Chapter 5: The Laws of Motion

PHY0101/PHY(PEN)101

Dynamics: What might cause one object to remain at rest and another object to accelerate?

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Outline

5.1 The Concept of Force
5.2 Newton’s First Law and Inertial Frames
5.3 Mass
5.4 Newton’s Second Law
5.5 The Gravitational Force and Weight
5.6 Newton’s Third Law
5.7 Some Applications of Newton’s Laws
5.8 Forces of Friction

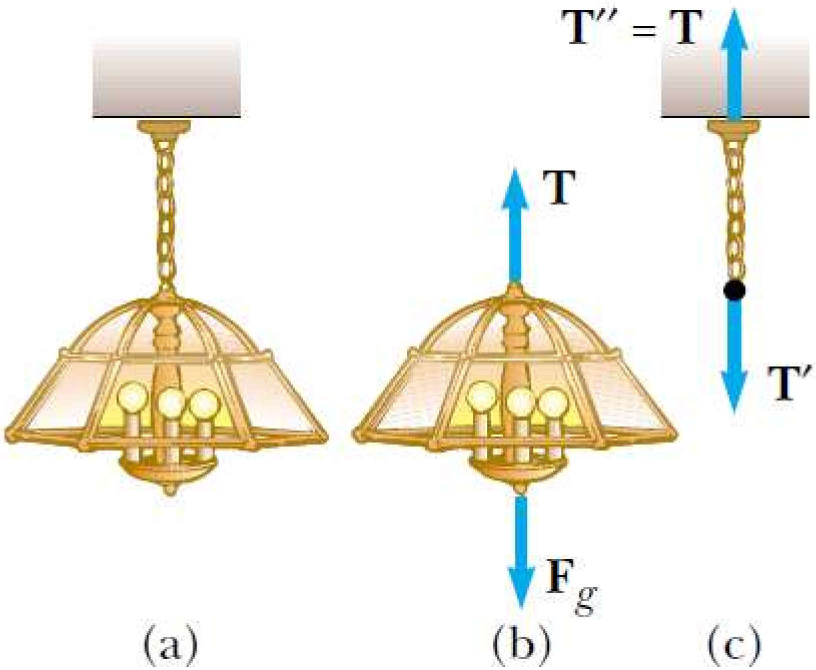
5.7 Some Applications of Newton's Laws

In this section we apply Newton's laws to objects that are either in equilibrium ($a=0$) or accelerating along a straight line under the action of constant external forces. Remember that when we apply Newton's laws to an object, we are interested only in **external** forces that act on the object.

We assume that the objects can be modeled as particles so that we need not worry about rotational motion. For now, we also neglect the effects of friction.

If the acceleration of an object that can be modeled as a particle is zero, the particle is in equilibrium.

Objects in Equilibrium



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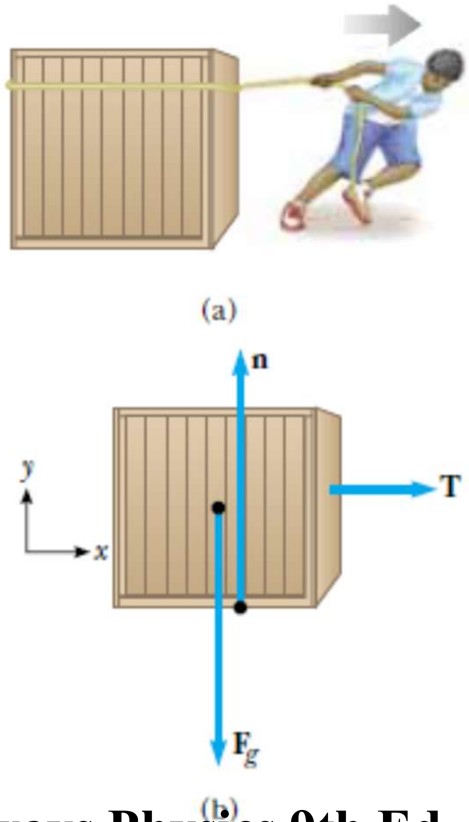
The condition $\Sigma F_y = ma_y = 0$ gives

$$\sum F_y = T - F_g = 0 \qquad \text{or} \qquad T = F_g$$

Objects Experiencing a Net Force



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$$\sum F_x = T = ma_x \qquad \text{or} \qquad a_x = \frac{T}{m}$$

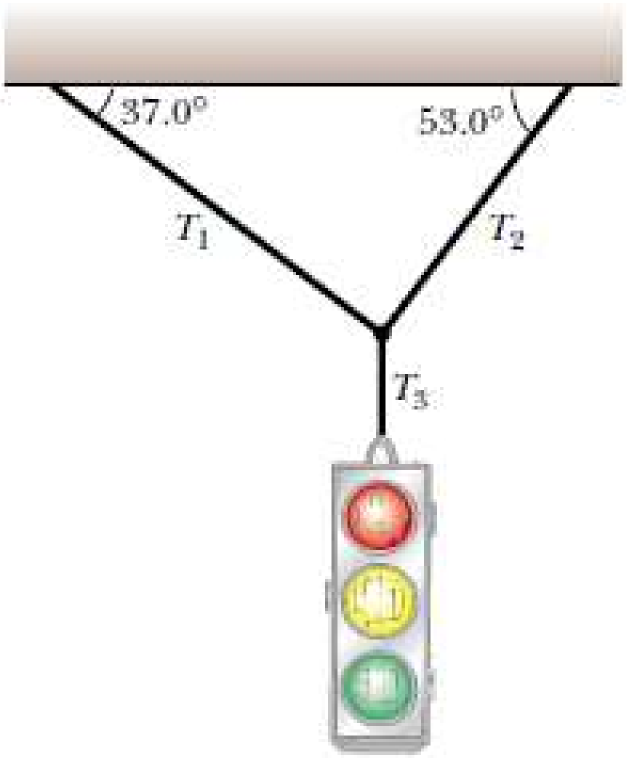
$$n = F_g$$

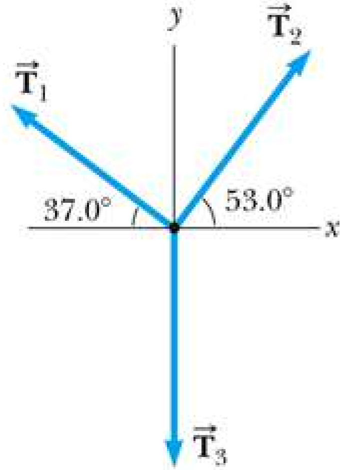
Example 5.4 A Traffic Light at Rest

A traffic light is weighting 122 N. 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 break?

($\sin 37° = 0.6, \cos 37° = 0.8$)

Solution:





$$T_3 = F_g = 122 \text{ N}$$

Force	x Component	y Component
$\mathbf{T}_1$	$-T_1 \cos 37.0°$	$T_1 \sin 37.0°$
$\mathbf{T}_2$	$T_2 \cos 53.0°$	$T_2 \sin 53.0°$
$\mathbf{T}_3$	0	-122 N

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$$\sum F_x = -T_1 \cos 37.0° + T_2 \cos 53.0° = 0$$

$$\sum F_y = T_1 \sin 37.0° + T_2 \sin 53.0° + (-122 \text{ N}) = 0$$

$$T_2 = T_1\left(\frac{\cos 37.0°}{\cos 53.0°}\right) = 1.33T_1$$

$$T_1 \sin 37.0° + (1.33T_1)(\sin 53.0°) - 122 \text{ N} = 0$$

$$T_1 = 73.4 \text{ N}$$

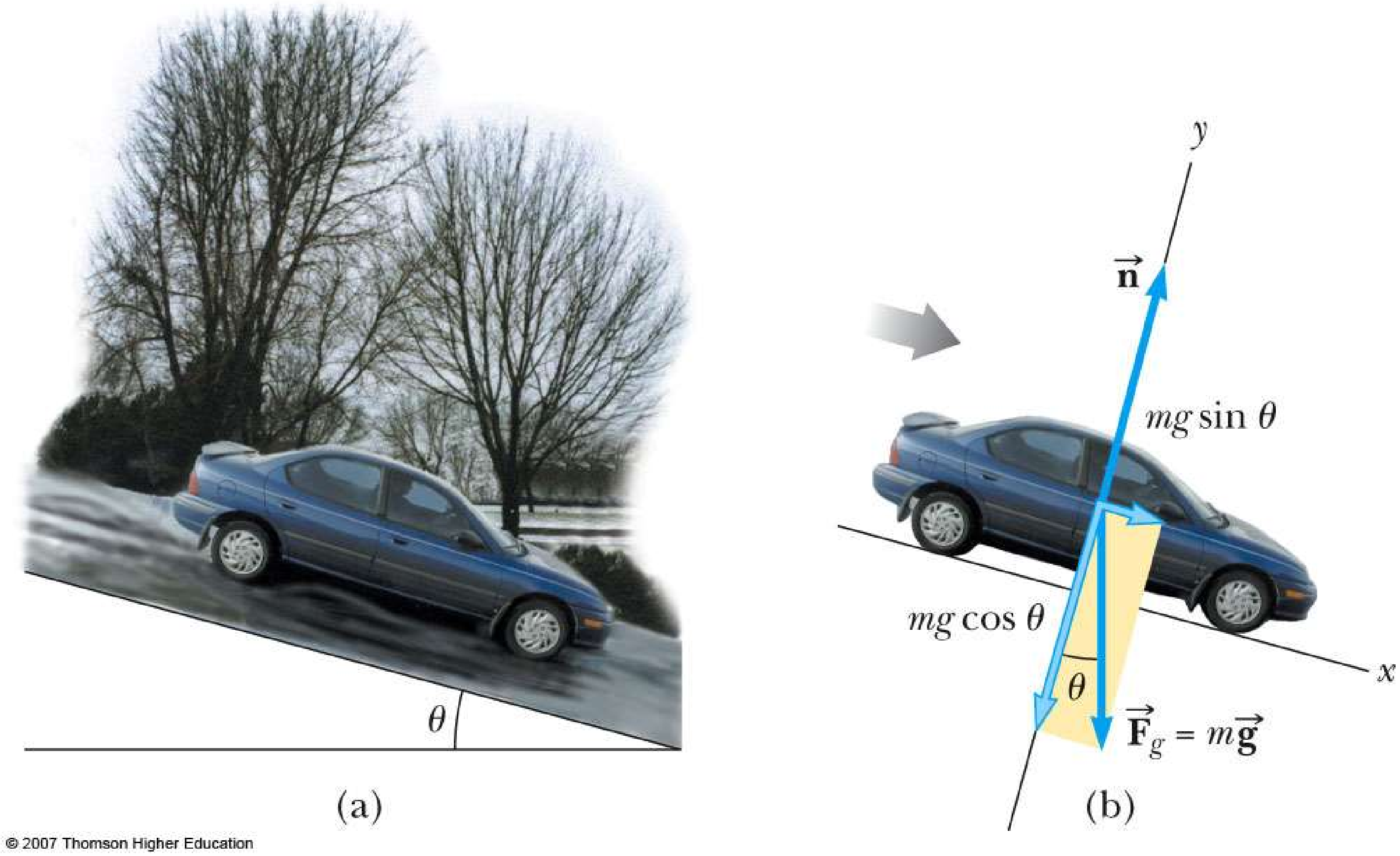
$$T_2 = 1.33T_1 = 97.4 \text{ N}$$

Both of these values are less than 100 N so the cables do not break.

Example 5.6: Runaway Car

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

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



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Solution: $$\sum F_x = mg \sin \theta = ma_x$$

$$\sum F_y = n - mg \cos \theta = 0$$

$$a_x = \boxed{g \sin \theta}$$

(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, and what is the car's speed as it arrives there?

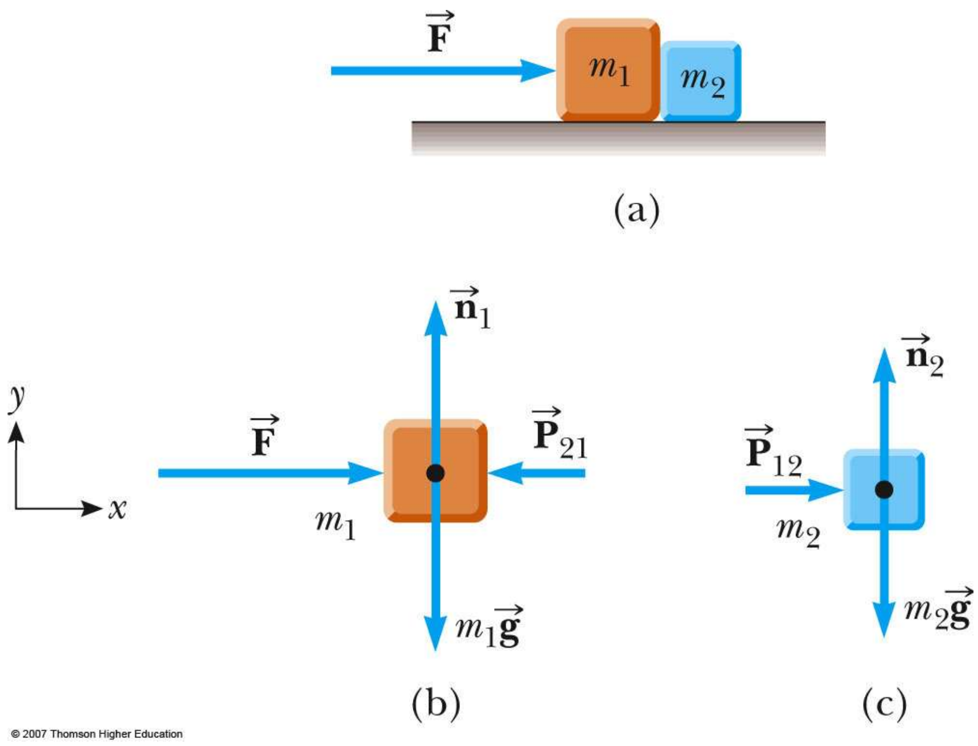
$$d = \frac{1}{2} a_x t^2 \qquad t = \sqrt{\frac{2d}{a_x}} = \boxed{\sqrt{\frac{2d}{g \sin \theta}}}$$

with $v_{xi} = 0$, we find that

$$v_{xf}^2 = 2a_x d \longrightarrow v_{xf} = \sqrt{2a_x d} = \boxed{\sqrt{2\, gd \sin \theta}}$$

Example 5.7: One Block Pushes Another

$m_1 > m_2$



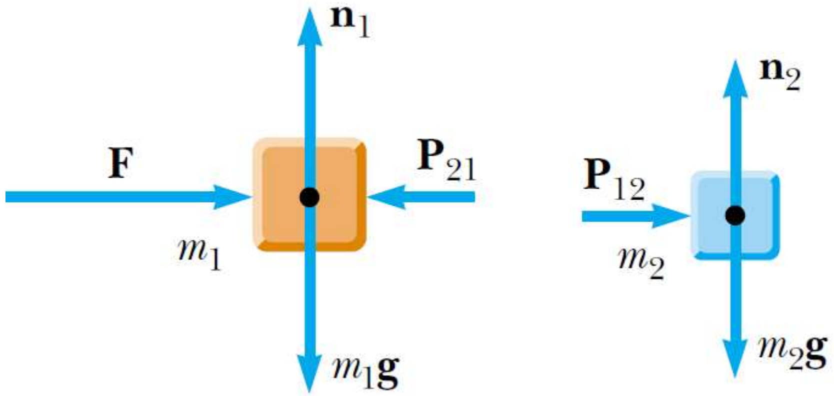
A) Find the magnitude of the acceleration of the system.

$$\sum F_x(\text{system}) = F = (m_1 + m_2)\,a_x$$

$$a_x = \boxed{\frac{F}{m_1 + m_2}}$$

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

$$\sum F_x = P_{12} = m_2 a_x$$



$$P_{12} = m_2 a_x = \boxed{\left(\frac{m_2}{m_1 + m_2}\right) F}$$

$$P_{12} = F - m_1 a_x = F - m_1\left(\frac{F}{m_1 + m_2}\right) = \left(\frac{m_2}{m_1 + m_2}\right) F$$

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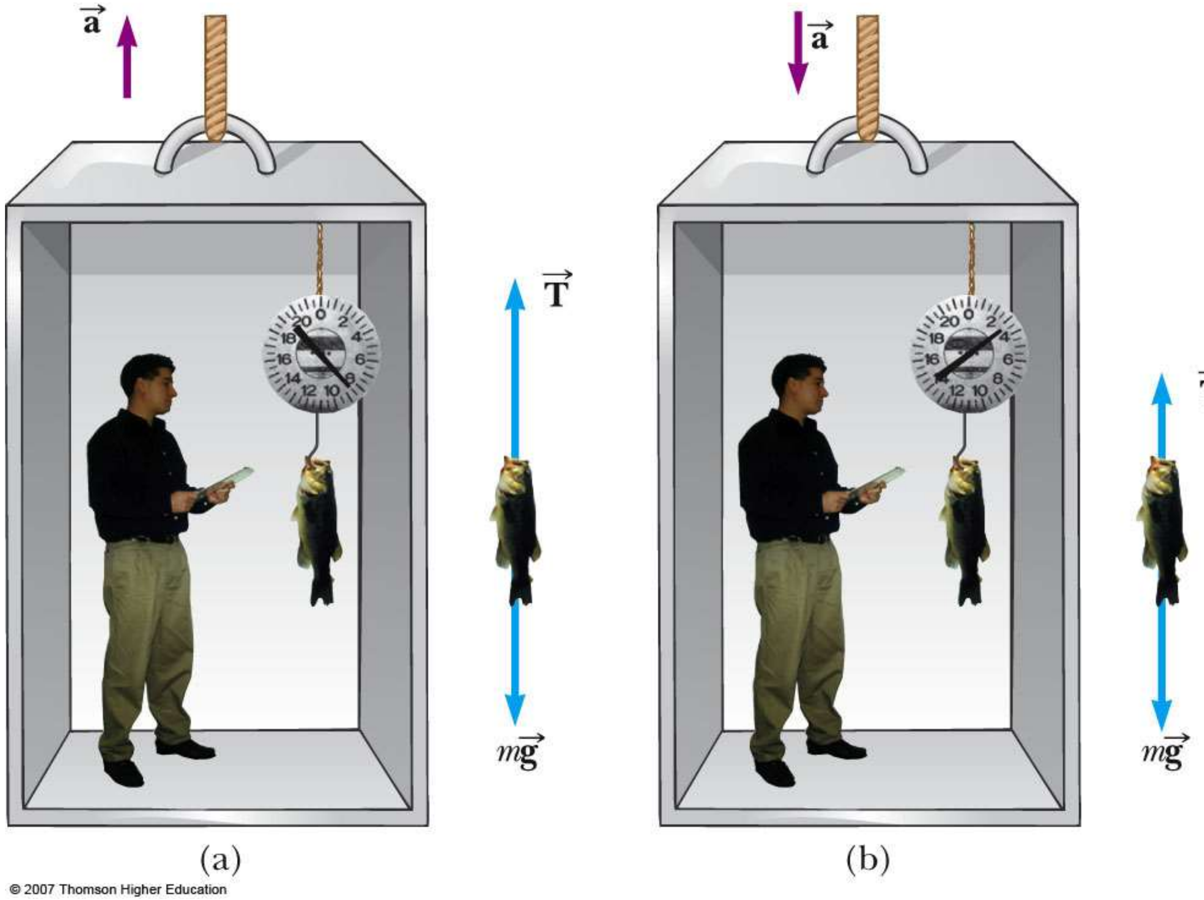
Example 5.8: Weighing a Fish in an Elevator



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.

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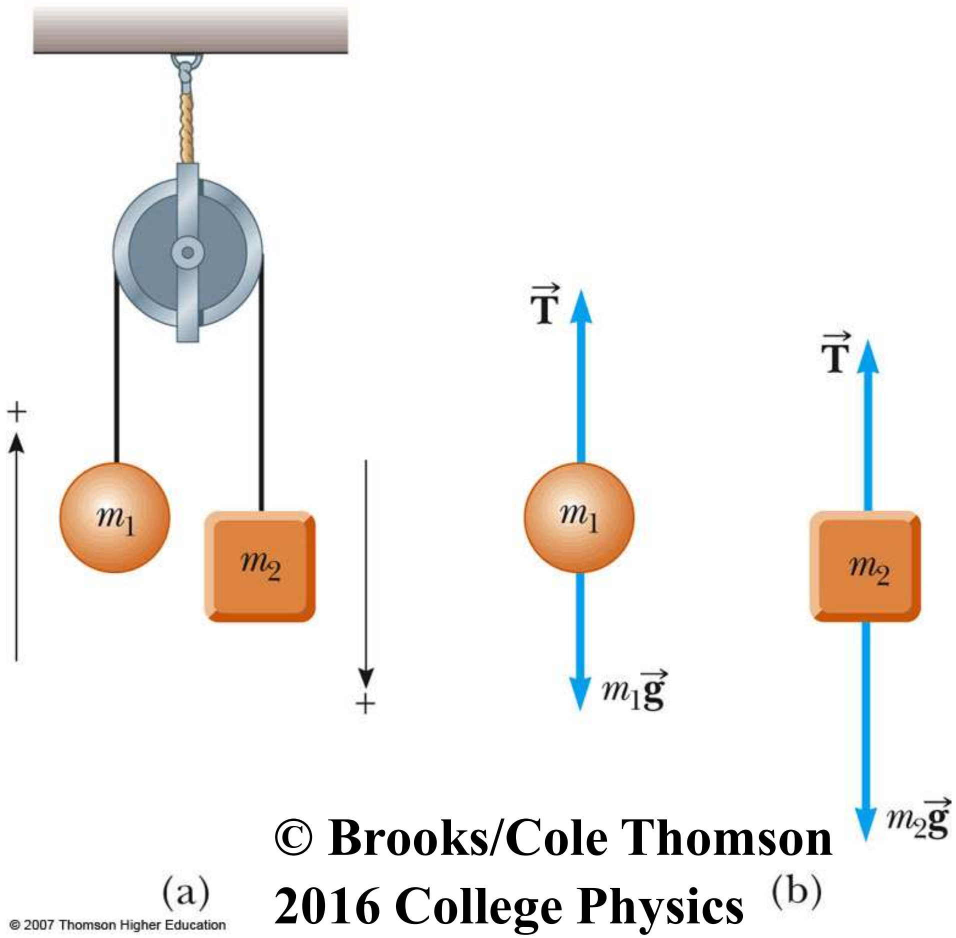
Solution:

$$\sum F_y = T - mg = ma_y$$

Thus, we conclude that the scale reading T is greater than the fish's weight mg if **a** is upward, so that a_y is positive, and that the reading is less than mg if a is downward, so that a_y is negative.

When the elevator accelerates upward, the spring scale reads a value greater than the weight of the fish. When the elevator accelerates downward, the spring scale reads a value less than the weight of the fish.

Example 5.9: Atwood Machine



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Determine the magnitude of the acceleration of the two objects and the tension in the lightweight cord.

Solution:

If object 1 accelerates upward, then object 2 accelerates downward. Thus, for consistency with signs, if we define the upward direction as positive for object 1, we must define the downward direction as positive for object 2. With this sign convention, both objects accelerate in the same direction as defined by the choice

$$\sum F_y = T - m_1 g = m_1 a_y$$

$$\sum F_y = m_2 g - T = m_2 a_y$$

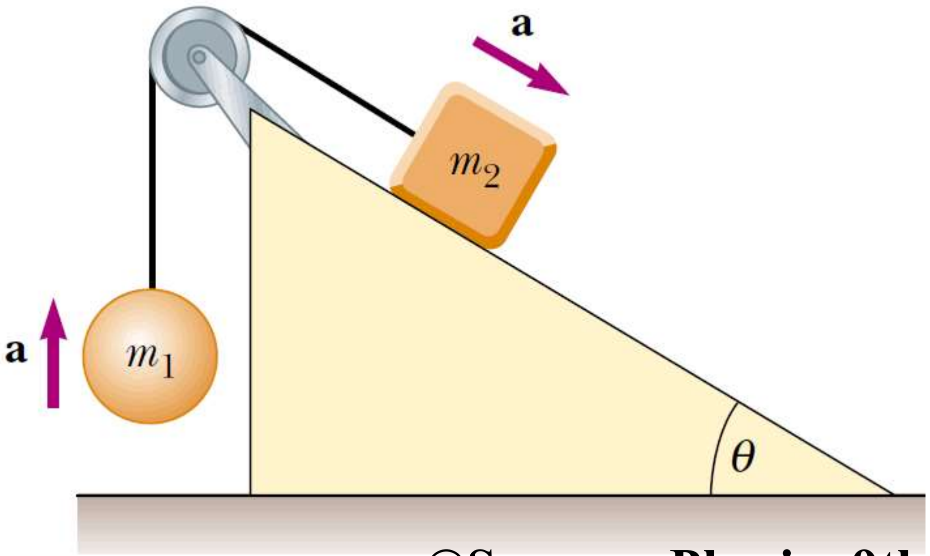
$$-m_1 g + m_2 g = m_1 a_y + m_2 a_y$$

$$a_y = \boxed{\left(\frac{m_2 - m_1}{m_1 + m_2}\right) g}$$

$$T = \boxed{\left(\frac{2 m_1 m_2}{m_1 + m_2}\right) g}$$

Example 5.10 Acceleration of Two Objects Connected by a Cord

Find the magnitude of the acceleration of the two objects and the tension in the cord.



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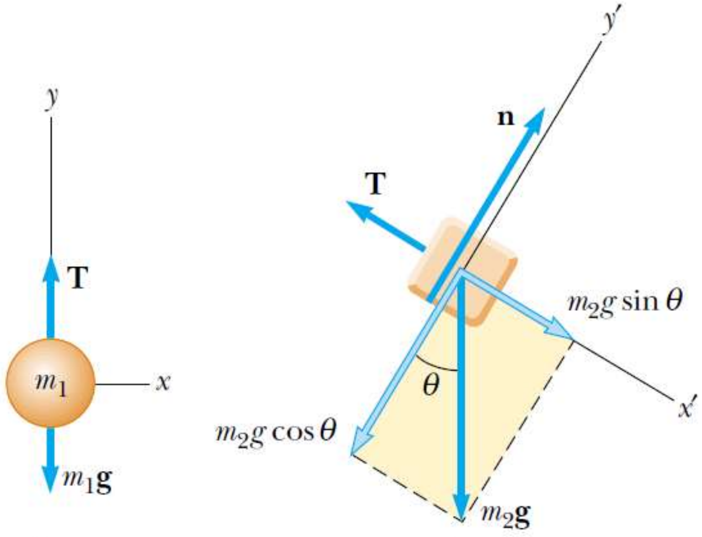
Solution:

$$\sum F_x = 0$$

$$\sum F_y = T - m_1 g = m_1 a_y = m_1 a$$

Solution:



$$\sum F_{x'} = m_2 g \sin\theta - T = m_2 a_{x'} = m_2 a$$

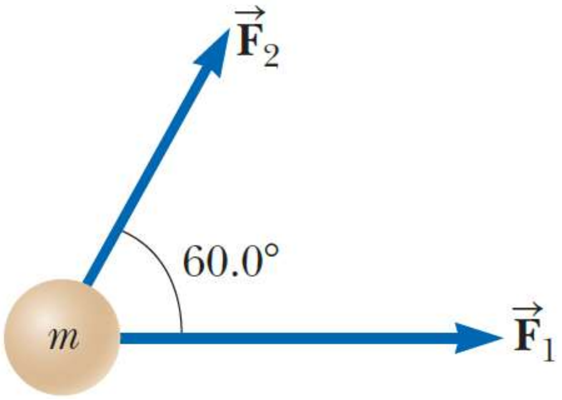
$$\sum F_{y'} = n - m_2 g \cos\theta = 0$$

$$a = \boxed{\frac{m_2 g \sin\theta - m_1 g}{m_1 + m_2}} \qquad T = \boxed{\frac{m_1 m_2 g(\sin\theta + 1)}{m_1 + m_2}}$$

Note that the block accelerates down the incline only if $m_2\sin\theta > m_1$.

19.

M



m=5 kg, F_1=20 N, F_2=15 N, a=?

Solution:

$$F_{2x} = 15.0\cos 60.0° = 7.50\ \text{N}$$

$$F_{2y} = 15.0\sin 60.0° = 13.0\ \text{N}$$

$$\vec{F}_2 = \left(7.50\hat{\mathbf{i}} + 13.0\hat{\mathbf{j}}\right)\ \text{N}$$

Then,

$$\sum\vec{F} = \vec{F}_1 + \vec{F}_2 = \left[20.0\hat{\mathbf{i}} + \left(7.50\hat{\mathbf{i}} + 13.0\hat{\mathbf{j}}\right)\right]\ \text{N}$$

$$= (27.5\hat{\mathbf{i}} + 13.0\hat{\mathbf{j}})\ \text{N}$$

and $\vec{a} = \dfrac{\sum\vec{F}}{m} = \left(5.50\hat{\mathbf{i}} + 2.60\hat{\mathbf{j}}\right)\ \text{m/s}^2 = \boxed{6.08\ \text{m/s}^2 \text{ at } 25.3°}$

5.8 Forces of Friction

When an object is in motion either on a surface or in a viscous medium such as air or water, there is resistance to the motion because the object interacts with its surroundings. We call such resistance a force of friction.

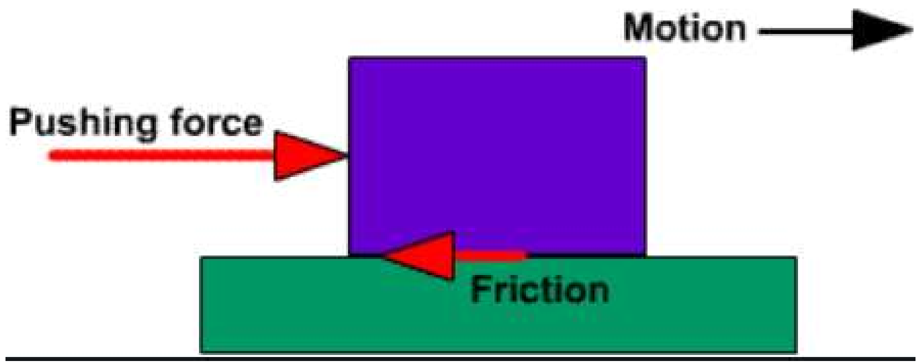
Forces of friction are very important in our everyday lives. They allow us to walk or run and are necessary for the motion of wheeled vehicles.

Conceptual Example:

What exerts the force to move a car?

Response

A common answer is that the engine makes the car move forward. But it is not so simple. The engine makes the wheels go around. But if the tires are on slick ice or deep mud, they just spin. ***Friction is needed.*** On firm ground, the tires push backward against the ground because of friction. By **Newton's 3rd Law**, the ground pushes on the tires in the opposite direction, accelerating the car forward.



- Friction is a type of force that opposes the motion of objects.

- There are 2 types of frictional forces:

Kinetic- the force of resistance on an object that causes the object to stop moving

Static- the force of resistance on an object that prevents motion

For example, pushing a car in neutral gear is hard to do….even more difficult if the car is stopped.

Pushing a car through snow is even harder!

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- Experiments find that the **maximum static friction force** $\mathbf{f_s^{(max)}}$ is proportional to the **magnitude** (size) of the normal force $\mathbf{n}$ **between** the 2 surfaces.
- **DIRECTIONS** of $\mathbf{f_k}$ & $\mathbf{n}$ are $\perp$ each other!! $\mathbf{f_k} \perp \mathbf{n}$
- Write the relation as $\mathbf{f_s^{(max)}} = \mu_s \mathbf{n}$ (magnitudes)

  $\mu_s \equiv$ **Coefficient of static friction**

  – Depends on the surfaces & their conditions

  – Dimensionless $\mu < 1$

  – *Always* find $\mu_s > \mu_k$

  $\Rightarrow$ Static friction force: $\mathbf{f_s} \leq \mu_s \mathbf{n}$

Coefficients of Friction

TABLE 5.1

Coefficients of Friction

	μ_s	μ_k
Rubber on concrete	1.0	0.8
Steel on steel	0.74	0.57
Aluminum on steel	0.61	0.47
Glass on glass	0.94	0.4
Copper on steel	0.53	0.36
Wood on wood	0.25–0.5	0.2
Waxed wood on wet snow	0.14	0.1
Waxed wood on dry snow	—	0.04
Metal on metal (lubricated)	0.15	0.06
Teflon on Teflon	0.04	0.04
Ice on ice	0.1	0.03
Synovial joints in humans	0.01	0.003

Note: All values are approximate. In some cases, the coefficient of friction can exceed 1.0.

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$$\mu_s > \mu_k \Rightarrow f_s^{(\text{max, static})} > f_k^{(\text{kinetic})}$$

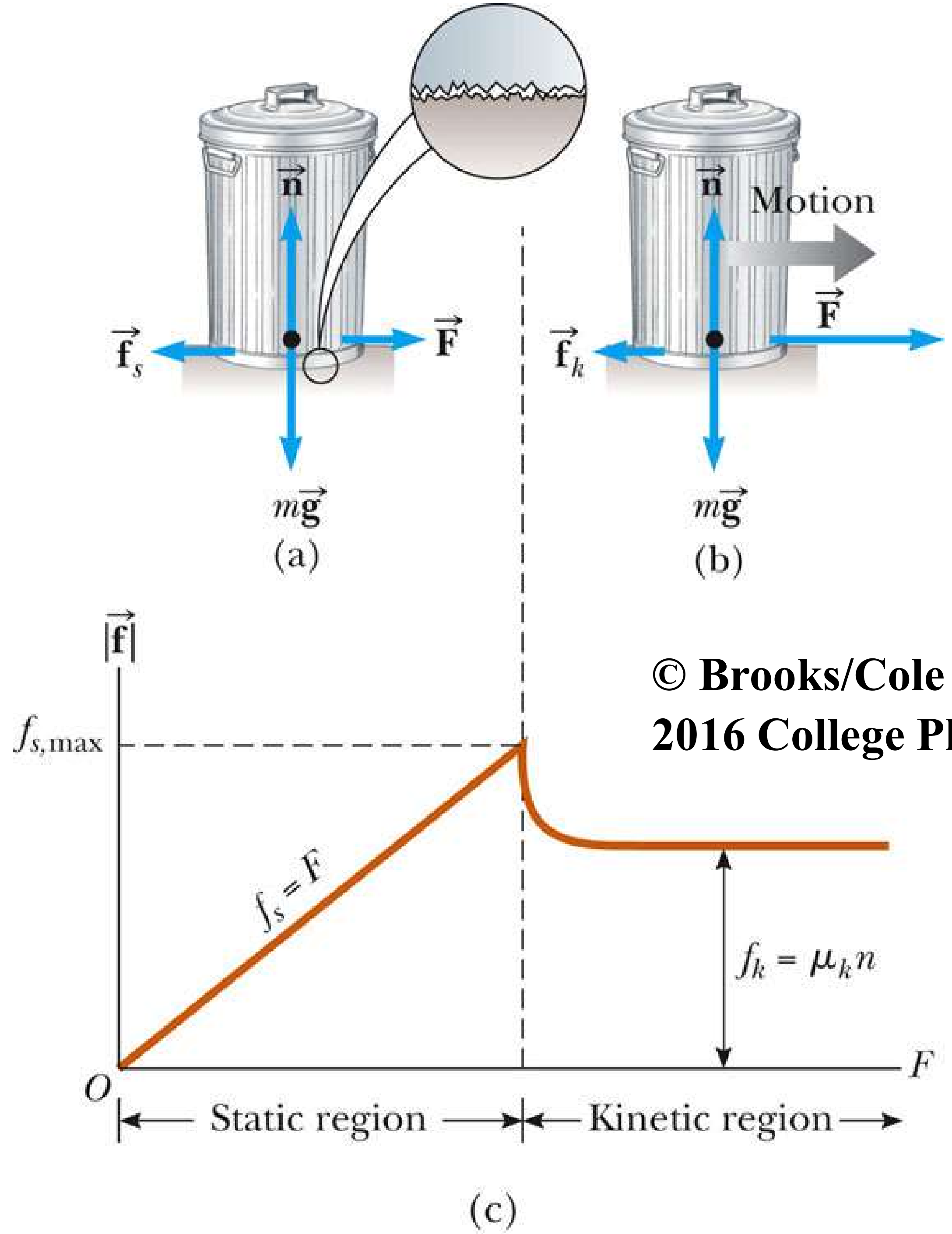

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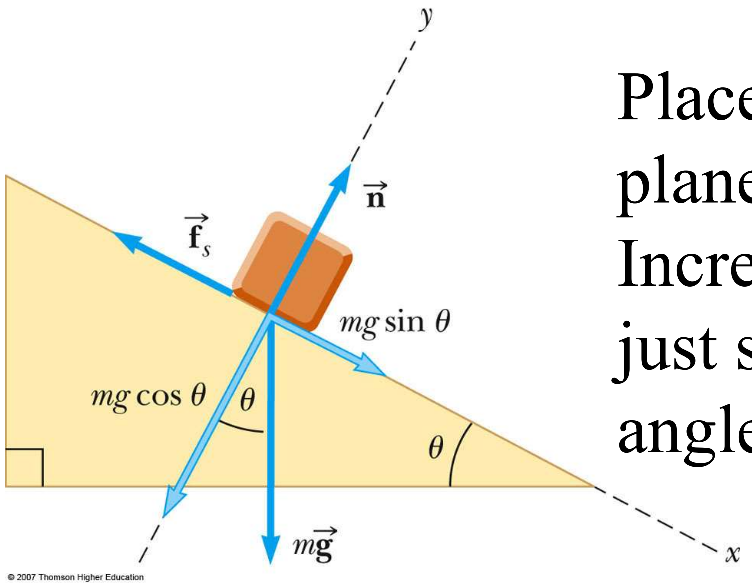
Fig. 5-16, p. 119

Example 5.11



Place a block, mass **m**, on an inclined plane with static friction coefficient μ_s. Increase incline angle θ until the block just starts to slide. Calculate the critical angle θ_c at which the sliding starts.

Solution: Newton's 2nd Law (static)

y direction: $\sum F_y = 0 \Rightarrow n - mg\cos\theta = 0;\ n = mg\cos\theta$ **(1)**

x direction: $\sum F_x = 0 \Rightarrow mg\sin\theta - f_s = 0;\ f_s = mg\sin\theta$ **(2)**

Also: $f_s = \mu_s n$ **(3)**

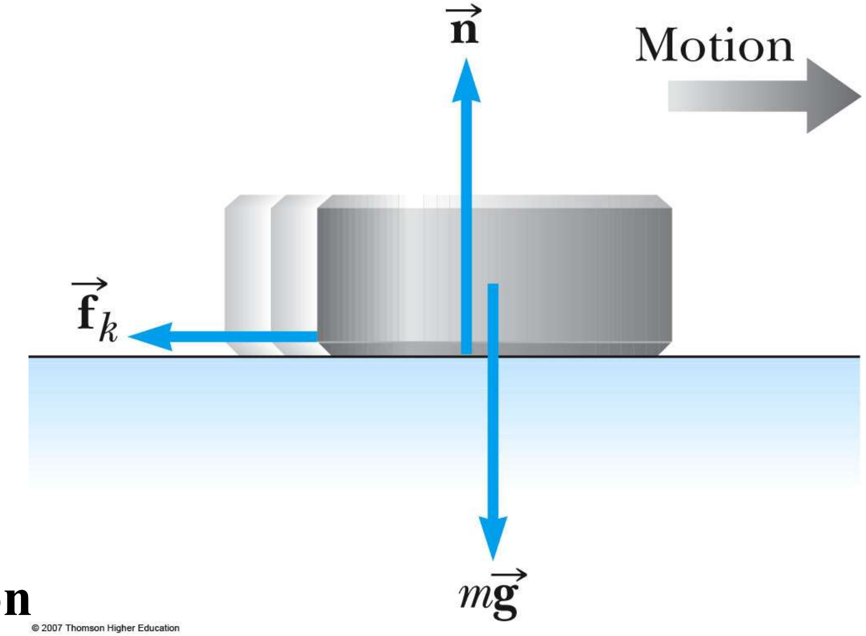
Put **(1)** into **(3)**: $\Rightarrow f_s = \mu_s\, mg\cos\theta$ **(4)**

Equate **(2)** & **(4)** & solve for $\mu_s \Rightarrow$ $\mu_s = \tan\theta_c$

$\theta_c = \tan^{-1}\mu_s$

Example 5.12 The Sliding Hockey Puck

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.



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Solution:

$$(1) \quad \sum F_x = -f_k = ma_x$$

$$(2) \quad \sum F_y = n - mg = 0$$

$$-\mu_k n = -\mu_k mg = ma_x$$

$$a_x = -\mu_k g$$

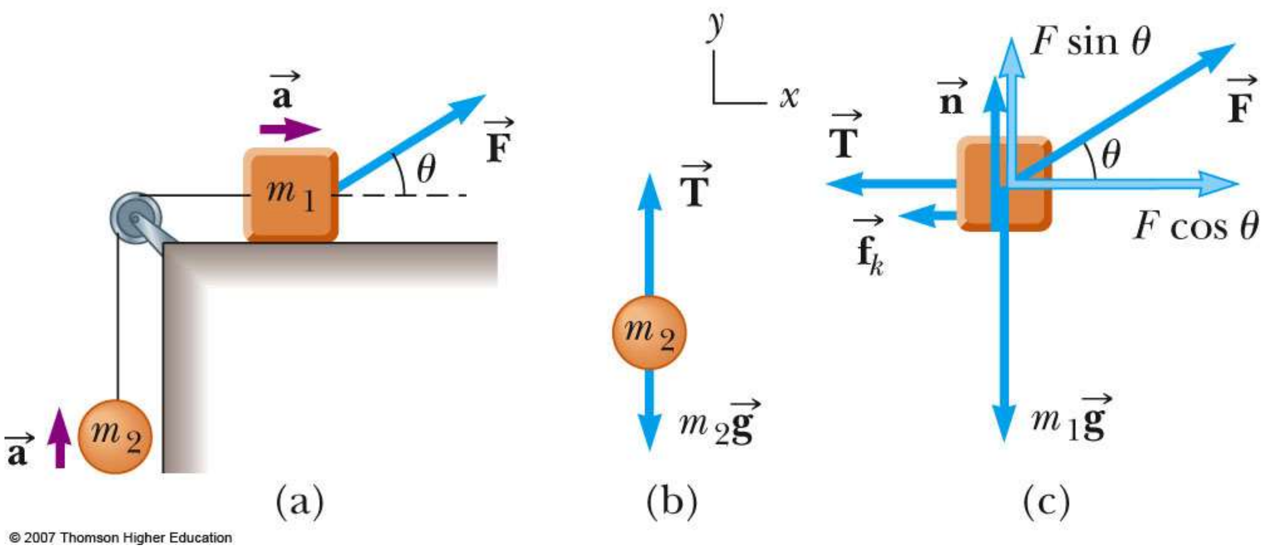
$$0 = v_{xi}^{\ 2} + 2a_x x_f = v_{xi}^{\ 2} - 2\mu_k g x_f$$

$$\mu_k = \frac{v_{xi}^{\ 2}}{2gx_f}$$

$$\mu_k = \frac{(20.0\ \mathrm{m/s})^2}{2(9.80\ \mathrm{m/s^2})(115\ \mathrm{m})} = \boxed{0.177}$$

Example 5.13

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. 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.



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Solution:

$$(1)\quad \sum F_x = F\cos\theta - f_k - T = m_2 a_x = m_2 a$$

$$(2)\quad \sum F_y = n + F\sin\theta - m_2 g = 0$$

$$(3)\quad \sum F_y = T - m_1 g = m_1 a_y = m_1 a$$

$$n = m_2 g - F\sin\theta$$

$$(4)\quad f_k = \mu_k(m_2 g - F\sin\theta)$$

$$F\cos\theta - \mu_k(m_2 g - F\sin\theta) - m_1(a + g) = m_2 a$$

$$(5)\quad a = \boxed{\frac{F(\cos\theta + \mu_k\sin\theta) - (m_1 + \mu_k m_2)g}{m_1 + m_2}}$$

60.

W

A woman at an airport is towing her 20.0-kg suitcase at constant speed by pulling on a strap at an angle θ above the horizontal

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$F = 35$ N, $F_{friction} = 20$ N

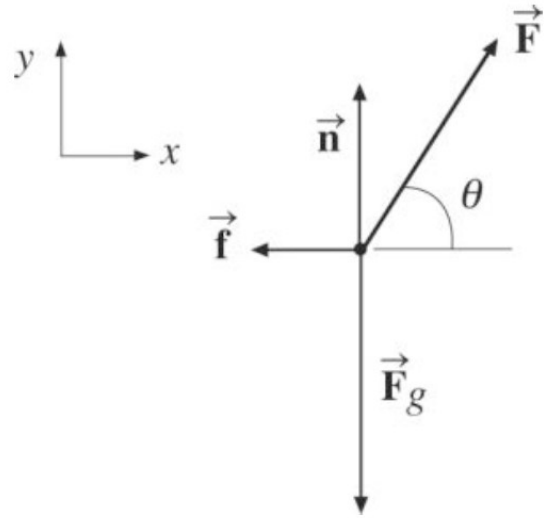
(a) Draw a free-body diagram of the suitcase.

(b) What angle does the strap make with the horizontal?

(c) What is the magnitude of the normal force?

Solution

(b) $m_{\text{suitcase}} = 20.0\text{ kg}, F = 35.0\text{ N}$



$$\sum F_x = ma_x: \quad -20.0\text{ N} + F\cos\theta = 0$$
$$\sum F_y = ma_y: \quad +n + F\sin\theta - F_g = 0$$

$$F\cos\theta = 20.0\text{ N}$$

$$\cos\theta = \frac{20.0\text{ N}}{35.0\text{ N}} = 0.571$$

$$\boxed{\theta = 55.2°}$$

(c) With $F_g = (20.0\text{ kg})(9.80\text{ m/s}^2)$,

$$n = F_g - F\sin\theta = [196\text{ N} - (35.0\text{ N})(0.821)]$$

$$\boxed{n = 167\text{ N}}$$

- Newton’s first law, inertial frame of references
- Newton’s second law, gravitational force exerted on an object
- Newton’s third law
- Friction force, coefficient of static friction and coefficient of kinetic friction

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