec{F}_{\text{hammer on nail}}$

The members of the pair point in *opposite directions*, but are of *equal magnitude*.

Runners and Rockets

- The rocket pushes hot gases out the back, and this results in a forward force (*thrust*) on the rocket.

The rocket pushes the hot gases backward. The gases push the rocket forward.

$\vec{F}_{\text{gases on rocket}}$

Action/reaction pair

$\vec{F}_{\text{rocket on gases}}$

QuickCheck 4.17

A mosquito runs head-on into a truck. Splat! Which is true during the collision?

A. The mosquito exerts more force on the truck than the truck exerts on the mosquito.
B. The truck exerts more force on the mosquito than the mosquito exerts on the truck.
C. The mosquito exerts the same force on the truck as the truck exerts on the mosquito.
D. The truck exerts a force on the mosquito but the mosquito does not exert a force on the truck.
E. The mosquito exerts a force on the truck but the truck does not exert a force on the mosquito.

QuickCheck 4.17

A mosquito runs head-on into a truck. Splat! Which is true during the collision?

    A. The mosquito exerts more force on the truck than the truck exerts on the mosquito.

    B. The truck exerts more force on the mosquito than the mosquito exerts on the truck.

✔ C. **The mosquito exerts the same force on the truck as the truck exerts on the mosquito.**

    D. The truck exerts a force on the mosquito but the mosquito does not exert a force on the truck.

    E. The mosquito exerts a force on the truck but the truck does not exert a force on the mosquito.

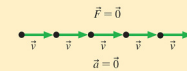
Summary

GENERAL PRINCIPLES

Newton's First Law

Consider an object with no force acting on it. If it is at rest, it will remain at rest. If it is in motion, then it will continue to move in a straight line at a constant speed.
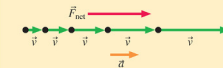
$$\vec{F} = \vec{0}$$

$$\vec{a} = \vec{0}$$

The first law tells us that an object that experiences no force will experience no acceleration.

Newton's Second Law

An object with mass m will undergo acceleration

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

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

$$\vec{F}_{net}$$

$$\vec{a}$$

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

Newton's Third Law

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

• act on two *different* objects.

• point in opposite directions and are equal in magnitude:

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

$$\vec{F}_{B\ on\ A}$$

Action/reaction pair

$$\vec{F}_{A\ on\ B}$$
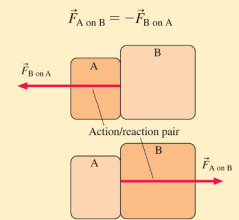
Text: p. 118

Summary

IMPORTANT CONCEPTS

Force is a push or pull on an object.

• Force is a vector, with a magnitude and a direction.

• A force requires an agent.

• A force is either a contact force or a long-range force.

The SI unit of force is the **newton** (N). A 1 N force will cause a 1 kg mass to accelerate at 1 m/s².

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

$$\vec{F}_1 \quad \vec{F}_2$$

$$\vec{F}_3$$

$$= \quad \vec{F}_{net} = \vec{F}_1 + \vec{F}_2 + \vec{F}_3$$
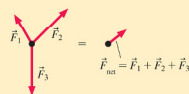
Mass is the property of an object that determines its resistance to acceleration.

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

$$\frac{a_A}{a_B} = \frac{m_B}{m_A}$$

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

Text: p. 118

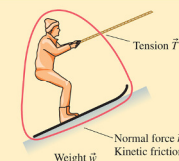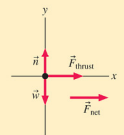
Summary

APPLICATIONS

Identifying Forces

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

Tension $\vec{T}$

Normal force $\vec{n}$

Kinetic friction $\vec{f}_k$

Weight $\vec{w}$

Free-Body Diagrams

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

$$\vec{n} \quad \vec{F}_{thrust}$$

$$\vec{w} \quad \vec{F}_{net}$$

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