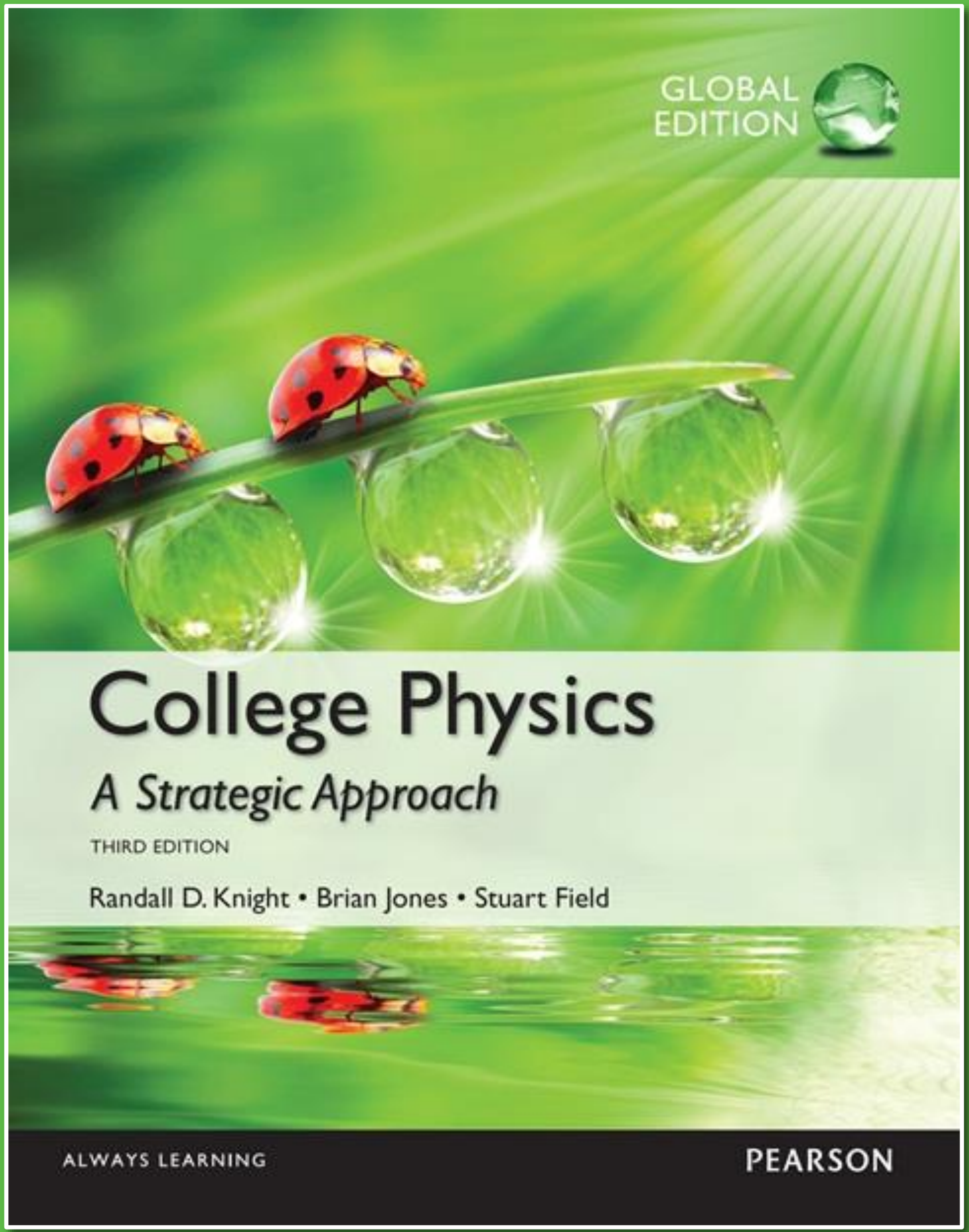


Lecture Presentation

Chapter 5

Applying Newton's Laws

Chapter 5 Appling Newton’s Laws

Chapter 5 Preview
Looking Ahead: Working with Forces

- In this chapter, you'll learn expressions for the different forces we've seen, and you'll learn how to use them to solve problems.

- You'll learn how a balance between weight and drag forces leads to a maximum speed for a skydiver.

Chapter 5 Preview
Looking Ahead: Equilibrium Problems

- The boy is pushing as hard as he can, but the sofa isn’t going anywhere. It’s in **equilibrium**—the sum of the forces on it is zero.

- You’ll learn to solve equilibrium problems by using the fact that there is no net force.

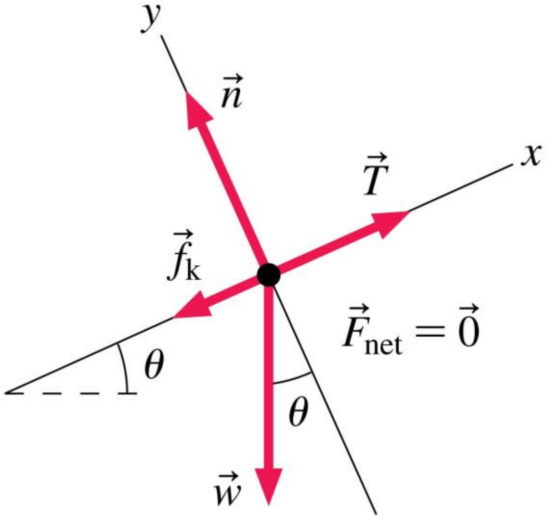
Chapter 5 Preview
Looking Ahead: Dynamics Problems

- Newton's laws allow us to relate the forces acting on an object to its motion, and so to solve a wide range of **dynamics** problems.

- This skier is picking up speed. You'll see how her acceleration is determined by the forces acting on her.

Chapter 5 Preview
Looking Back: Free-Body Diagrams

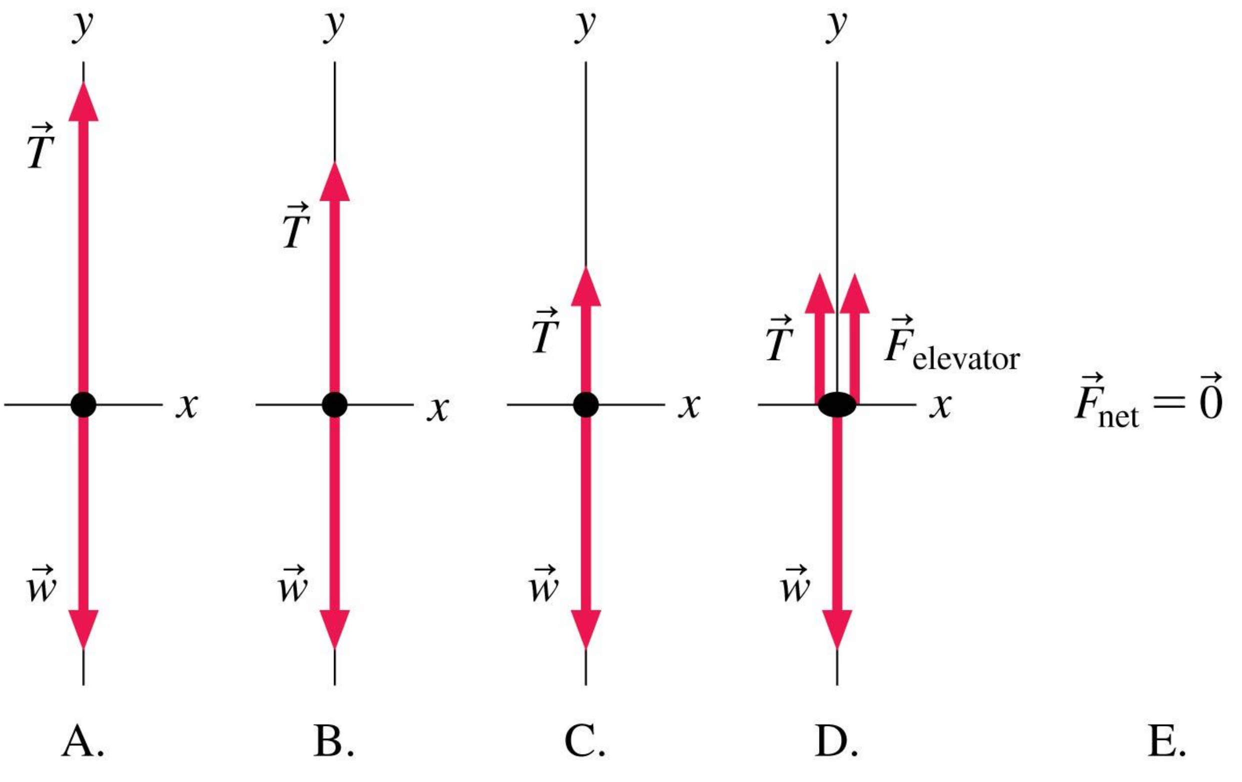
- In chapter 4 you learned to draw a free-body diagram showing the magnitudes and directions of the forces acting on an object.



- In this chapter, you'll use free-body diagrams as an essential problem-solving tool for single objects and interacting objects.

Chapter 5 Preview
Stop to Think

An elevator is suspended from a cable. It is moving upward at a steady speed. Which is the correct free-body diagram for this situation?



Section 5.1 Equilibrium

Equilibrium

- We say that an object at rest is in **static equilibrium**.
- An object moving in a straight line at a constant speed ($\vec{a} = \vec{0}$) is in **dynamic equilibrium**.
- In both types of equilibrum there is no net force acting on the object:

$$\sum F_x = ma_x = 0 \qquad \text{and} \qquad \sum F_y = ma_y = 0$$

In equilibrium, the sums of the *x*- and *y*-components of the force are zero

Reading Question 5.1

Which of these objects is in equilibrium?

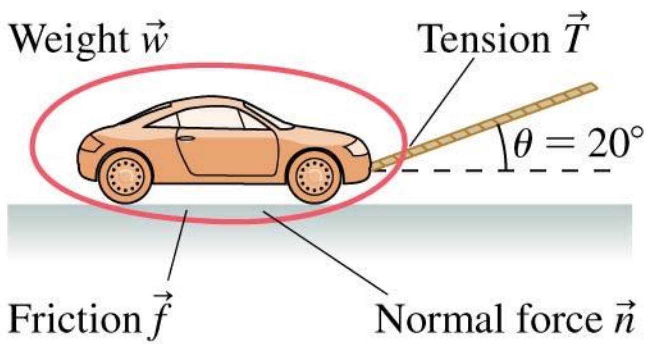
A. A car driving down the road at a constant speed
B. A block sitting at rest on a table
C. A skydiver falling at a constant speed
D. All of the above

Example 5.4 Tension in towing a car

A car with a mass of 1500 kg is being towed at a steady speed by a rope held at a 20° angle from the horizontal.

A friction force of 320 N opposes the car's motion.

What is the tension in the rope?



Known

$\theta = 20°$

$m = 1500$ kg

$f = 320$ N

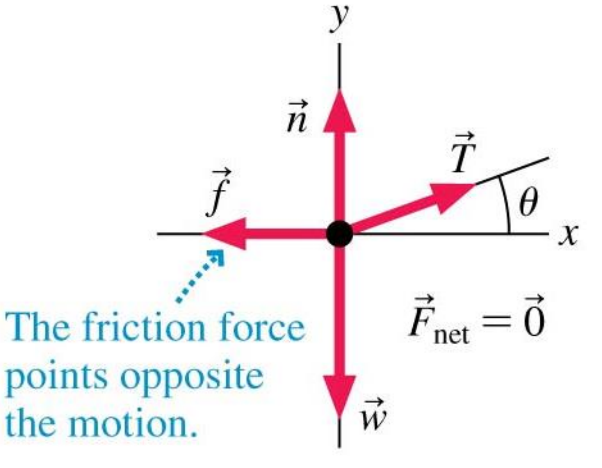
Find

T

Example 5.4 Tension in towing a car (cont.)

PREPARE The car is moving in a straight line at a constant speed ($\vec{a} = \vec{0}$) so it is in dynamic equilibrium and must have $\vec{F}_{\text{net}} = m\vec{a} = \vec{0}$. The figure shows three contact forces acting on the car—the tension force $\vec{T}$, friction $\vec{f}$, and the normal force $\vec{n}$—and the long-range force of gravity $\vec{w}$.

These four forces are shown on the free-body diagram.



Example 5.4 Tension in towing a car (cont.)

SOLVE This is still an equilibrium problem, even though the car is moving, so our problem-solving procedure is unchanged. With four forces, the requirement of equilibrium is

$$\Sigma F_x = n_x + T_x + f_x + w_x = ma_x = 0$$

$$\Sigma F_y = n_y + T_y + f_y + w_y = ma_y = 0$$

We can again determine the horizontal and vertical components of the forces by "reading" the free-body diagram. The results are shown in the table.

Force	Name of x-component	Value of x-component	Name of y-component	Value of y-component
$\vec{n}$	n_x	0	n_y	n
$\vec{T}$	T_x	$T\cos\theta$	T_y	$T\sin\theta$
$\vec{f}$	f_x	$-f$	f_y	0
$\vec{w}$	w_x	0	w_y	$-w$

Example 5.4 Tension in towing a car (cont.)

With these components, Newton's second law becomes

$$T\cos\theta - f = 0$$

$$n + T\sin\theta - w = 0$$

The first equation can be used to solve for the tension in the rope:

$$T = \frac{f}{\cos\theta} = \frac{320\ \text{N}}{\cos 20°} = 340\ \text{N}$$

to two significant figures. It turned out that we did not need the y-component equation in this problem. We would need it if we wanted to find the normal force $\vec{n}$.

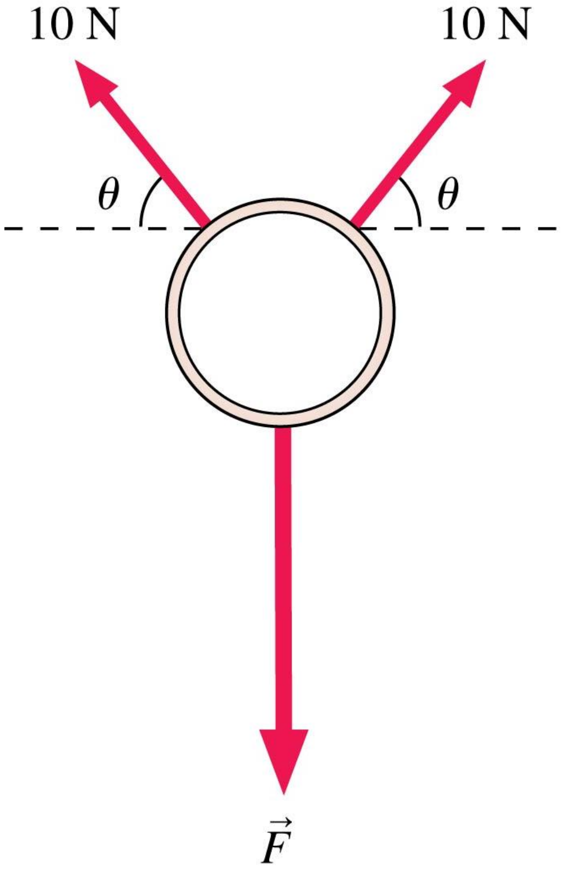
Example 5.4 Tension in towing a car (cont.)

ASSESS Had we pulled the car with a horizontal rope, the tension would need to exactly balance the friction force of 320 N. Because we are pulling at an angle, however, part of the tension in the rope pulls *up* on the car instead of in the forward direction. Thus we need a little more tension in the rope when it’s at an angle, so our result seems reasonable.

QuickCheck 5.1

A ring, seen from above, is pulled on by three forces. The ring is not moving. How big is the force F?

A. 20 N
B. $10 \cos\theta$ N
C. $10 \sin\theta$ N
D. $20 \cos\theta$ N
E. $20 \sin\theta$ N



Example Problem

A 100-kg block with a weight of 980 N hangs on a rope. Find the tension in the rope if the block is stationary, then if it's moving upward at a steady speed of 5 m/s.

The block is in static equilibrium if it is stationary and in dynamic equilibrium if it's moving at a steady speed. In both cases the tension in the rope must equal the weight: 980 N.

Section 5.2 Dynamics and Newton's Second Law

Dynamics and Newton's Second Law

- The essence of Newtonian mechanics can be expressed in two steps:
  - The forces acting on an object determine its acceleration $\vec{a} = \vec{F}_{\text{net}}/m$.
  - The object's motion can be found by using $\vec{a}$ in the equations of kinematics.
- Thus Newton's second law, $\vec{F}_{\text{net}} = m\vec{a}$, is

$$\sum F_x = ma_x \quad \text{and} \quad \sum F_y = ma_y$$

Newton's second law in component form

Example 5.5 Putting a golf ball

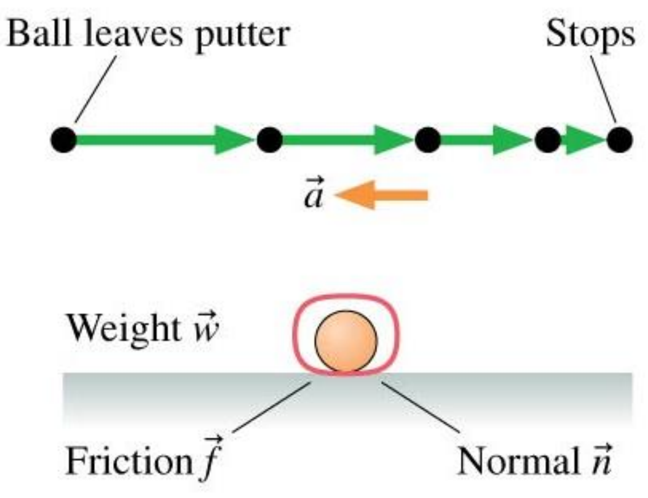
A golfer putts a 46 g ball with a speed of 3.0 m/s. Friction exerts a 0.020 N retarding force on the ball, slowing it down. Will her putt reach the hole, 10 m away?

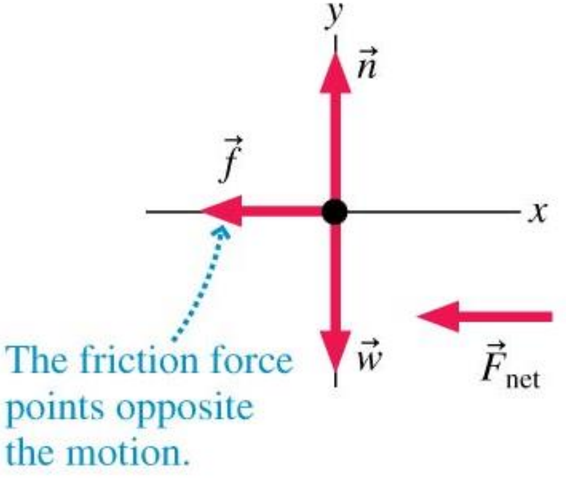
PREPARE The figure is a visual overview of the problem. We've collected the known information, drawn a sketch, and identified what we want to find.

Known		Find
$x_i = 0$ m	$f = 0.020$ N	x_f
$(v_x)_i = 3.0$ m/s	$m = 0.046$ kg	
$(v_x)_f = 0$ m/s		

Example 5.5 Putting a golf ball (cont.)

The motion diagram shows that the ball is slowing down as it rolls to the right, so the acceleration vector points to the left. Next, we identify the forces acting on the ball and show them on a free-body diagram. Note that the net force points to the left, as it must because the acceleration points to the left.





Example 5.5 Putting a golf ball (cont.)

SOLVE Newton's second law in component form is

$$\Sigma F_x = n_x + f_x + w_x = 0 - f + 0 = ma_x$$

$$\Sigma F_y = n_y + f_y + w_y = n + 0 - w = ma_y = 0$$

We've written the equations as sums, as we did with equilibrium problems, then "read" the values of the force components from the free-body diagram. The components are simple enough in this problem that we don't really need to show them in a table. It is particularly important to notice that we set $a_y = 0$ in the second equation. This is because the ball does not move in the *y*-direction, so it can't have any acceleration in the *y*-direction. This will be an important step in many problems.

Example 5.5 Putting a golf ball (cont.)

The first equation is $-f = ma_x$, from which we find

$$a_x = -\frac{f}{m} = \frac{-(0.020\ \text{N})}{0.046\ \text{kg}} = -0.435\ \text{m/s}^2$$

To avoid rounding errors we keep an extra digit in this intermediate step in the calculation. The negative sign shows that the acceleration is directed to the left, as expected.

Example 5.5 Putting a golf ball (cont.)

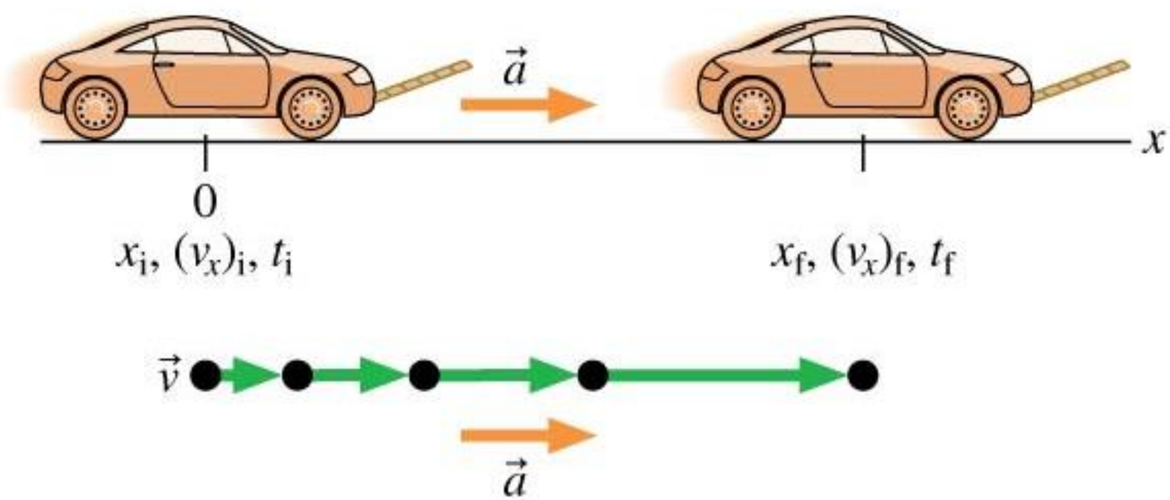
Now that we know the acceleration, we can use kinematics to find how far the ball will roll before stopping. We don't have any information about the time it takes for the ball to stop, so we'll use the kinematic equation $(v_x)_f^2 = (v_x)_i^2 + 2a_x (x_f - x_i)$. This gives

$$x_f = x_i + \frac{(v_x)_f^2 - (v_x)_i^2}{2a_x} = 0\text{ m} + \frac{(0\text{ m/s})^2 - (3.0\text{ m/s})^2}{2(-0.435\text{ m/s}^2)} = 10.3\text{ m}$$

If her aim is true, the ball will just make it into the hole.

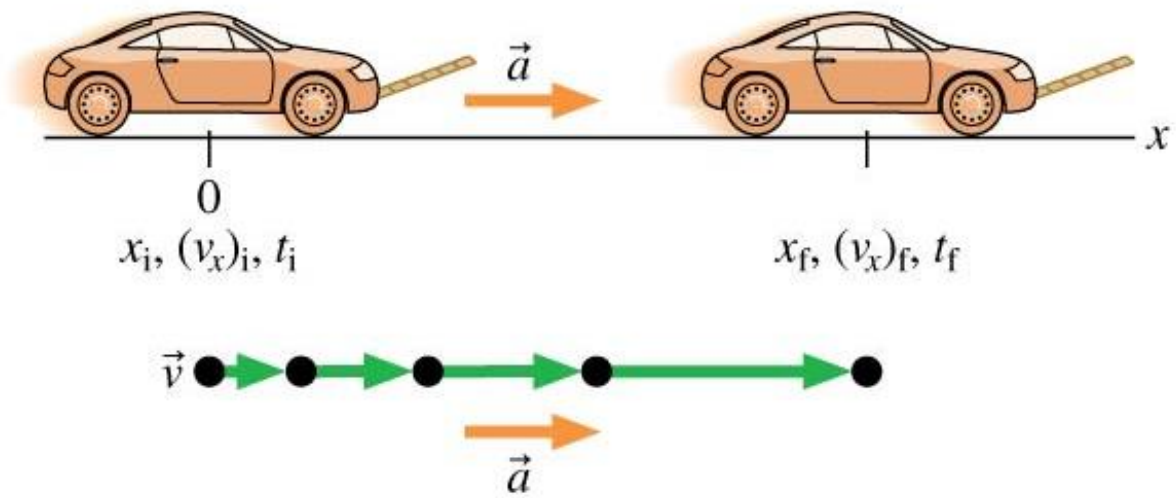
Example 5.6 Towing a car with acceleration

A car with a mass of 1500 kg is being towed by a rope held at a 20° angle to the horizontal. A friction force of 320 N opposes the car's motion. What is the tension in the rope if the car goes from rest to 12 m/s in 10 s?



Example 5.6 Towing a car with acceleration (cont.)

PREPARE You should recognize that this problem is almost identical to Example 5.4. The difference is that the car is now accelerating, so it is no longer in equilibrium. This means, as shown in the figure, that the net force is not zero.



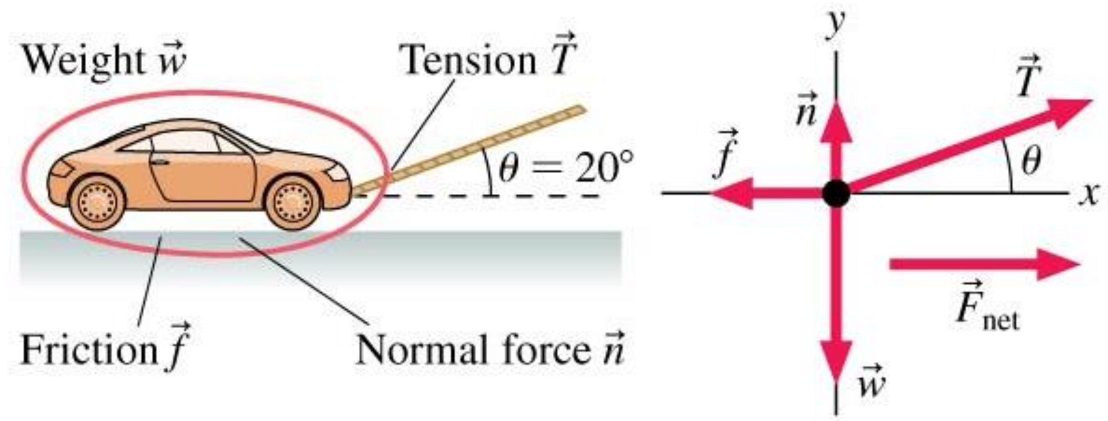
Example 5.6 Towing a car with acceleration (cont.)

Known

$x_i = 0$ m
$(v_x)_i = 0$ m/s
$t_i = 0$ s, $\theta = 20°$
$m = 1500$ kg
$f = 320$ N
$(v_x)_f = 12$ m/s
$t_f = 10$ s

Find

T



Example 5.6 Towing a car with acceleration (cont.)

SOLVE Newton's second law in component form is

$$\Sigma F_x = n_x + T_x + f_x + w_x = ma_x$$

$$\Sigma F_y = n_y + T_y + f_y + w_y = ma_y = 0$$

We've again used the fact that $a_y = 0$ for motion that is purely along the *x*-axis.

The Newton's second law in component form is:

$$T\cos\theta - f = ma_x$$

$$n + T\sin\theta - w = 0$$

Example 5.6 Towing a car with acceleration (cont.)

Because the car speeds up from rest to 12 m/s in 10 s, we can use kinematics to find the acceleration:

$$a_x = \frac{\Delta v_x}{\Delta t} = \frac{(v_x)_\text{f} - (v_x)_\text{i}}{t_\text{f} - t_\text{i}} = \frac{(12\text{ m/s}) - (0\text{ m/s})}{(10\text{ s}) - (0\text{ s})} = 1.2\text{ m/s}^2$$

Example 5.6 Towing a car with acceleration (cont.)

We can now use the first Newton's-law equation above to solve for the tension. We have

$$T = \frac{ma_x + f}{\cos\theta} = \frac{(1500\ \text{kg})(1.2\ \text{m/s}^2) + 320\ \text{N}}{\cos 20^\circ} = 2300\ \text{N}$$

ASSESS The tension is substantially greater than the 340 N found in Example 5.4. It takes much more force to accelerate the car than to keep it rolling at a constant speed.

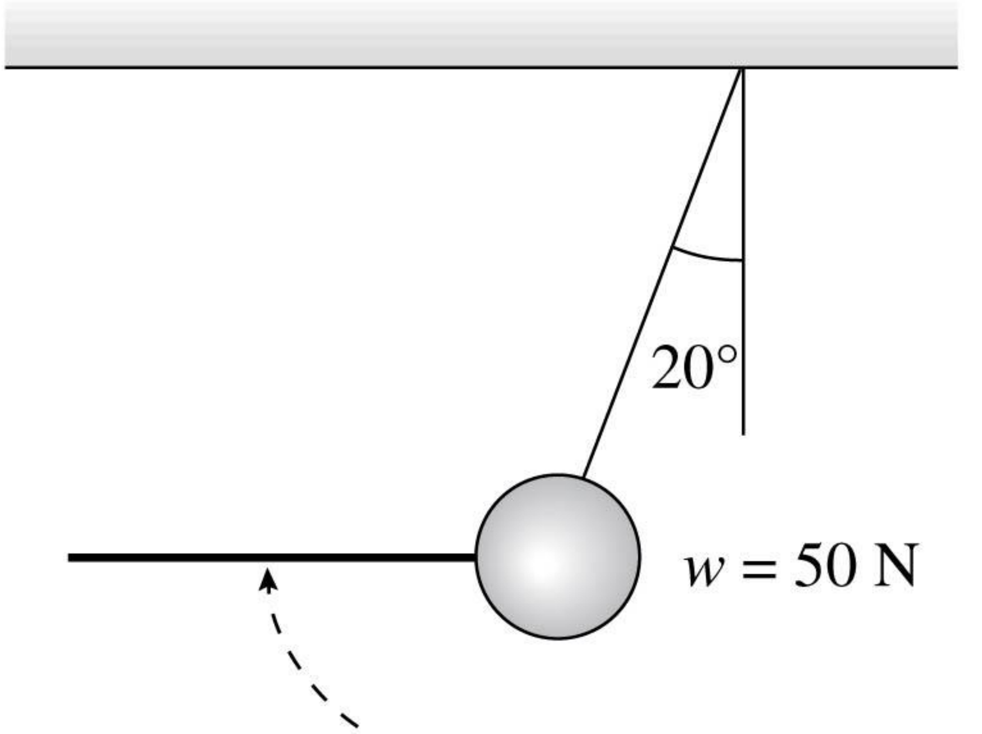
Example Problem

A 100-kg block with a weight of 980 N hangs on a rope. Find the tension in the rope if the block is accelerating upwards at 5 m/s^2.

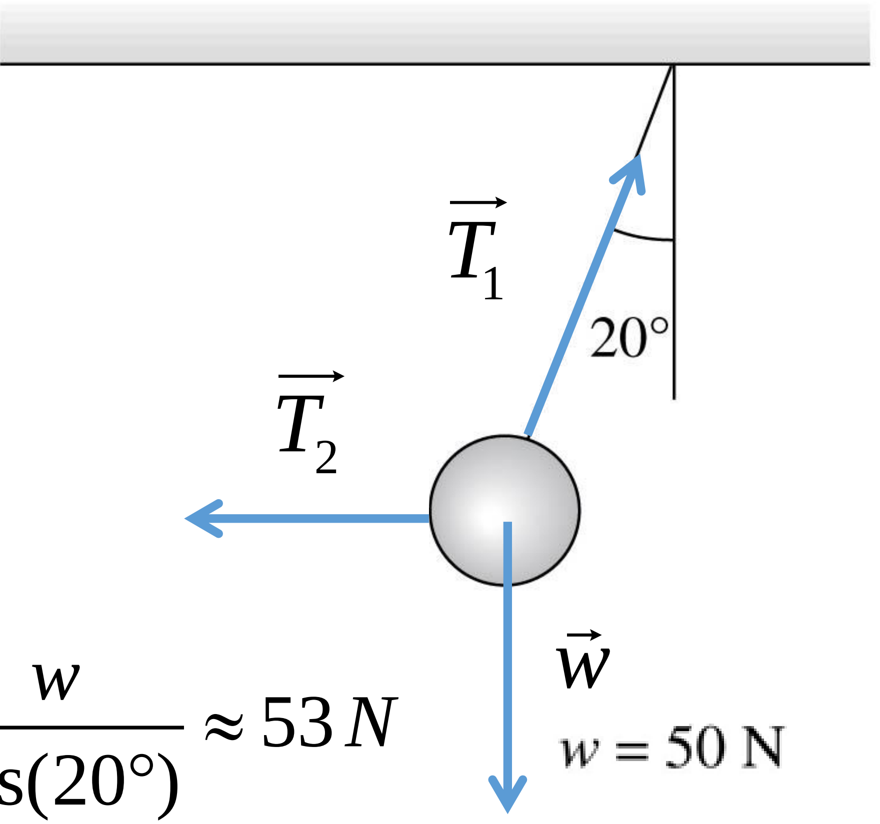
The block is not in equilibrium; it is accelerating. Newton's second law gives $m \times a = T - 980$ or $T = 1480$ N.

Example Problem

A ball weighing 50 N is pulled back by a rope by an angle of 20°. What is the tension in the pulling rope?



Example Problem



$$T_1 \cos(20°) - w = 0 \Rightarrow T_1 = \frac{w}{\cos(20°)} \approx 53\,N$$

$$T_2 - T_1 \sin(20°) = 0 \Rightarrow T_2 = T_1 \sin(20°) \approx 18\,N$$

The ball is in static equilibrium.

The tension in the upper rope is 53 N and the tension in the horizontal rope is 18 N.

Example Problem

A sled with a mass of 20 kg slides along frictionless ice at 4.5 m/s. It then crosses a rough patch of snow that exerts a friction force of 12 N. How far does it slide on the snow before coming to rest?

$$-f = ma \Rightarrow a = \frac{-f}{m} = \frac{-12}{20} = -0.6 \text{ m/s}^2$$

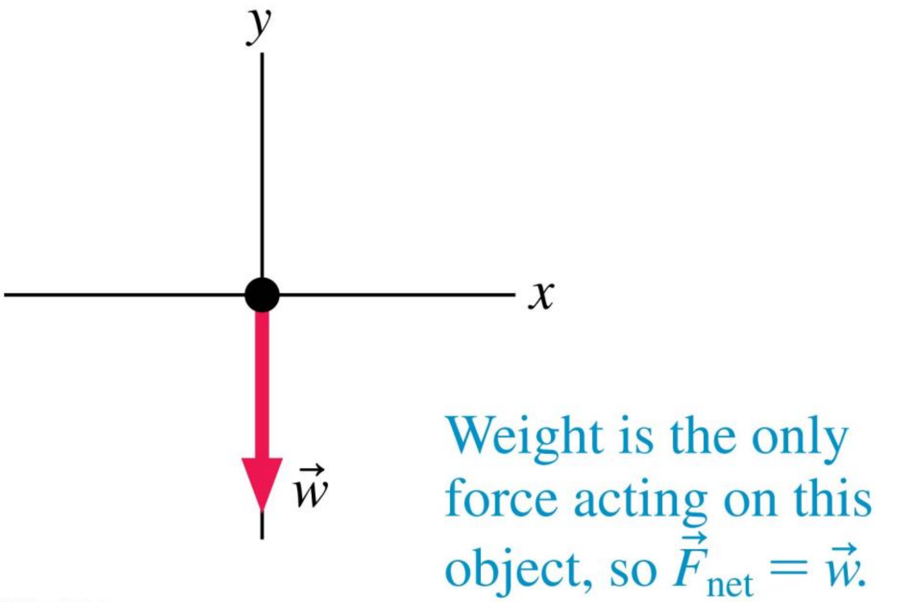
$$v_f^2 - v_i^2 = 2a\Delta x \Rightarrow \Delta x = \frac{v_f^2 - v_i^2}{2a} = \frac{0 - 4.5^2}{2 \times (-0.6)} \approx 17 \text{ m}$$

The acceleration is -0.6 m/s^2.
The initial velocity is 4.5 m/s and the final velocity is 0.
The distance traveled before stopping is 17 m.

Section 5.3 Mass and Weight

Mass, Weight and Apparent Weight

- **Mass and weight are not the same thing.**
- Mass is a quantity that describes an object's inertia, its tendency to resist being accelerated.



- Weight is the gravitational force exerted on an object by a planet:

$$w = -mg$$

Apparent Weight

- The weight of an object is the force of gravity on that object.
- Your *sensation* of weight is due to *contact forces* supporting you.
- Let's define your **apparent weight** w_{app} in terms of the force you feel:

$$w_{app} = \text{magnitude of supporting contact forces}$$

Definition of apparent weight

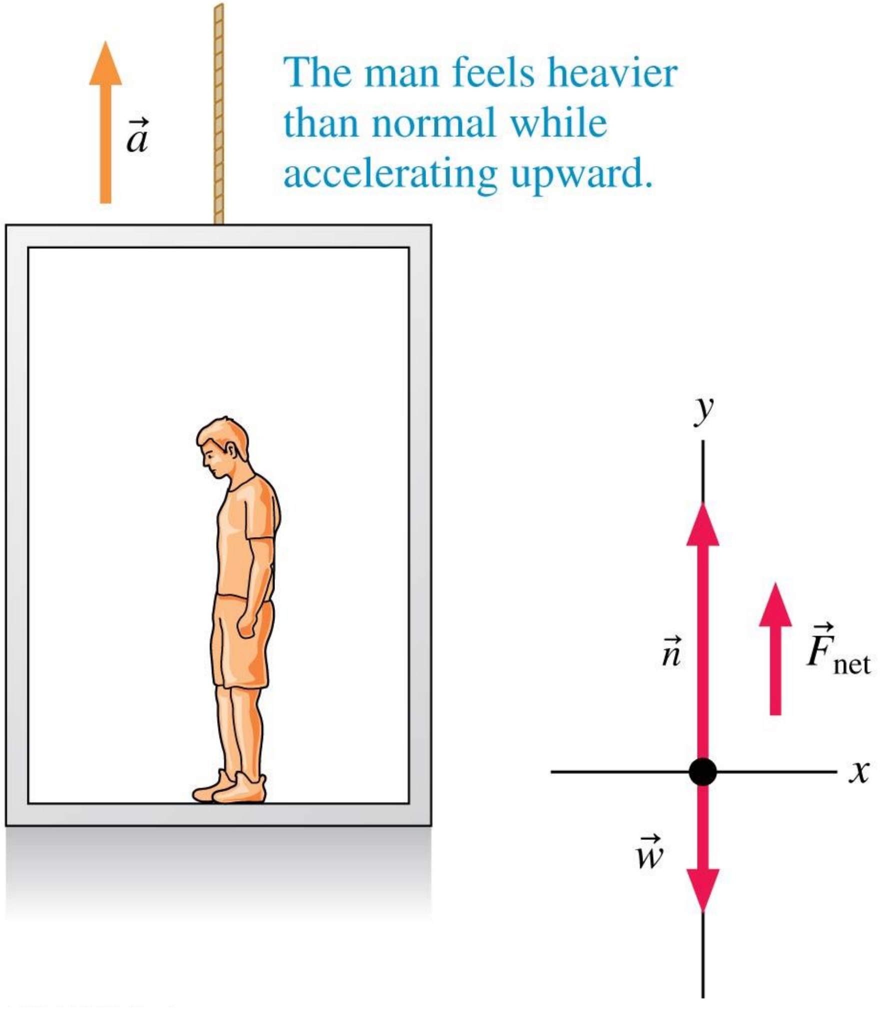
Apparent Weight

- The only forces acting on the man are the upward normal force of the floor and the downward weight force:

$$n = w + ma$$

$$w_{app} = w + ma$$

- Thus $w_{app} > w$ and the man feels heavier than normal.



Example 5.8 Apparent weight in an elevator

Anis's mass is 70 kg. He is standing on a scale in an elevator that is moving at 5.0 m/s. As the elevator stops, the scale reads 750 N. Before it stopped, was the elevator moving up or down? How long did the elevator take to come to rest?

PREPARE The scale reading as the elevator comes to rest, 750 N, is Anis's *apparent* weight.

Anis's *actual* weight is:

$$w = mg = (70\text{ kg})(9.80\text{ m/s}^2) = 686\text{ N}$$

Example 5.8 Apparent weight in an elevator (cont.)

This is an intermediate step in the calculation, so we are keeping an extra significant figure. Anis's apparent weight, which is the upward force of the scale on him, is greater than his actual weight, so there is a net upward force on Anis. His acceleration must be upward as well, so we can use this figure as the free-body diagram for this problem. We can find the net force on Anis, and then we can use this net force to determine his acceleration. Once we know the acceleration, we can use kinematics to determine the time it takes for the elevator to stop.

Example 5.8 Apparent weight in an elevator (cont.)

SOLVE We can read components of vectors from the figure. The vertical component of Newton's second law for Anis's motion is

$$\Sigma F_y = n - w = ma_y$$

n is the normal force, which is the scale force on Anis, 750 N. w is his weight, 686 N.

We can thus solve for a_y:

$$a_y = \frac{n - w}{m} = \frac{750\ \text{N} - 686\ \text{N}}{70\ \text{kg}} = +0.91\ \text{m/s}^2$$

Example 5.8 Apparent weight in an elevator (cont.)

The acceleration is positive and so is directed upward, exactly as we assumed—a good check on our work. The elevator is slowing down, but the acceleration is directed upward. This means that the elevator was moving *downward*, with a negative velocity, before it stopped.

Example 5.8 Apparent weight in an elevator (cont.)

To find the stopping time, we can use the kinematic equation

$$(v_y)_f = (v_y)_i + a_y \Delta t$$

The elevator is initially moving downward, so $(v_y)_i = -5.0$ m/s, and it then comes to a halt, so $(v_y)_f = 0$. We know the acceleration, so the time interval is

$$\Delta t = \frac{(v_y)_f - (v_y)_i}{a_y} = \frac{0 - (-5.0\ \text{m/s})}{0.91\ \text{m/s}^2} = 5.5\ \text{s}$$

Example 5.8 Apparent weight in an elevator (cont.)

ASSESS Think back to your experiences riding elevators. If the elevator is moving downward and then comes to rest, you "feel heavy." This gives us confidence that our analysis of the motion is correct. And 5.0 m/s is a pretty fast elevator: At this speed, the elevator will be passing more than one floor per second. If you've been in a fast elevator in a tall building, you know that 5.5 s is reasonable for the time it takes for the elevator to slow to a stop.

Reading Question 5.2

You are riding in an elevator that is accelerating upward. Suppose you stand on a scale. The reading on the scale is

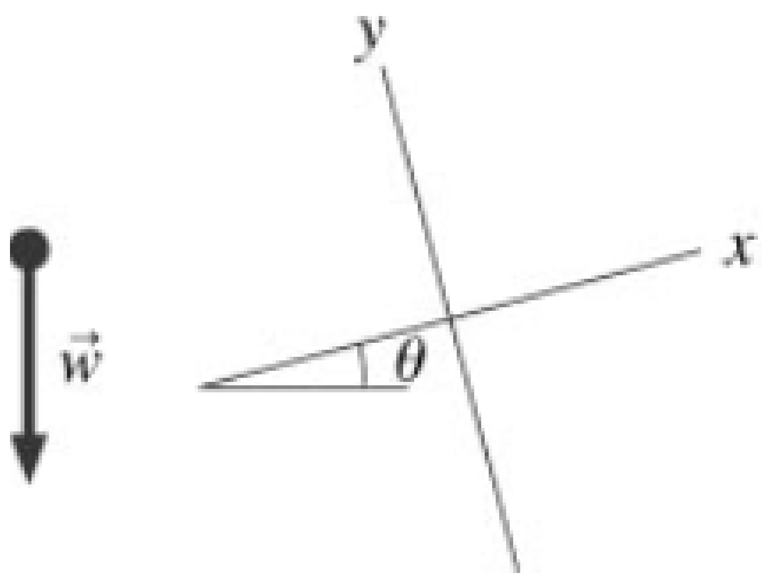
A. Greater than your true weight.
B. Equal to your true weight.
C. Less than your true weight.

Weightlessness

- A person in free fall has zero apparent weight.
- "Weightless" does not mean "no weight."
- An object that is **weightless** has no apparent weight.

QuickCheck 5.4

What are the components of $\vec{w}$ in the coordinate system shown?



A $w_x = w \cos\theta$
$w_y = w \sin\theta$

B $w_x = -w \cos\theta$
$w_y = w \sin\theta$

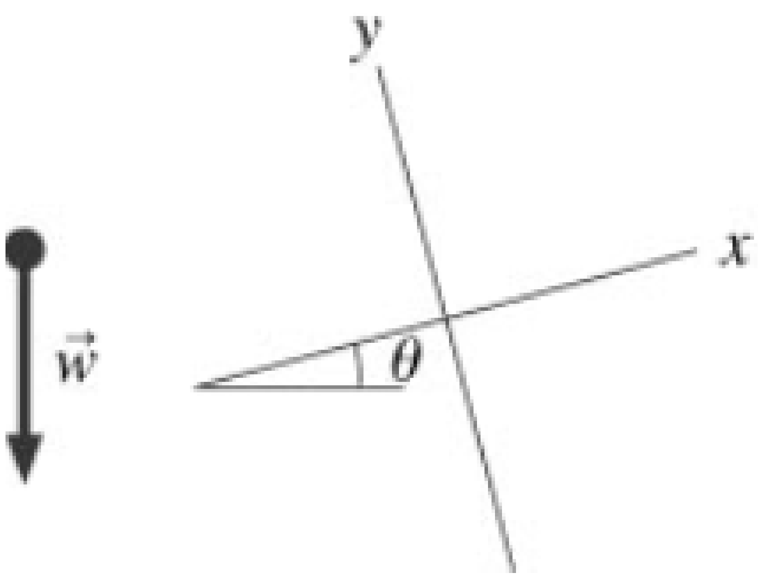
C $w_x = w \cos\theta$
$w_y = -w \sin\theta$

D $w_x = -w \sin\theta$
$w_y = -w \cos\theta$

E $w_x = w \sin\theta$
$w_y = -w \cos\theta$

QuickCheck 5.4

What are the components of $\vec{w}$ in the coordinate system shown?



A $w_x = w \cos\theta$
$w_y = w \sin\theta$

B $w_x = -w \cos\theta$
$w_y = w \sin\theta$

C $w_x = w \cos\theta$
$w_y = -w \sin\theta$

✔ **D** $w_x = -w \sin\theta$
$w_y = -w \cos\theta$

E $w_x = w \sin\theta$
$w_y = -w \cos\theta$

QuickCheck 5.5

A 50-kg student (mg = 490 N) gets in a 1000-kg elevator at rest and stands on a metric bathroom scale. As the elevator **accelerates upward**, the scale reads

A. > 490 N
B. 490 N
C. < 490 N but not 0 N
D. 0 N

QuickCheck 5.6

A 50-kg student (mg = 490 N) gets in a 1000-kg elevator at rest and stands on a metric bathroom scale. Sadly, the **elevator cable breaks**. What is the reading on the scale during the few seconds it takes the student to plunge to his doom?

A. > 490 N
B. 490 N
C. < 490 N but not 0 N
D. 0 N

Example Problem

A 50-kg student gets in a 1000-kg elevator at rest. As the elevator begins to move, she has an apparent weight of 600 N for the first 3 s. How far has the elevator moved, and in which direction, at the end of 3 s?

$$w = mg = 50 \times 9.8 = 490 \text{ N}$$

$$w_{app} = 600 \text{ N} = m(g + a) \Rightarrow a = \frac{w_{app}}{m} - g = \frac{600}{50} - 9.8 = 2.2 \text{ m/s}^2$$

$$v_i = 0 \text{ ; } v_f = a \times \Delta t = 2.2 \times 3 = 6.6 \text{ m/s}$$

$$v_f^2 - v_i^2 = 2a\Delta x \Rightarrow \Delta x = \frac{v_f^2 - v_i^2}{2a} = \frac{6.6^2}{2 \times 2.2} = 9.9 \text{ m}$$

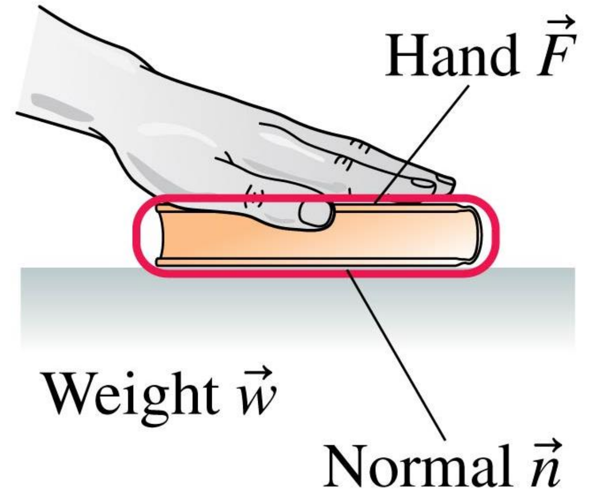
Section 5.4 Normal Forces

Normal Forces

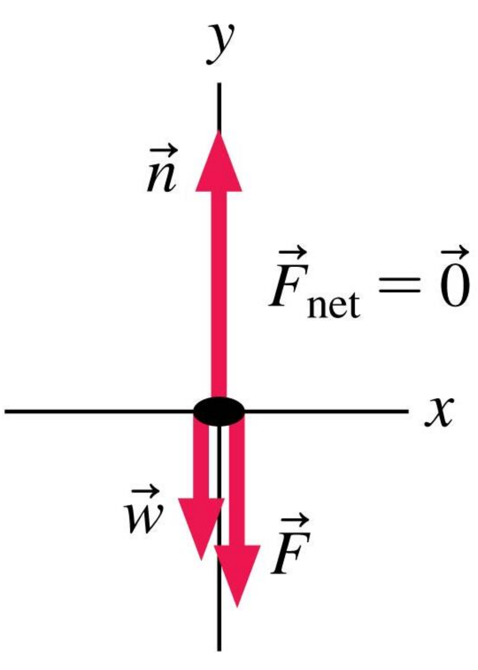
- An object at rest on a table is subject to an upward force due to the table.
- This force is called the *normal force* because it is always directed normal, or perpendicular, to the surface of contact.
- The normal force adjusts itself so that the object stays on the surface without penetrating it.

Example 5.9 Normal force on a pressed book

A 1.2 kg book lies on a table. The book is pressed down from above with a force of 15 N. What is the normal force acting on the book from the table below?



PREPARE The book is not moving and is thus in static equilibrium. We need to identify the forces acting on the book and prepare a free-body diagram showing these forces.



Example 5.9 Normal force on a pressed book (cont.)

SOLVE Because the book is in static equilibrium, the net force on it must be zero. The only forces acting are in the *y*-direction, so Newton's second law is

$$\Sigma F_y = n_y + w_y + F_y = n - w - F = ma_y = 0$$

We learned in the last section that the weight force is $w = mg$. The weight of the book is thus

$$w = mg = (1.2\text{ kg})(9.8\text{ m/s}^2) = 12\text{ N}$$

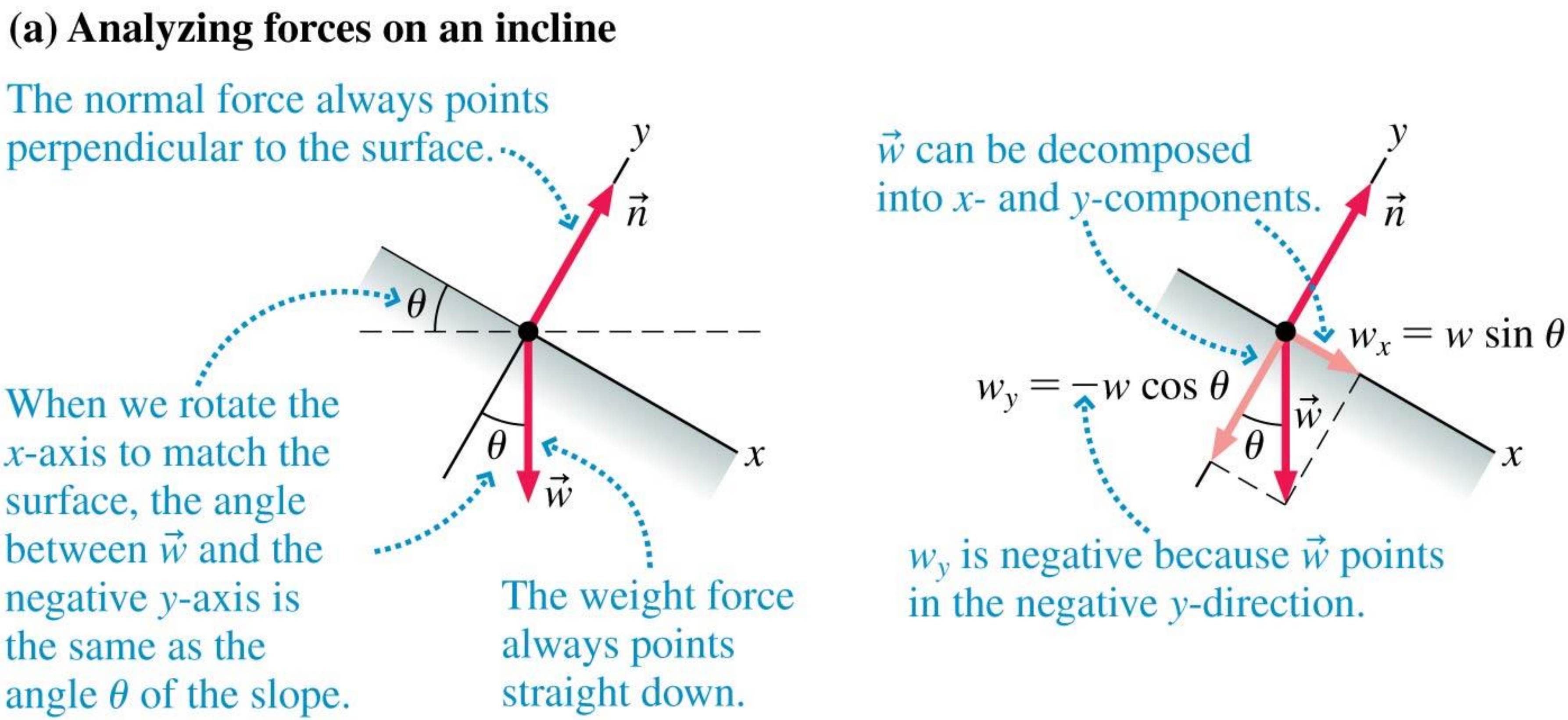
With this information, we see that the normal force exerted by the table is

$$n = F + w = 15\text{ N} + 12\text{ N} = 27\text{ N}$$

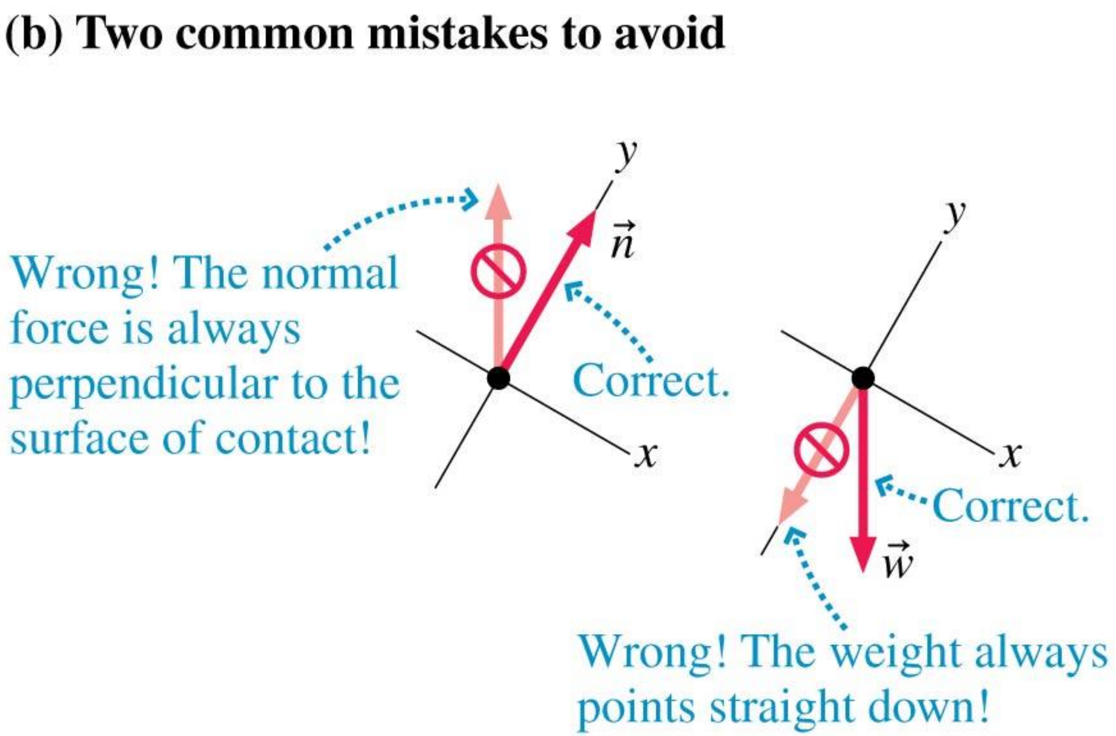
Example 5.9 Normal force on a pressed book (cont.)

ASSESS The magnitude of the normal force is *larger* than the weight of the book. From the table's perspective, the extra force from the hand pushes the book further into the atomic springs of the table. These springs then push back harder, giving a normal force that is greater than the weight of the book.

Normal Forces

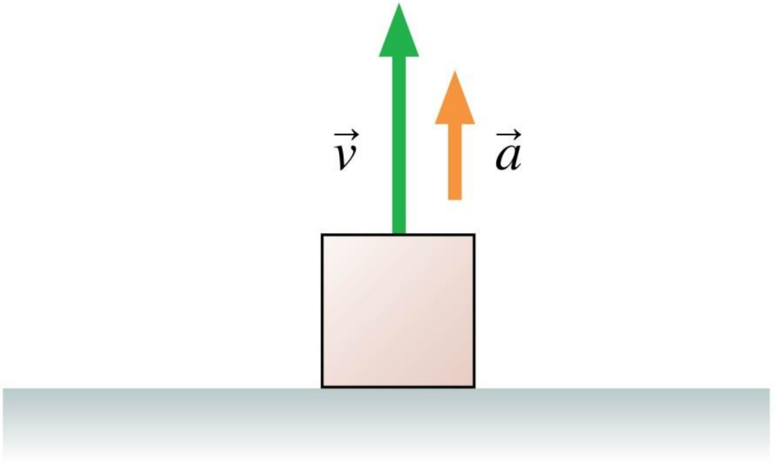


Normal Forces



QuickCheck 5.2

The box is sitting on the floor of an elevator. The elevator is accelerating upward. The magnitude of the normal force on the box is



A. $n > mg$

B. $n = mg$

C. $n < mg$

D. $n = 0$

E. Not enough information to tell

QuickCheck 5.3

A box is being pulled to the right at steady speed by a rope that angles upward. In this situation:

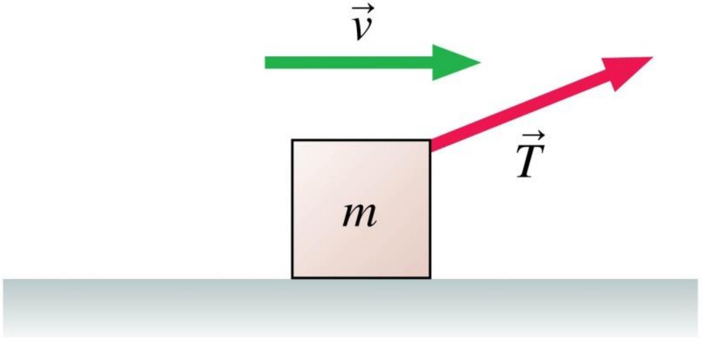
A. $n > mg$

B. $n = mg$

C. $n < mg$

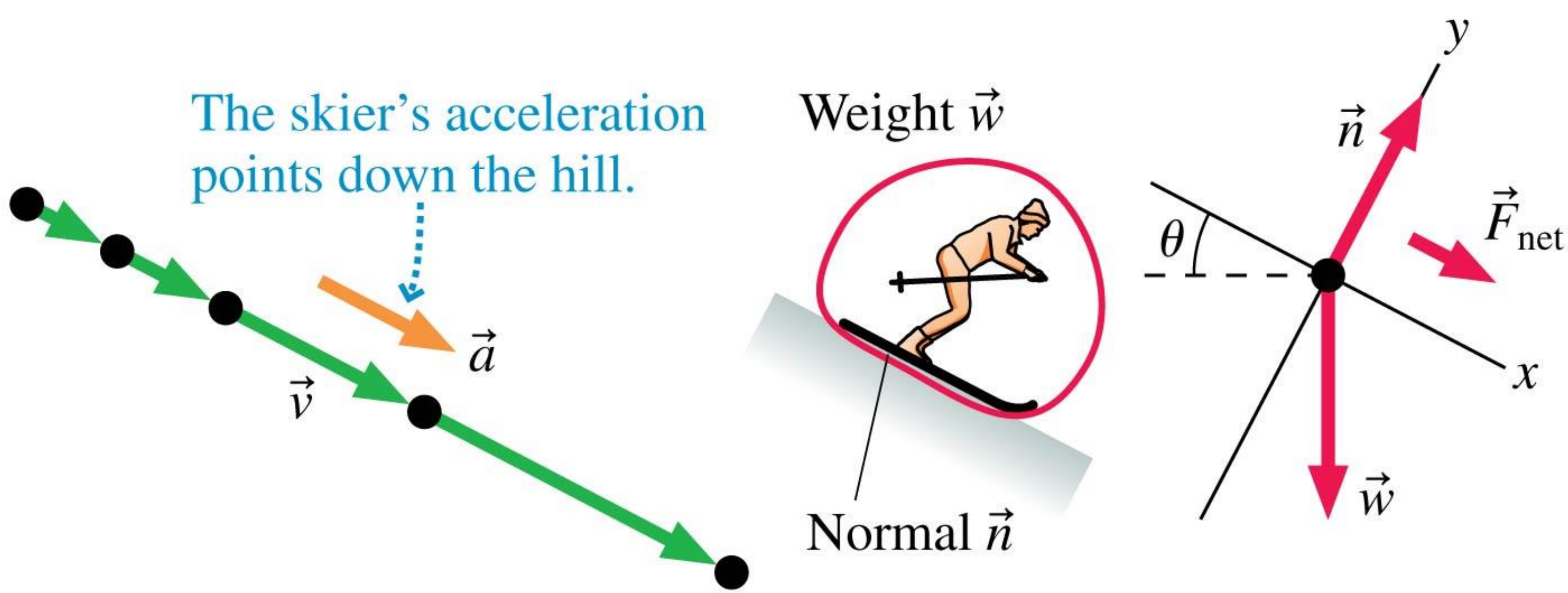
D. $n = 0$

E. Not enough information to judge the size of the normal force



Example 5.10 Acceleration of a downhill skier

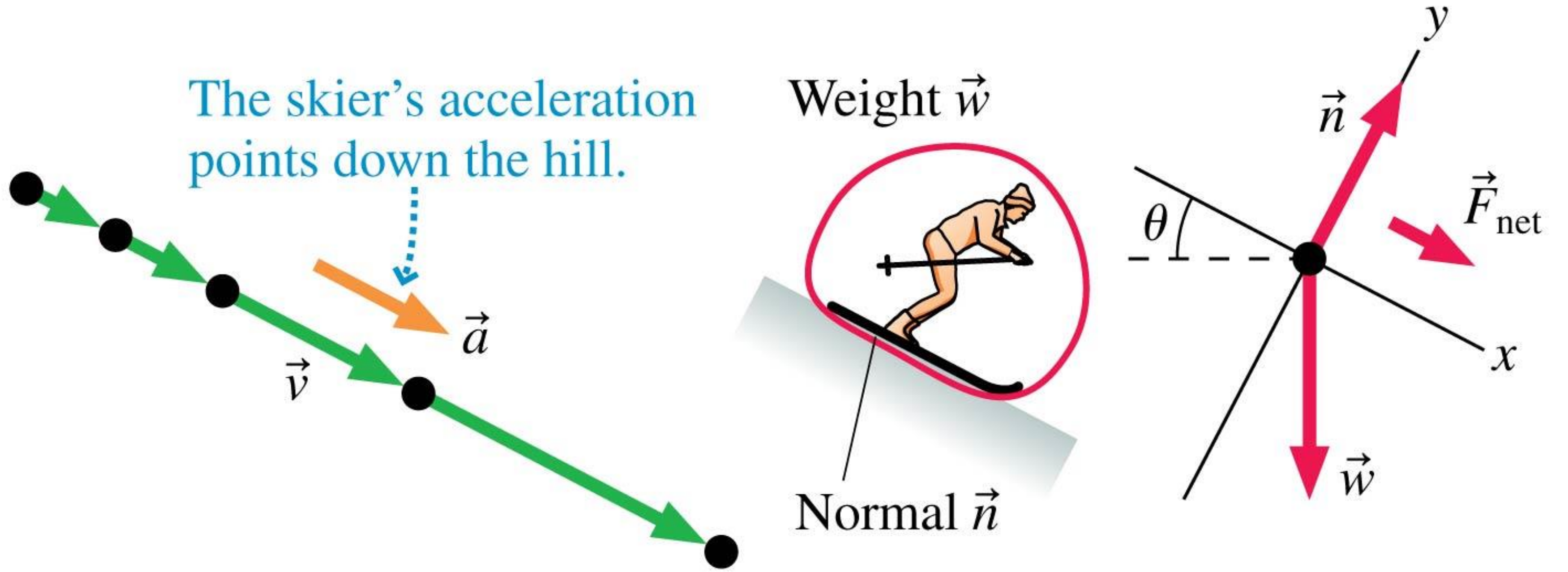
A skier slides down a steep 27° slope. On a slope this steep, friction is much smaller than the other forces at work and can be ignored. What is the skier's acceleration?



Example 5.10 Acceleration of a downhill skier (cont.)

PREPARE We choose a coordinate system tilted so that the *x*-axis points down the slope.

This greatly simplifies the analysis because with this choice $a_y = 0$ (the skier does not move in the *y*-direction at all). The free-body diagram is based on the information in the figure.



Example 5.10 Acceleration of a downhill skier (cont.)

SOLVE We can now use Newton's second law in component form to find the skier's acceleration:

$$\Sigma F_x = w_x + n_x = ma_x$$

$$\Sigma F_y = w_y + n_y = ma_y$$

Because $\vec{n}$ points directly in the positive y-direction, $n_y = n$ and $n_x = 0$. The figure showed the important fact that the angle between $\vec{w}$ and the negative y-axis is the *same* as the slope angle θ. With this information, the components of $\vec{w}$ are $w_x = w \sin\theta = mg \sin\theta$ and $w_y = -w \cos\theta = -mg \cos\theta$, where we used the fact that $w = mg$. With these components in hand, Newton's second law becomes

$$\Sigma F_x = w_x + n_x = m_x\, g \sin\theta = ma_x$$

$$\Sigma F_y = w_y + n_y = -mg \cos\theta + n = ma_y = 0$$

Example 5.10 Acceleration of a downhill skier (cont.)

In the second equation we used the fact that $a_y = 0$. The *m* cancels in the first of these equations, leaving us with

$$a_x = g \sin\theta$$

This is the expression for acceleration on a frictionless surface that we presented, without proof, in Chapter 3. Now we've justified our earlier assertion. We can use this to calculate the skier's acceleration:

$$a_x = g \sin\theta = (9.8 \text{ m/s}^2) \sin 27° = 4.4 \text{ m/s}^2$$

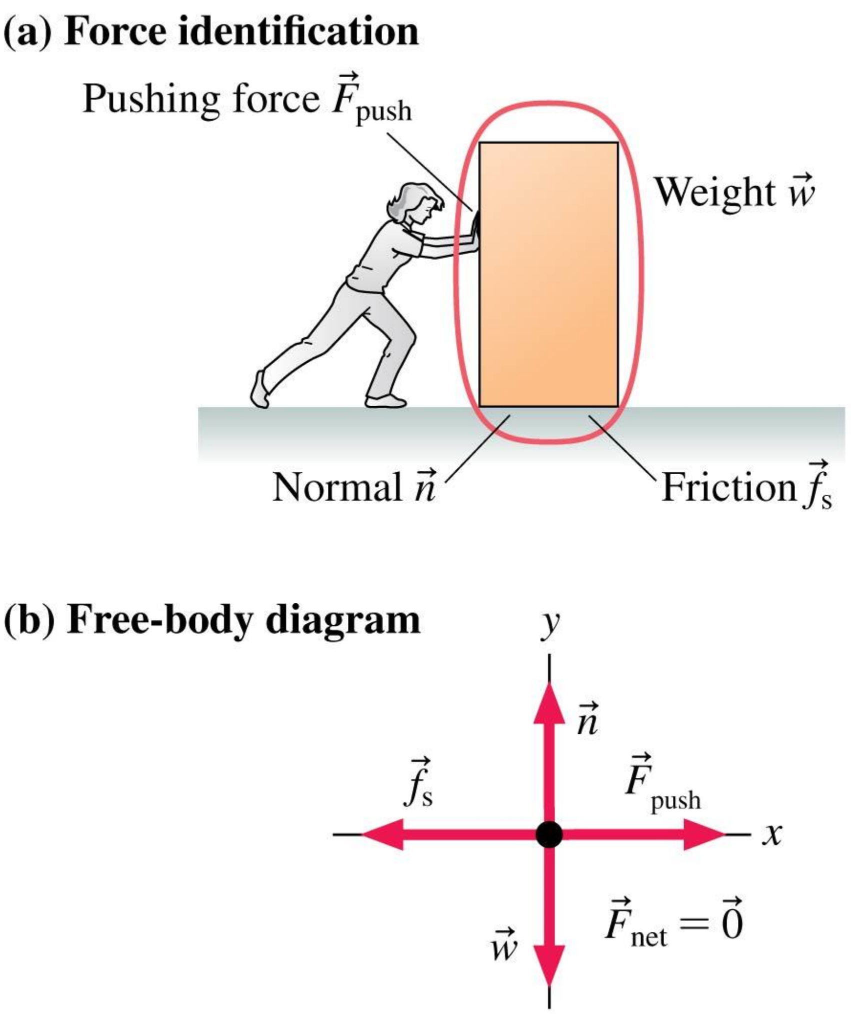
Example 5.10 Acceleration of a downhill skier (cont.)

ASSESS Our result shows that when $\theta = 0$, so that the slope is horizontal, the skier's acceleration is zero, as it should be. Further, when $\theta = 90°$ (a vertical slope), his acceleration is g, which makes sense because he's in free fall when $\theta = 90°$. Notice that the mass canceled out, so we didn't need to know the skier's mass. We first saw the formula for the acceleration, but now we see the physical reasons behind it.

Section 5.5 Friction

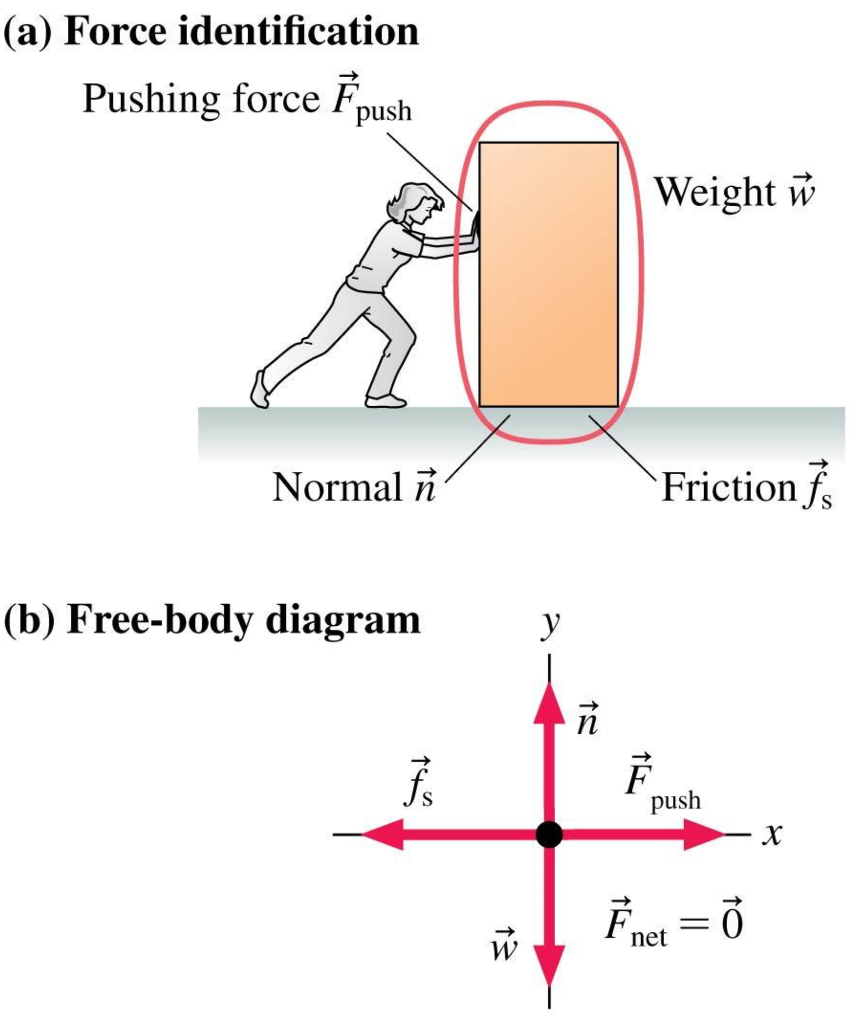
Static Friction

- Static friction is the force that a surface exerts on an object to keep it from slipping across the surface.
- To find the direction of $\vec{f}_s$, decide which way the object would move if there were no friction. The static friction force then points in the opposite direction.



Static Friction

- The box is in static equilibrium.
- The static friction force must exactly balance the pushing force.

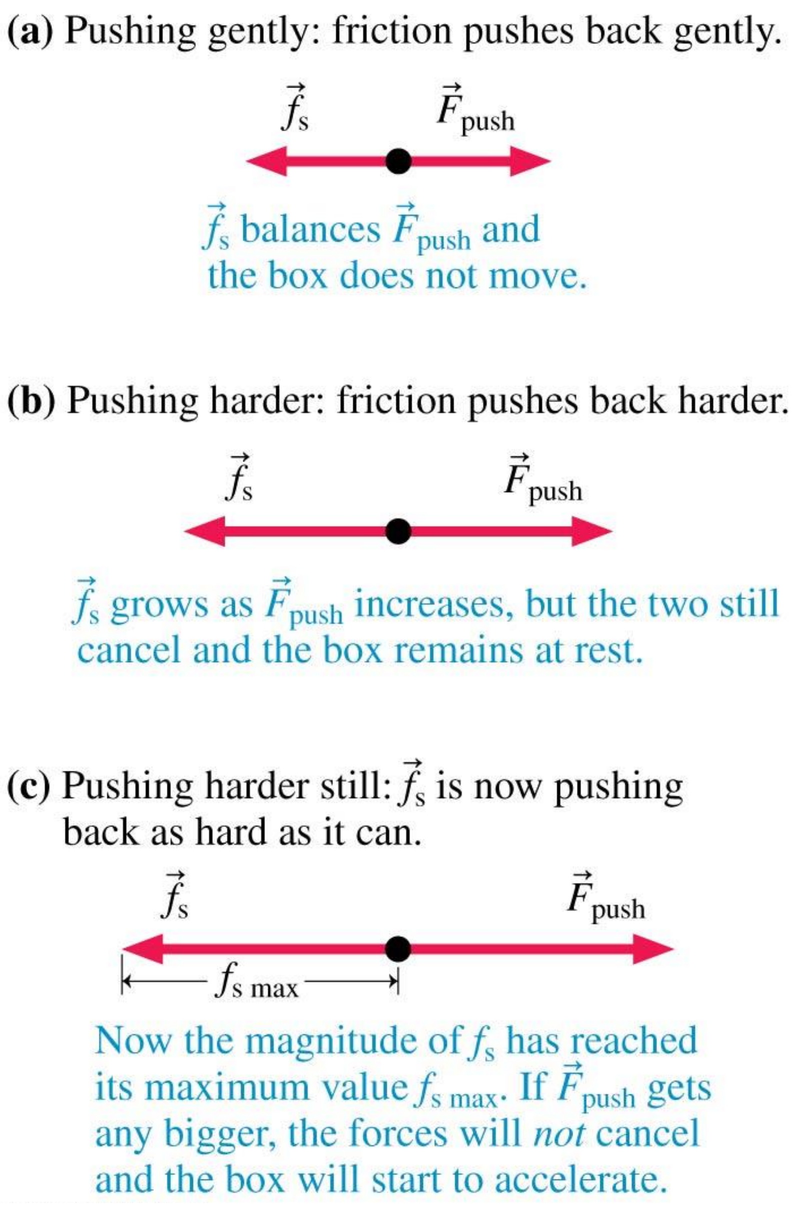


Static Friction

- The harder the woman pushes, the harder the friction force from the floor pushes back.
- If the woman pushes hard enough, the box will slip and start to move.
- The static friction force has a maximum possible magnitude:

$$f_{s\,max} = \mu_s n$$

where μ_s is called the **coefficient of static friction.**

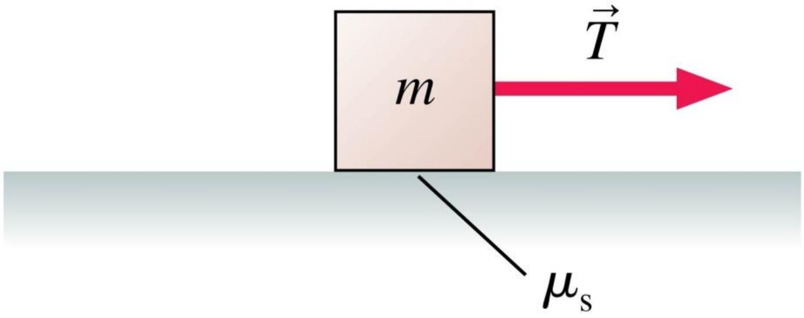


Static Friction

- The direction of static friction is such as to oppose motion.
- The magnitude f_s of static friction adjusts itself so that the net force is zero and the object doesn't move.
- The magnitude of static friction cannot exceed the maximum value $f_{s\ max}$. If the friction force needed to keep the object stationary is greater than $f_{s\ max}$, the object slips and starts to move.

QuickCheck 5.7

A box on a rough surface is pulled by a horizontal rope with tension T. The box **is not moving**. In this situation:



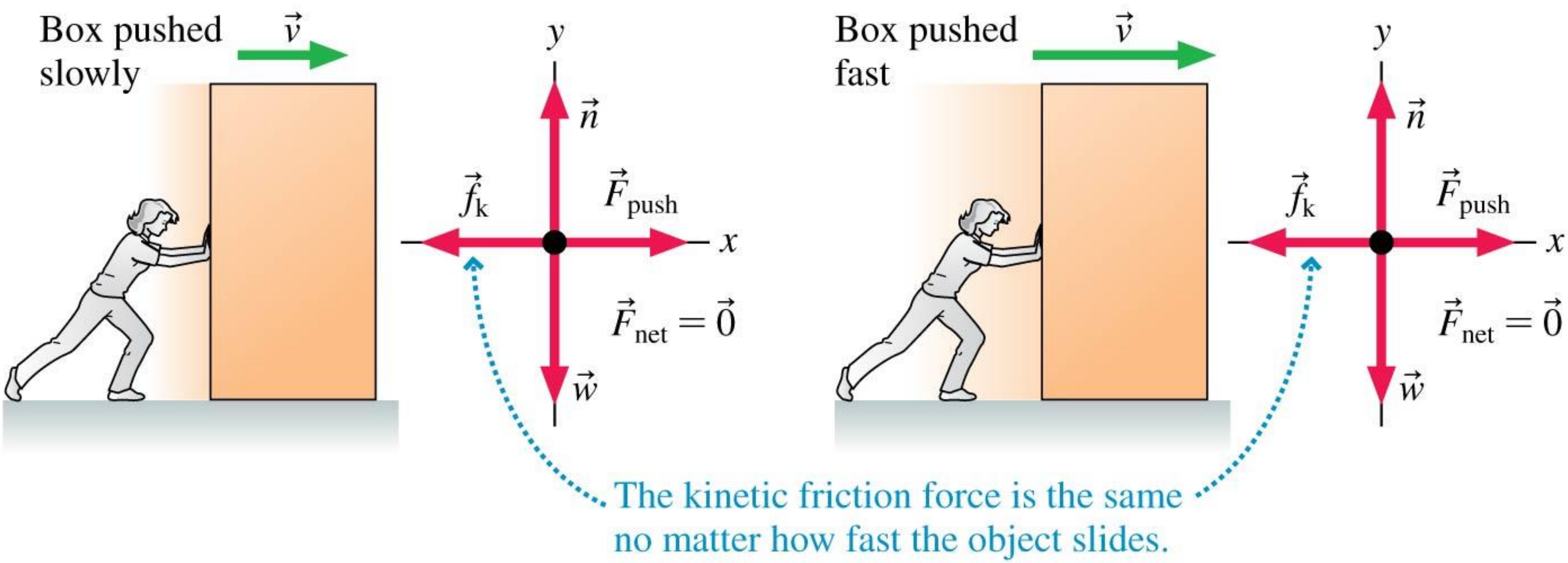
A. $f_s > T$
B. $f_s = T$
C. $f_s < T$
D. $f_s = \mu_s mg$
E. $f_s = 0$

Kinetic Friction

- Kinetic friction, unlike static friction, has a nearly constant magnitude given by

$$f_k = \mu_k n$$

where μ_k is called the **coefficient of kinetic friction.**



Friction Forces

TABLE 5.2 Coefficients of friction

Materials	Static μ_s	Kinetic μ_k
Rubber on concrete	1.00	0.80
Steel on steel (dry)	0.80	0.60
Steel on steel (lubricated)	0.10	0.05
Wood on wood	0.50	0.20
Wood on snow	0.12	0.06
Ice on ice	0.10	0.03

Working with Friction Forces

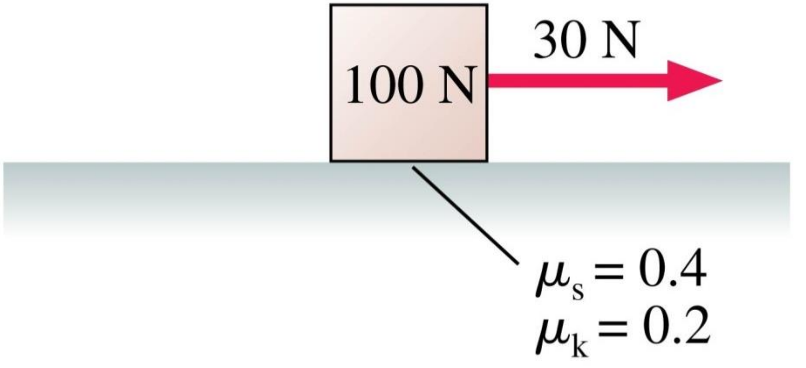
$$\text{Static: } \vec{f}_{\text{s}} = (\text{magnitude} \le f_{\text{s max}} = \mu_{\text{s}} n,$$
$$\text{direction as necessary to prevent motion})$$

$$\text{Kinetic: } \vec{f}_{\text{k}} = (\mu_{\text{k}} n, \text{ direction opposite the motion})$$

QuickCheck 5.8

A box with a weight of 100 N is at rest. It is then pulled by a 30 N horizontal force.

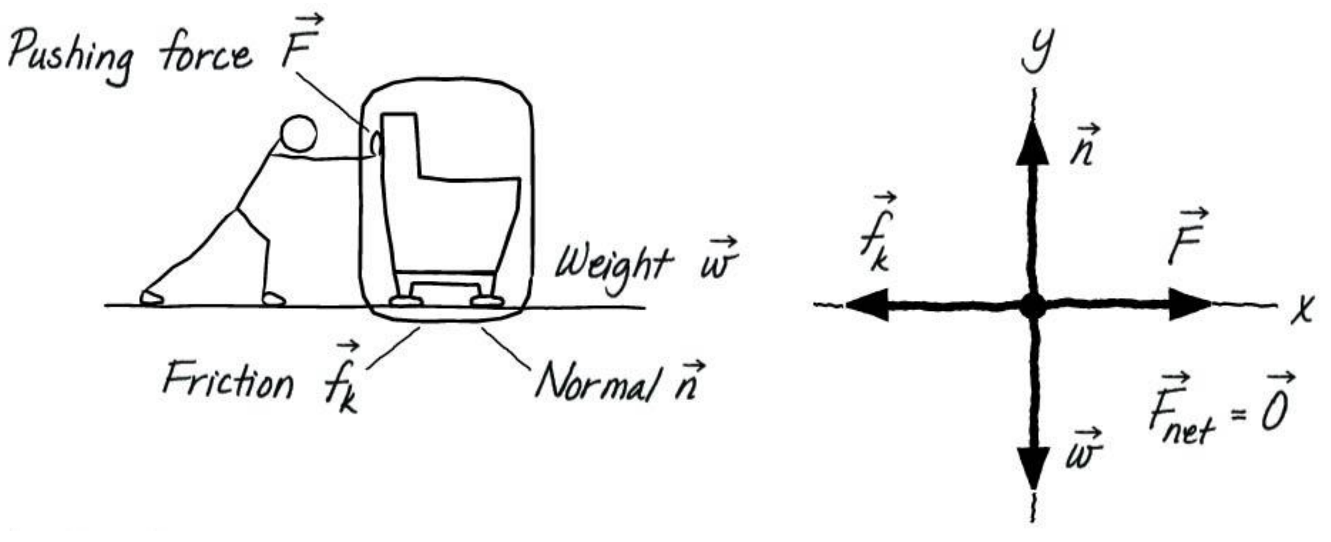
Does the box move?



A. Yes
B. No
C. Not enough information to say

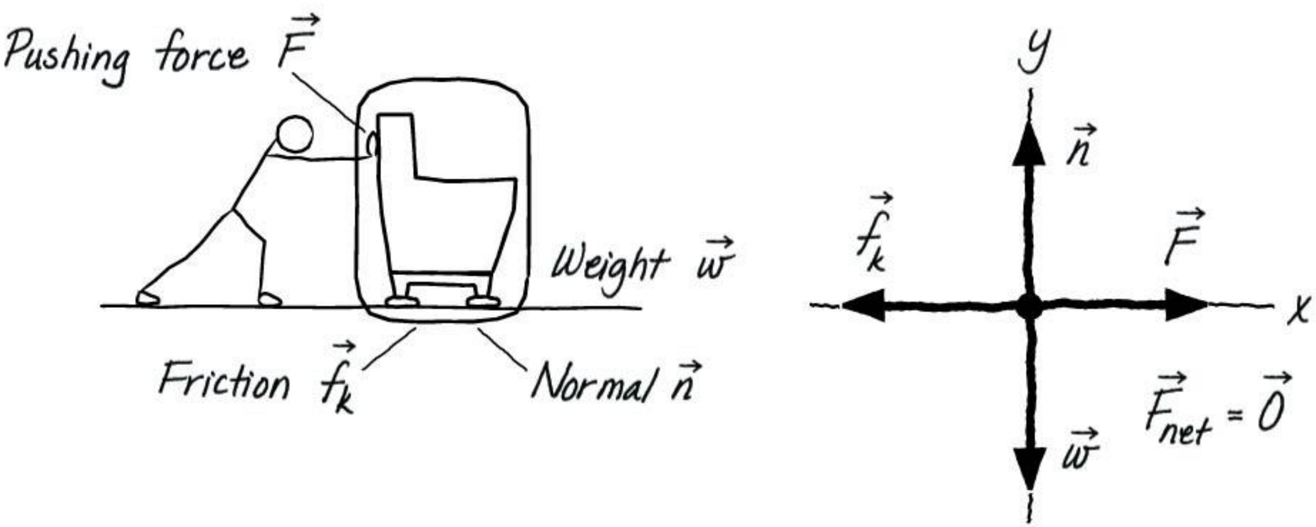
Example 5.11 Finding the force to slide a sofa

Sarah wants to move her 32 kg sofa to a different room in the house. She places "sofa sliders," slippery disks with $\mu_k = 0.080$, on the carpet, under the feet of the sofa. She then pushes the sofa at a steady 0.40 m/s across the floor. How much force does she apply to the sofa?



Example 5.11 Finding the force to slide a sofa (cont.)

PREPARE Let's assume the sofa slides to the right. In this case, a kinetic friction force $\vec{f}_k$, opposes the motion by pointing to the left. In the figure, we identify the forces acting on the sofa and construct a free-body diagram.



Example 5.11 Finding the force to slide a sofa (cont.)

SOLVE The sofa is moving at a constant speed, so it is in dynamic equilibrium with $\vec{F}_{\text{net}} = \vec{0}$. This means that the x- and y-components of the net force must be zero:

$$\Sigma F_x = n_x + w_x + F_x + (f_k)_x = 0 + 0 + F - f_k = 0$$

$$\Sigma F_y = n_y + w_y + F_y + (f_k)_y = n - w + 0 + 0 = 0$$

In the first equation, the x-component of $\vec{f}_k$ is equal to $-f_k$ because $\vec{f}_k$ is directed to the left. Similarly, $w_y = -w$ because the weight force points down.

From the first equation, we see that Sarah's pushing force is $F = f_k$. To evaluate this, we need f_k. Here we can use our model for kinetic friction:

$$f_k = \mu_k n$$

Example 5.11 Finding the force to slide a sofa (cont.)

Let's look at the vertical motion first. The second equation ultimately reduces to

$$n - w = 0$$

The weight force $w = mg$, so we can write

$$n = mg$$

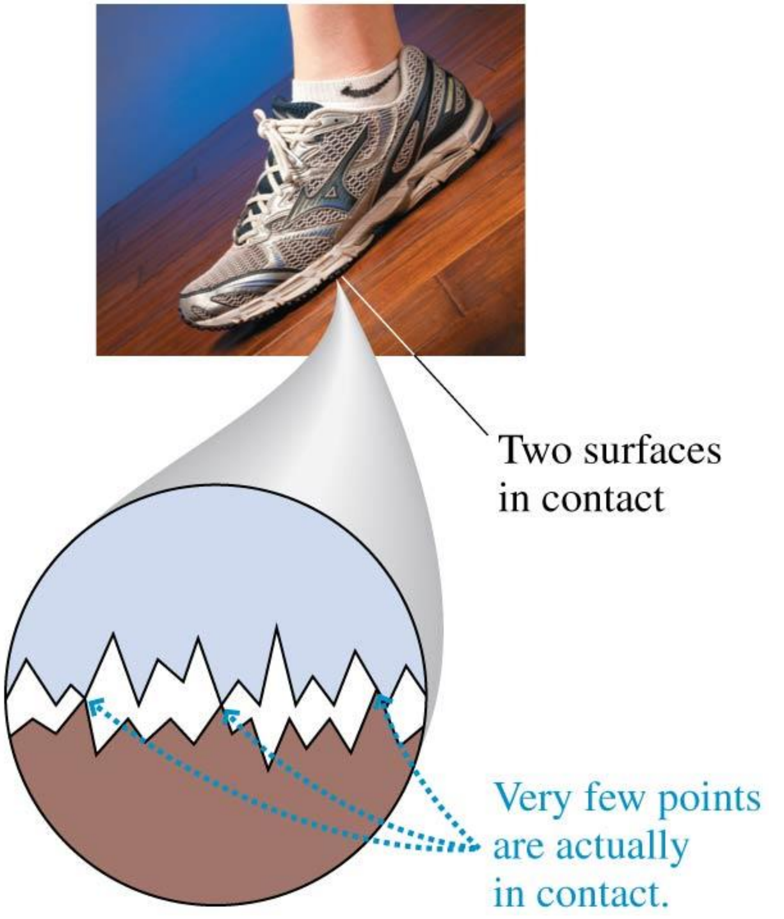
This is a common result we'll see again. The force that Sarah pushes with is equal to the friction force, and this depends on the normal force and the coefficient of kinetic friction, $\mu_k = 0.080$:

$$F = f_k = \mu_k n = \mu_k mg$$

$$= (0.080)(32\text{ kg})(9.80\text{ m/s}^2) = 25\text{ N}$$

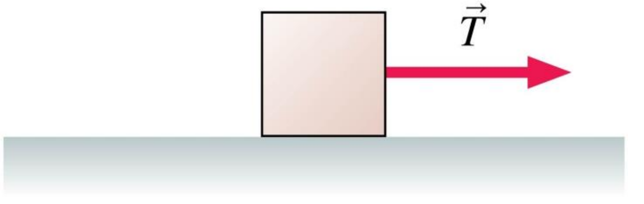
Causes of Friction

- All surfaces are very rough on a microscopic scale.
- When two objects are placed in contact, the high points on one surface become jammed against the high points on the other surface.
- The amount of contact depends on how hard the surfaces are pushed together.



QuickCheck 5.9

A box is being pulled to the right over a rough surface. $T > f_k$, so the box is speeding up. Suddenly the rope breaks. What happens? The box



A. Stops immediately.

B. Continues with the speed it had when the rope broke.

C. Continues speeding up for a short while, then slows and stops.

D. Keeps its speed for a short while, then slows and stops.

E. Slows steadily until it stops.

Reading Question 5.3

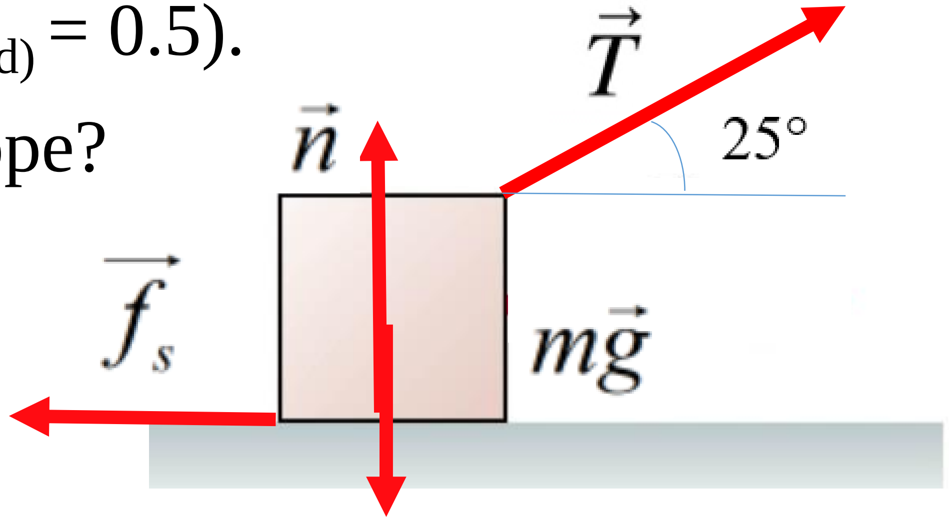
In general, the coefficient of static friction is

A. Smaller than the coefficient of kinetic friction.
B. Equal to the coefficient of kinetic friction.
C. Greater than the coefficient of kinetic friction.

Example Problem

A wooden box, with a mass of 22 kg, is pulled at a constant speed with a rope that makes an angle of 25° with the wooden floor ($\mu_s = \mu_{s(wood\text{-}wood)} = 0.5$).

What is the tension in the rope?



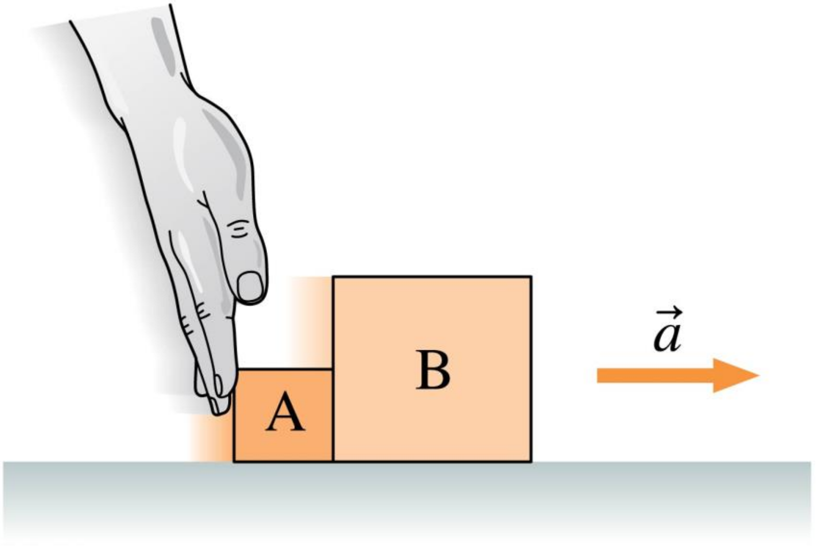
$$\left.\begin{aligned} T\sin(25°) + n - mg &= 0 \\ T\cos(25°) - f_s &= 0 \\ f_s = \mu_s n = \mu_{s(wood-wood)} n &= 0.5n \end{aligned}\right\} \Rightarrow T = \frac{\mu_s mg}{\cos(25°) + \mu_s \sin(25°)} \approx 96.5\ \text{N}$$

Section 5.7 Interacting Objects

Interacting Objects

- Newton's third law states:
  - Every force occurs as one member of an action/reaction pair of forces. The two members of the pair always act on *different* objects.
  - The two members of an action/reaction pair point in *opposite* directions and are equal in magnitude.

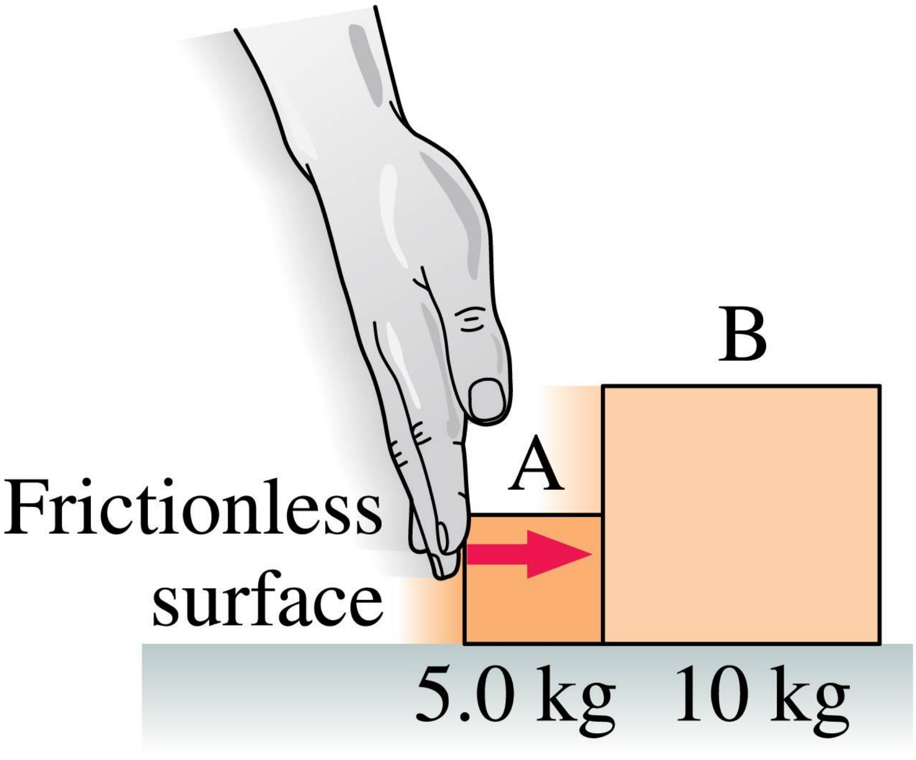
Objects in Contact



- To analyze block A's motion, we need to identify all the forces acting on it and then draw its free-body diagram.
- We repeat the same steps to analyze the motion of block B.
- However, the forces on A and B are *not* independent: Forces $\vec{F}_{\text{B on A}}$ acting on block A and $\vec{F}_{\text{A on B}}$ acting on block B are an action/reaction pair and thus have the same magnitude.
- Because the two blocks are in contact, their accelerations must be the same: $a_{\text{A}x} = a_{\text{B}x} = a_x$.
- We can't solve for the motion of one block without considering the motion of the other block.

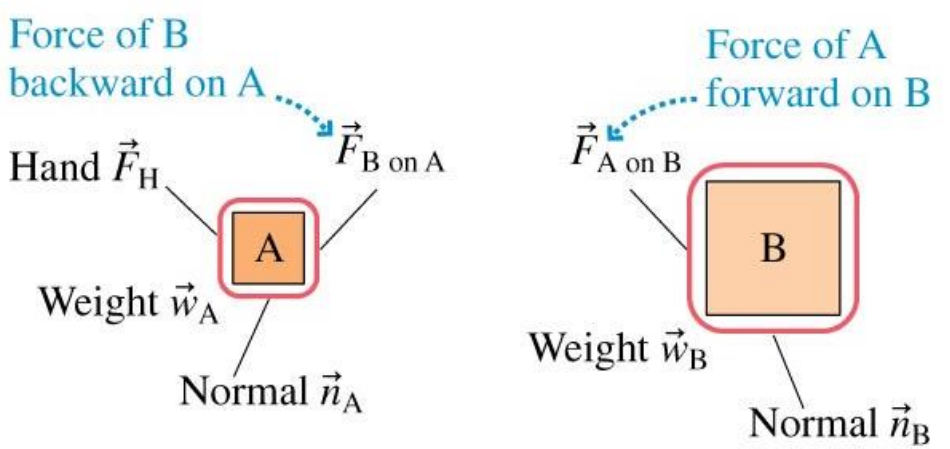
Example 5.15 Pushing two blocks

The figure shows a 5.0 kg block A being pushed with a 3.0 N force. In front of this block is a 10 kg block B; the two blocks move together. What force does block A exert on block B?

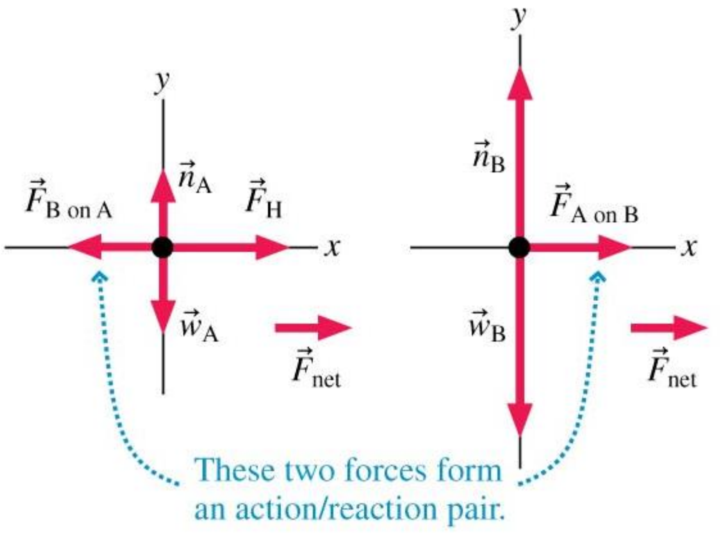


Example 5.15 Pushing two blocks (cont.)

PREPARE The visual overview of the figure lists the known information and identifies $F_{\text{A on B}}$ as what we're trying to find. Then, we've drawn *separate* force identification diagrams and *separate* free-body diagrams for the two blocks. Both blocks have a weight force and a normal force, so we've used subscripts A and B to distinguish between them.



Example 5.15 Pushing two blocks (cont.)



The force $\vec{F}_{A\ on\ B}$ is the contact force that block A exerts on B; it forms an action/reaction pair with the force $\vec{F}_{B\ on\ A}$ that block B exerts on A. Notice that force $\vec{F}_{A\ on\ B}$ is drawn acting on block B; it is the force *of* A *on* B. **Force vectors are always drawn on the free-body diagram of the object that *experiences* the force**, not the object exerting the force. Because action/reaction pairs act in opposite directions, force $\vec{F}_{B\ on\ A}$ pushes backward on block A and appears on A's free-body diagram.

Example 5.15 Pushing two blocks (cont.)

SOLVE We begin by writing Newton's second law in component form for each block. Because the motion is only in the *x*-direction, we need only the *x*-component of the second law. For block A,

Known
$m_A = 5.0\text{ kg}$
$m_B = 10\text{ kg}$
$F_H = 3.0\text{ N}$

Find
$F_{A\text{ on }B}$

$$\Sigma F_x = (F_H)_x + (F_{B\text{ on }A})_x = m_A a_{Ax}$$

The force components can be "read" from the free-body diagram, where we see $\vec{F}$ pointing to the right and $\vec{F}_{B\text{ on }A}$ pointing to the left. Thus

$$F_H - F_{B\text{ on }A} = m_A a_{Ax}$$

Example 5.15 Pushing two blocks (cont.)

For B, we have

$$\Sigma F_x = (F_{\text{A on B}})_x = F_{\text{A on B}} = m_{\text{B}} a_{\text{B}x}$$

Known

$m_{\text{A}} = 5.0$ kg

$m_{\text{B}} = 10$ kg

$F_{\text{H}} = 3.0$ N

Find

$F_{\text{A on B}}$

We have two additional pieces of information: First, Newton's third law tells us that $F_{\text{B on A}} = F_{\text{A on B}}$. Second, the boxes are in contact and must have the same acceleration a_x; that is, $a_{\text{A}x} = a_{\text{B}x} = a_x$. With this information, the two x-component equations become

$$F_{\text{H}} - F_{\text{A on B}} = m_{\text{A}} a_x$$

$$F_{\text{A on B}} = m_{\text{B}} a_x$$

Example 5.15 Pushing two blocks (cont.)

$$F_{\mathrm{H}} - F_{\mathrm{A\,on\,B}} = m_{\mathrm{A}} a_x$$

$$F_{\mathrm{A\,on\,B}} = m_{\mathrm{B}} a_x$$

Our goal is to find $F_{\mathrm{A\,on\,B}}$, so we need to eliminate the unknown acceleration a_x. From the second equation, $a_x = F_{\mathrm{A\,on\,B}}/m_{\mathrm{B}}$. Substituting this into the first equation gives

$$F_{\mathrm{H}} - F_{\mathrm{A\,on\,B}} = \frac{m_{\mathrm{A}}}{m_{\mathrm{B}}} F_{\mathrm{A\,on\,B}}$$

This can be solved for the force of block A on block B, giving

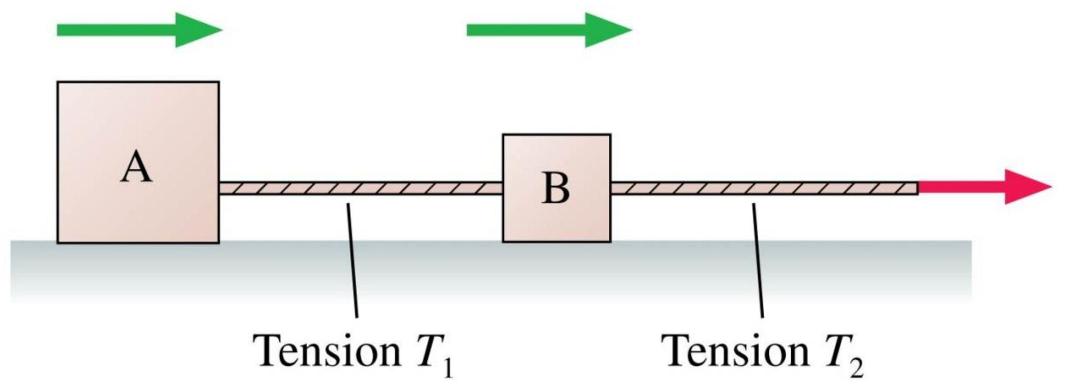
$$F_{\mathrm{A\,on\,B}} = \frac{F_{\mathrm{H}}}{1 + m_{\mathrm{A}}/m_{\mathrm{B}}} = \frac{3.0\ \mathrm{N}}{1 + (5.0\ \mathrm{kg})/(10\ \mathrm{kg})} = \frac{3.0\ \mathrm{N}}{1.5} = 2.0\ \mathrm{N}$$

Example 5.15 Pushing two blocks (cont.)

ASSESS Force F_H accelerates both blocks, a total mass of 15 kg, but force $F_{A\ on\ B}$ accelerates only block B, with a mass of 10 kg. Thus it makes sense that $F_{A\ on\ B} < F_H$.

QuickCheck 5.12

Boxes A and B are being pulled to the right on a frictionless surface; the boxes are speeding up. Box A has a larger mass than Box B. How do the two tension forces compare?

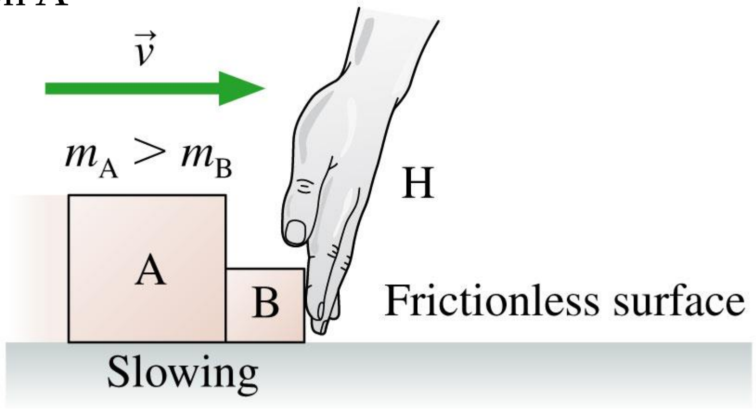


A. $T_1 > T_2$
B. $T_1 = T_2$
C. $T_1 < T_2$
D. Not enough information to tell

QuickCheck 5.13

Boxes A and B are sliding to the right on a frictionless surface. Hand H is slowing them. Box A has a larger mass than Box B. Considering only the *horizontal* forces:

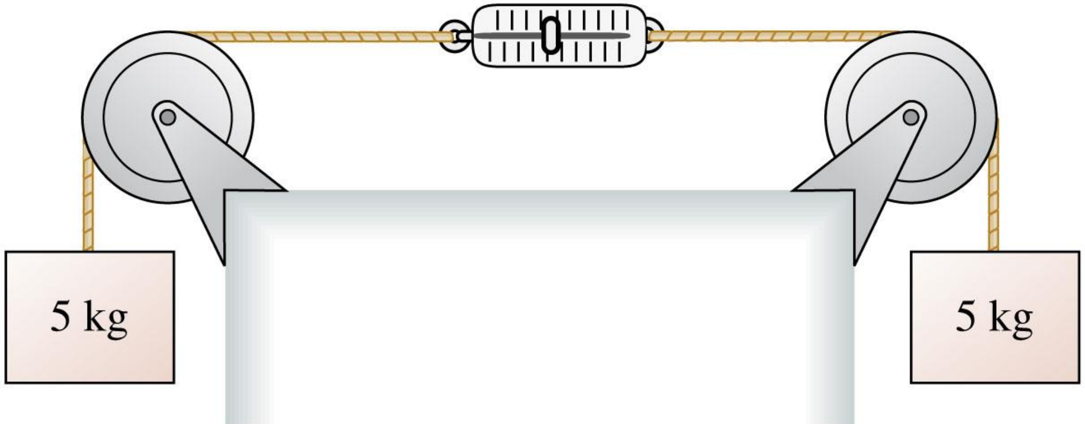
A. $F_{\text{B on H}} = F_{\text{H on B}} = F_{\text{A on B}} = F_{\text{B on A}}$
B. $F_{\text{B on H}} = F_{\text{H on B}} > F_{\text{A on B}} = F_{\text{B on A}}$
C. $F_{\text{B on H}} = F_{\text{H on B}} < F_{\text{A on B}} = F_{\text{B on A}}$
D. $F_{\text{H on B}} = F_{\text{H on A}} > F_{\text{A on B}}$



QuickCheck 5.14

The two masses are at rest. The pulleys are frictionless. The scale reads

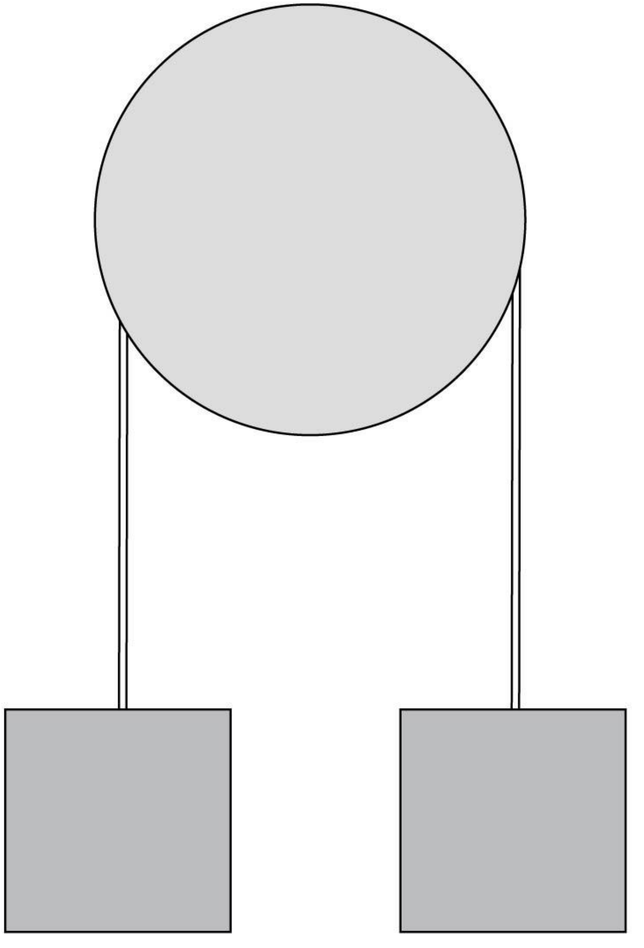
A. 0 kg
B. 5 kg
C. 10 kg



Reading Question 5.5

Two boxes are suspended from a rope over a pulley. Each box has weight 50 N. What is the tension in the rope?

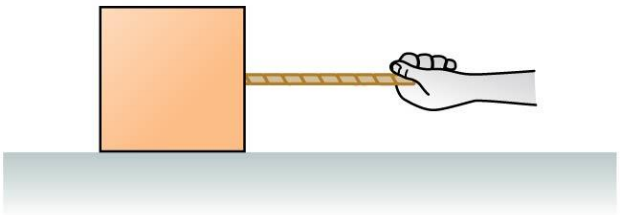
A. 25 N
B. 50 N
C. 100 N
D. 200 N

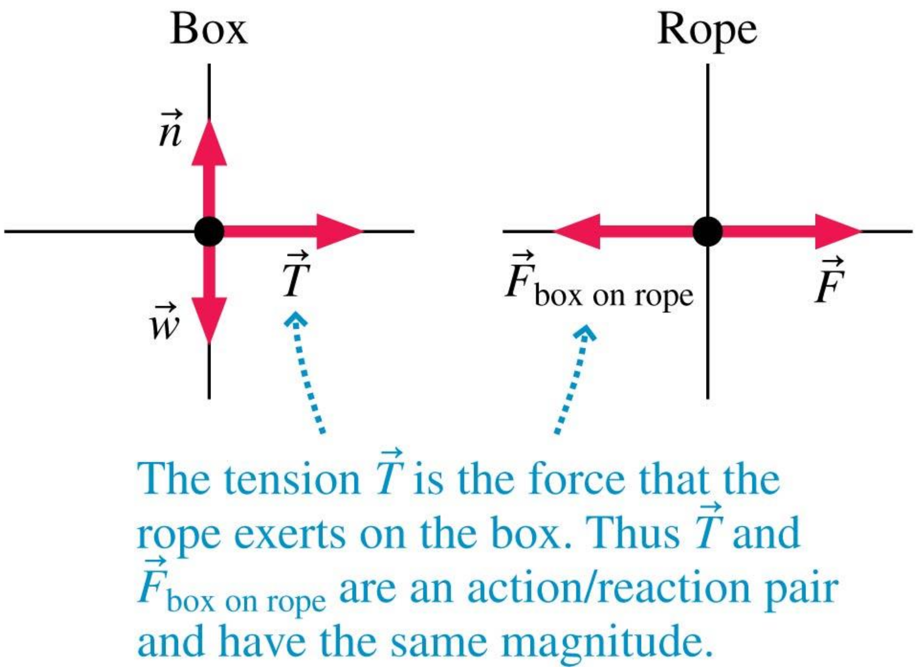


Section 5.8 Ropes and Pulleys

Ropes

- The box is pulled by the rope, so the box's free-body diagram shows a tension force $\vec{T}$.
- We make the massless string approximation that $m_{\text{rope}} = 0$.
- Newton's second law *for the rope* is thus





$$\Sigma F_x = F_{\text{box on rope}} = F - T = m_{\text{rope}} a_x = 0$$

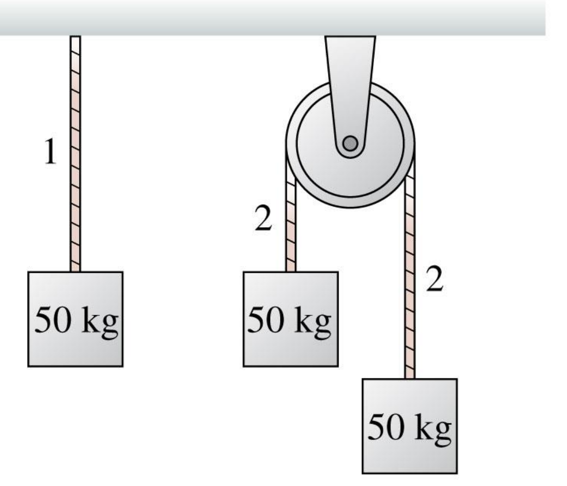
Ropes

- Generally, **the tension in a massless string or rope equals the magnitude of the force pulling on the end of the string or rope.** As a result:
  - A massless string or rope "transmits" a force undiminished from one end to the other: If you pull on one end of a rope with force F, the other end of the rope pulls on what it's attached to with a force of the same magnitude F.
  - The tension in a massless string or rope is the same from one end to the other.

QuickCheck 5.10

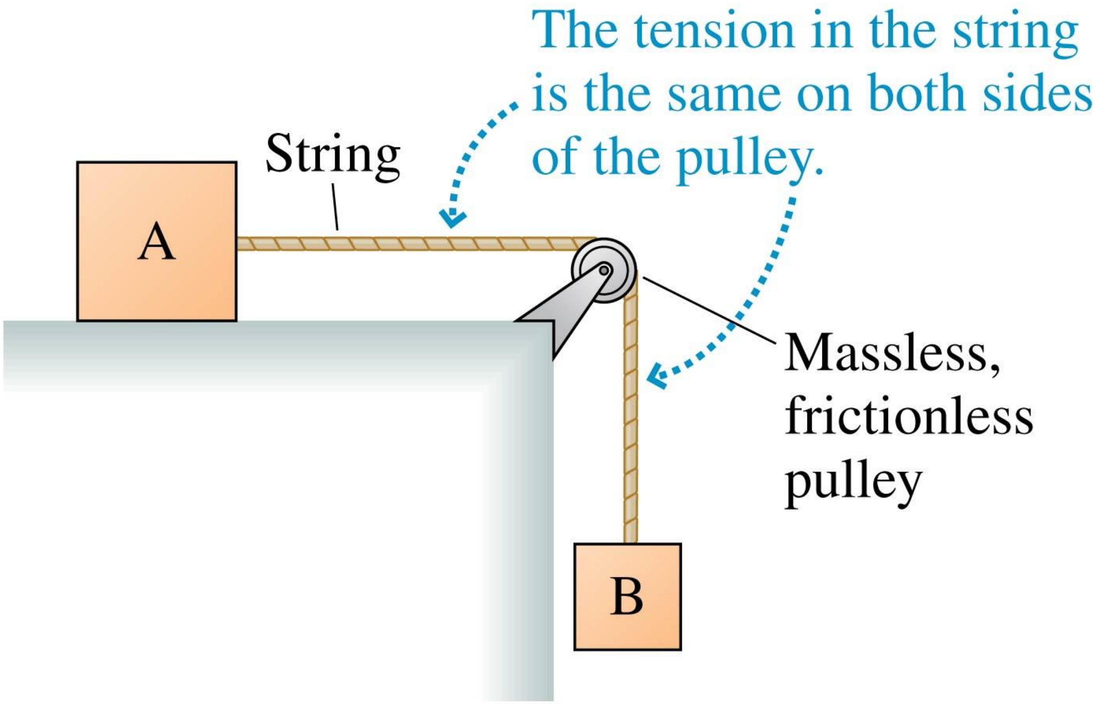
All three 50-kg blocks are at rest. The tension in rope 2 is

A. Greater than the tension in rope 1.
B. Equal to the tension in rope 1.
C. Less than the tension in rope 1.



Pulleys

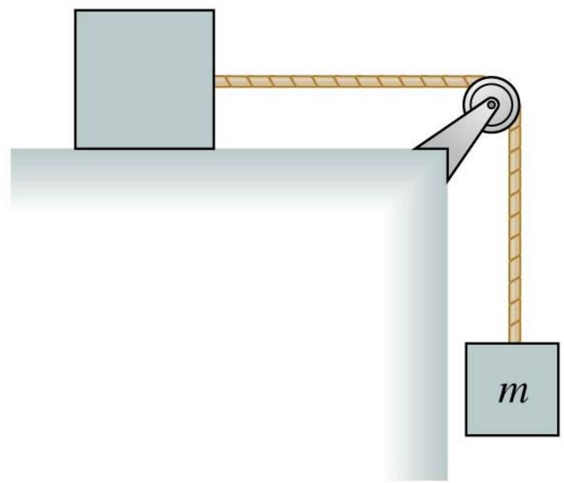
- The tension in a massless string is unchanged by passing over a massless, frictionless pulley.
- We'll assume such an ideal pulley for problems in this chapter.



QuickCheck 5.15

The top block is accelerated across a frictionless table by the falling mass m. The string is massless, and the pulley is both massless and frictionless. The tension in the string is

A. $T < mg$
B. $T = mg$
C. $T > mg$



Example 5.18 Lifting a stage set

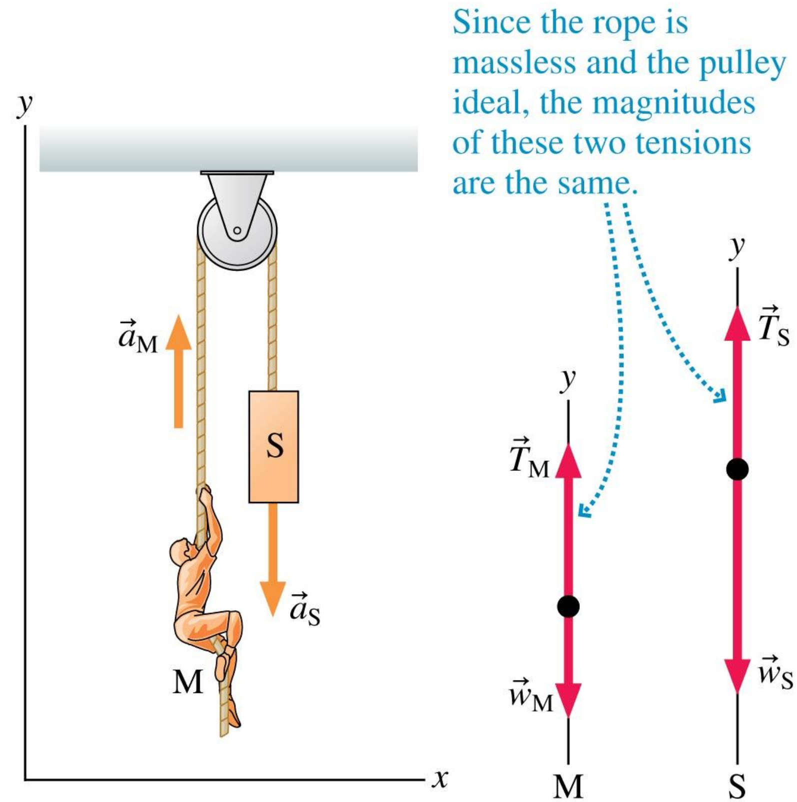
A 200 kg set used in a play is stored in the loft above the stage. The rope holding the set passes up and over a pulley, then is tied backstage. The director tells a 100 kg stagehand to lower the set. When he unties the rope, the set falls and the unfortunate man is hoisted into the loft. What is the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

Known

$m_M = 100$ kg
$m_S = 200$ kg

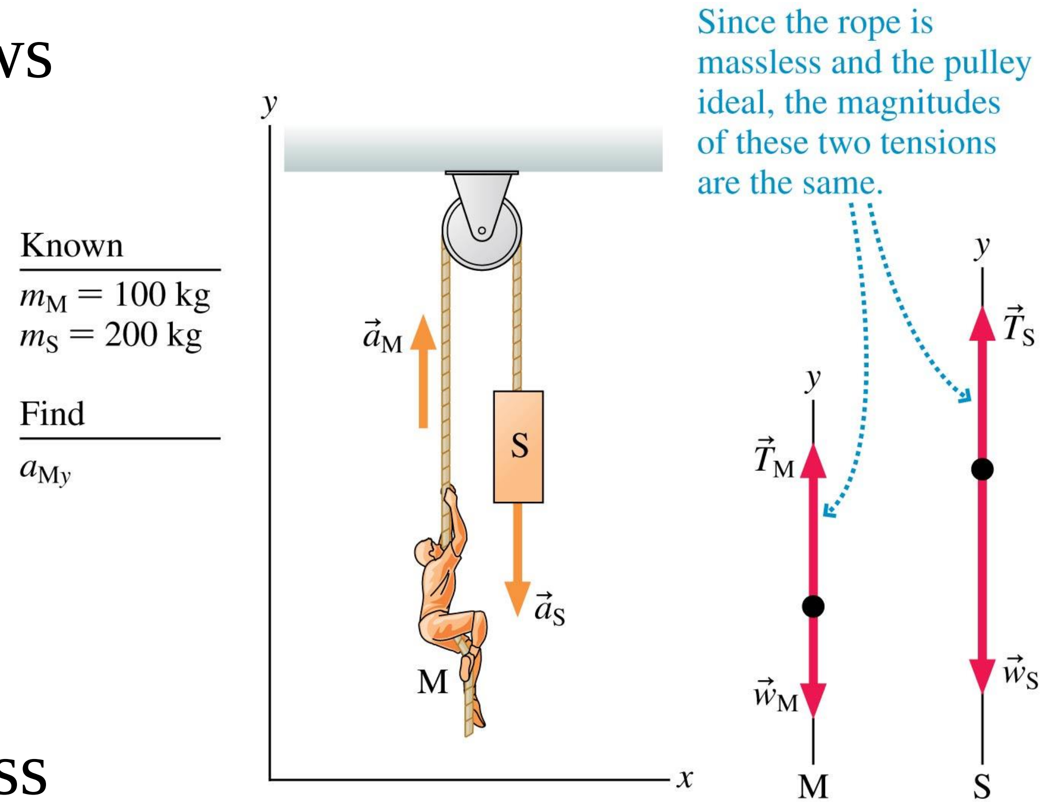
Find

a_{My}



Example 5.18 Lifting a stage set (cont.)

PREPARE The figure shows the visual overview. The objects of interest are the stagehand M and the set S, for which we've drawn separate free-body diagrams. Assume a massless rope and a massless, frictionless pulley. Tension forces $\vec{T}_S$ and $\vec{T}_M$ are due to a massless rope going over an ideal pulley, so their magnitudes are the same.



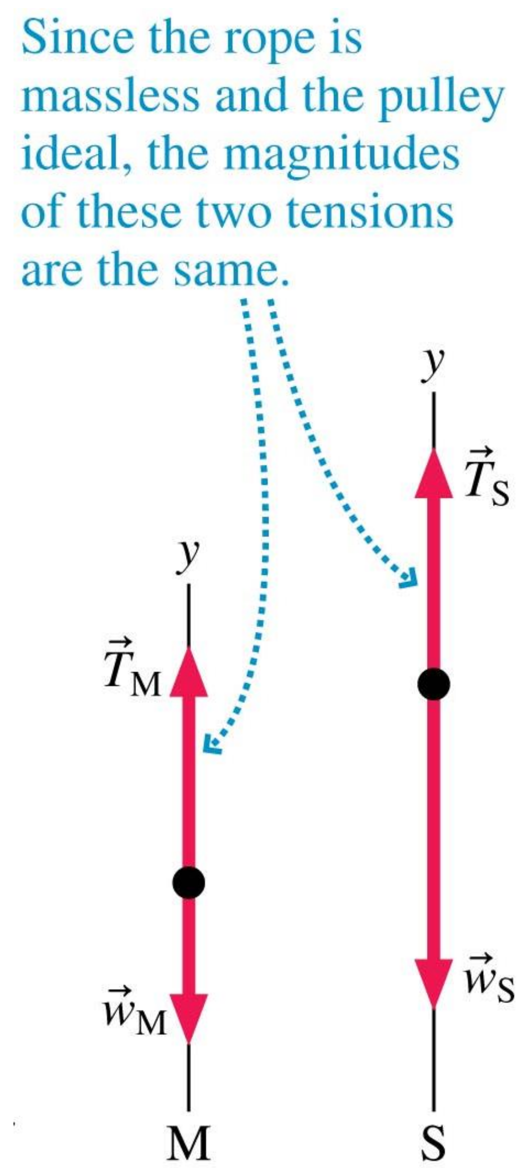
Example 5.18 Lifting a stage set (cont.)

SOLVE From the two free-body diagrams, we can write Newton's second law in component form. For the man we have

$$\Sigma F_{My} = T_M - w_M = T_M - m_M g = m_M a_{My}$$

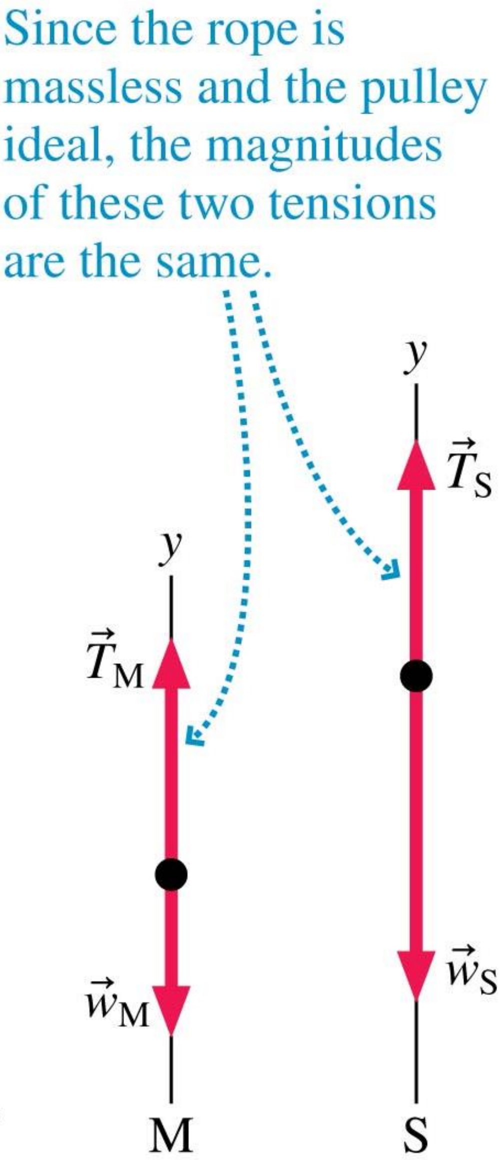
For the set we have

$$\Sigma FS_y = T_S - w_S = T_S - m_S g = m_S a_{Sy}$$



Example 5.18 Lifting a stage set (cont.)

Only the *y*-equations are needed. Because the stagehand and the set are connected by a rope, the upward distance traveled by one is the *same* as the downward distance traveled by the other. Thus the *magnitudes* of their accelerations must be the same, but, as the figure shows, their *directions* are opposite.

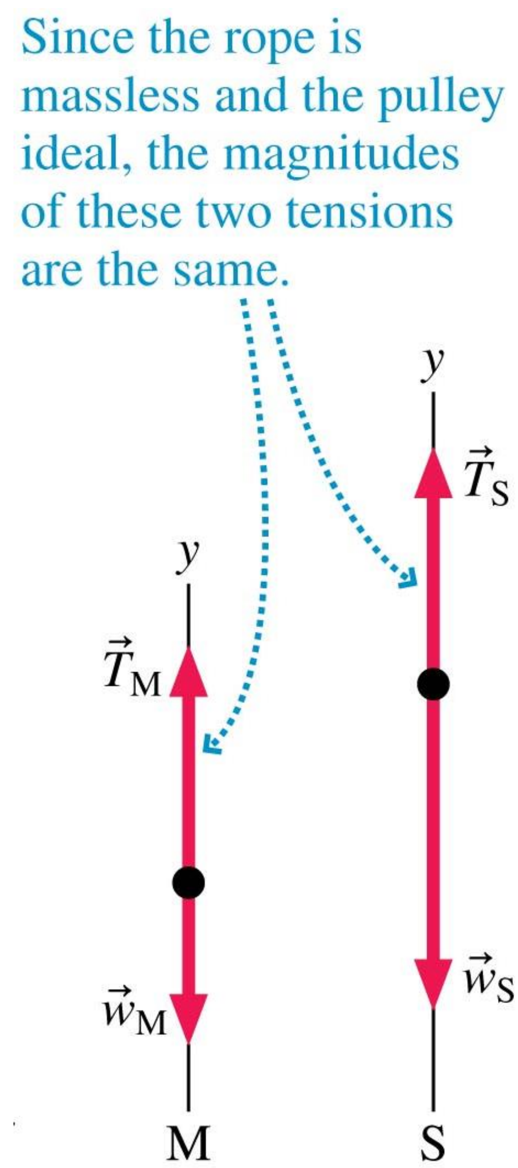


Example 5.18 Lifting a stage set (cont.)

We can express this mathematically as $a_{Sy} = -a_{My}$. We also know that the two tension forces have equal magnitudes, which we'll call T. Inserting this information into the above equations gives

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

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



Example 5.18 Lifting a stage set (cont.)

These are simultaneous equations in the two unknowns T and $a_{\mathrm{M}y}$. We can solve for T in the first equation to get

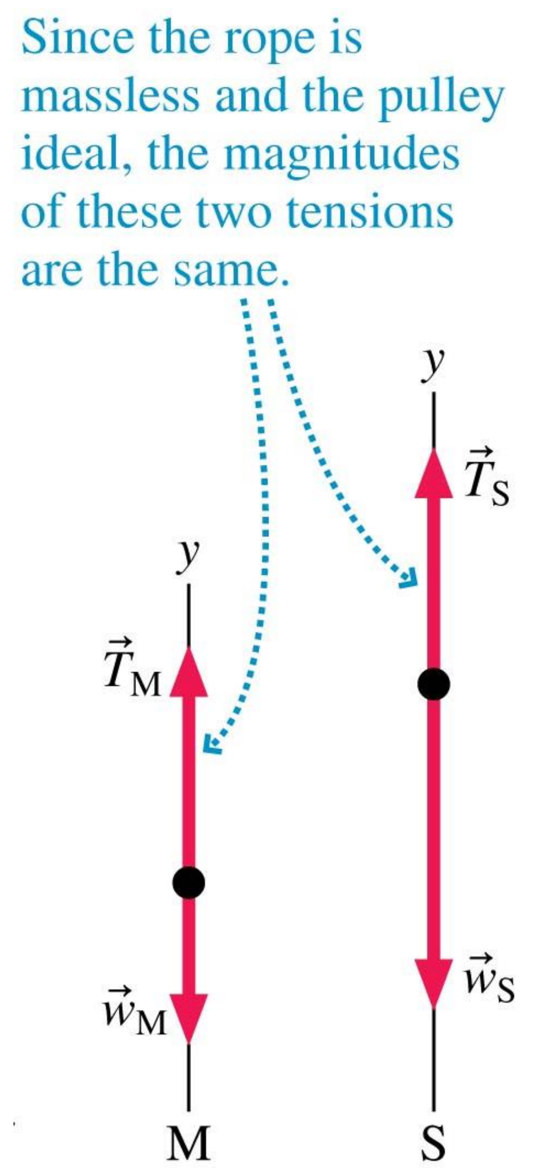
$$T = m_{\mathrm{M}}a_{\mathrm{M}y} + m_{\mathrm{M}}g$$

Inserting this value of T into the second equation then gives

$$m_{\mathrm{M}}a_{\mathrm{M}y} + m_{\mathrm{M}}g - m_{\mathrm{S}}g = -m_{\mathrm{S}}a_{\mathrm{M}y}$$

which we can rewrite as

$$(m_{\mathrm{S}} - m_{\mathrm{M}})g = (m_{\mathrm{S}} + m_{\mathrm{M}})a_{\mathrm{M}y}$$



Example 5.18 Lifting a stage set (cont.)

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

$$a_{My} = \frac{m_S - m_M}{m_S + m_M} g = \left(\frac{100 \text{ kg}}{300 \text{ kg}}\right) \times 9.80 \text{ m/s}^2 = 3.3 \text{ m/s}^2$$

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

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

Summary: General Strategy

Equilibrium Problems

Object at rest or moving at constant velocity.

PREPARE Make simplifying assumptions.

- Check that the object is either at rest or moving with constant velocity ($\vec{a} = \vec{0}$).
- Identify forces and show them on a free-body diagram.

SOLVE Use Newton's second law in component form:

$$\sum F_x = ma_x = 0$$

$$\sum F_y = ma_y = 0$$

"Read" the components from the free-body diagram.

ASSESS Is your result reasonable?

Summary: General Strategy

Dynamics Problems

Object accelerating.

PREPARE Make simplifying assumptions.
Make a **visual overview:**

- Sketch a pictorial representation.
- Identify known quantities and what the problem is trying to find.
- Identify all forces and show them on a free-body diagram.

SOLVE Use Newton's second law in component form:

$$\sum F_x = ma_x \quad \text{and} \quad \sum F_y = ma_y$$

"Read" the components of the vectors from the free-body diagram.
If needed, use kinematics to find positions and velocities.

ASSESS Is your result reasonable?

Summary: Important Concepts

Specific information about three important forces:

Weight $\vec{w} = (mg, \text{downward})$

Friction $\vec{f}_s = (0 \text{ to } \mu_s n, \text{direction as necessary to prevent motion})$

$\vec{f}_k = (\mu_k n, \text{direction opposite the motion})$

Summary: Important Concepts

Newton's laws are vector expressions. You must write them out by **components:**

$$(F_{\text{net}})_x = \sum F_x = ma_x$$

$$(F_{\text{net}})_y = \sum F_y = ma_y$$

For equilibrium problems, $a_x = 0$ and $a_y = 0$.

Summary: Applications

Apparent weight is the magnitude of the contact force supporting an object. It is what a scale would read, and it is your sensation of weight.

Apparent weight equals your true weight $w = mg$ only when the vertical acceleration is zero.

Summary: Important Concepts