Chapter 5

Applying Newton's Laws

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University Physics, Thirteenth Edition
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Introduction

- This week and next, we will practice applying Newton's laws to physical problems.
- Newton's 1st law applies to objects in equilibrium, i.e. at rest or moving with constant velocity.
- Newton's 2nd law relates the acceleration of objects not in equilibrium to the forces applied to them.
- Friction is a contact force between surfaces that opposes motion.
- Forces are also needed to provide the centripetal acceleration to maintain circular motion at constant speed.

Newton's First Law in practice

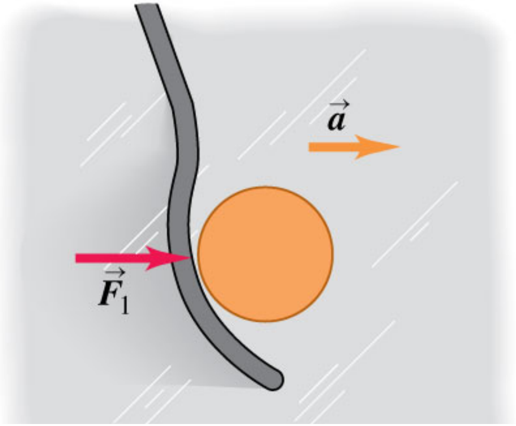
- A single hockey force exerts a force $\boldsymbol{F}_1$ on the puck causing an acceleration $\boldsymbol{a}$.

- If a second hockey stick exerts a second force $\boldsymbol{F}_2$ equal in magnitude to $\boldsymbol{F}_1$ but opposite in direction, the net force:

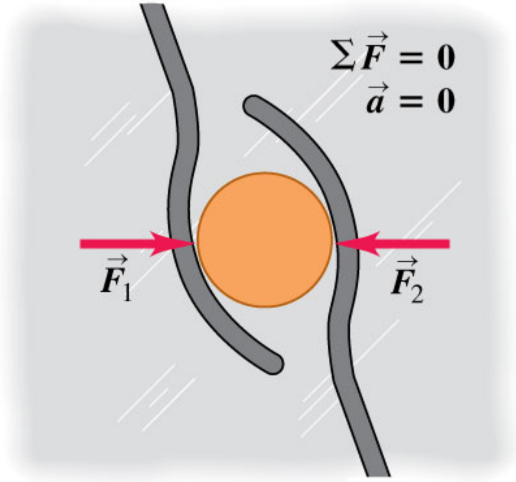
$$\boldsymbol{F} = \boldsymbol{F}_1 + \boldsymbol{F}_2 = 0$$

and the puck remains at rest.

(a) A puck on a frictionless surface accelerates when acted on by a single horizontal force.



(b) An object acted on by forces whose vector sum is zero behaves as though no forces act on it.



Example #1

A 75.0 kg wrecking ball hangs from a uniform, heavy-duty chain of mass 26.0 kg.

a. Find the maximum and minimum tensions in the chain.

b. What is the tension at a point three-fourths of the way up from the bottom of the chain?

Solution #1

Since the ball and chain are in equilibrium, the sum of the forces is zero by Newton's 1st law. Construct free-body diagrams for the ball and chain:

Ball: $F_y = T_{bot} - m_B g = 0 \Longrightarrow$

$T_{bot} = m_B g = (75.0 \text{ kg})(9.8 \text{ m/s}^2) = 735 \text{ N}$

Chain: $F_y = T_{top} - T_{bot} - m_C g = 0 \Longrightarrow$

$T_{top} = T_{bot} + m_C g = 735 \text{ N} + (26.0 \text{ kg})(9.8 \text{ m/s}^2) = 990 \text{ N}$

The tension in the chain is a linear function of the height like its density $\Longrightarrow F_{3/4} = 735 \text{ N} + \frac{3}{4}(990 \text{ N} - 735 \text{ N}) = 926 \text{ N}$

Two-dimensional equilibrium

Equilibrium can occur in higher dimensions as well, in which case $\Sigma\, \boldsymbol{F}_i = 0$ must be solved component by component:

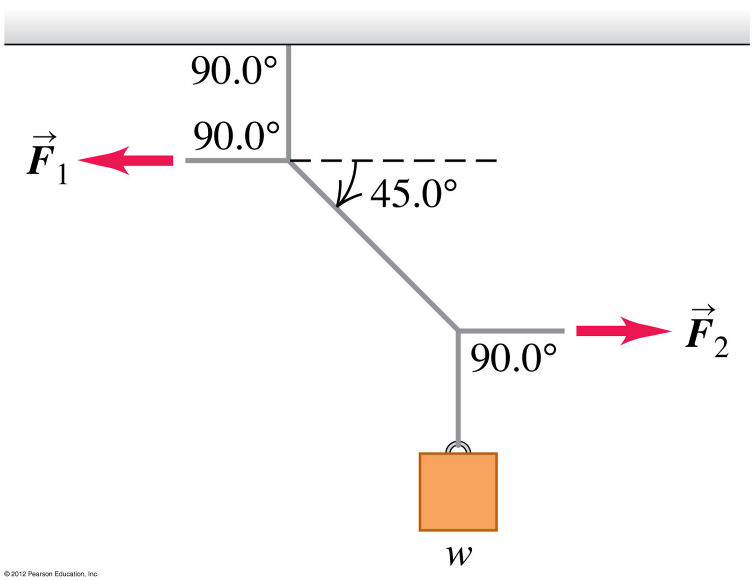
$$\Sigma F_x = 0 \qquad \Sigma F_y = 0 \qquad \Sigma F_z = 0$$

Example #2

Consider the 60.0 N weight suspended by string below.

a. What is the tension in the diagonal string?

b. Find the magnitudes of the horizontal forces $\boldsymbol{F}_1$ and $\boldsymbol{F}_2$ that must be applied to maintain equilibrium?



Solution #2

Apply Newton's 1st law to the bottom intersection. Choose y in the vertical direction.

$F_y = T \sin 45° - w = 0 \Rightarrow T = (60.0 \text{ N})\sqrt{2} = 84.9 \text{ N}$

Now in the x direction:

$F_x = F_2 - T \cos 45° = 0 \Rightarrow F_2 = T \cos 45° = 60.0 \text{ N}$

Now apply Newton's 1st law to the top intersection:

$F_x = T \cos 45° - F_1 = 0 \Rightarrow F_1 = T \cos 45° = 60.0 \text{ N}$

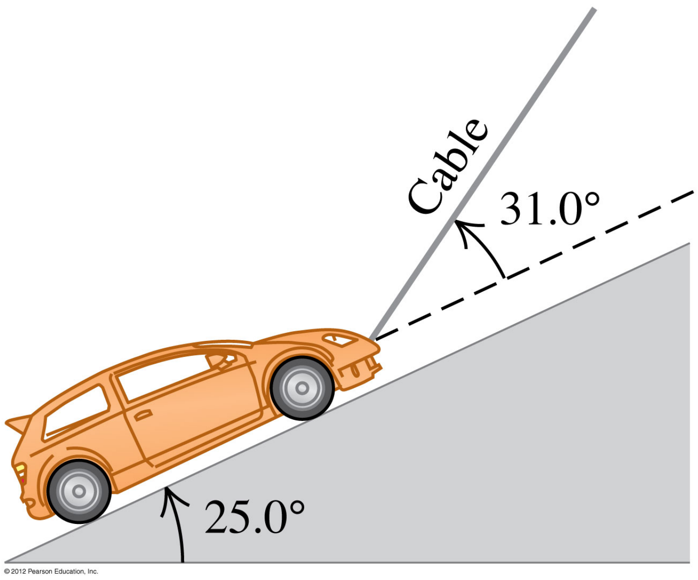
Example #3

A 1130 kg car is held in place by a light cable on a very smooth (frictionless) ramp. The cable makes an angle of 31.0° above the surface of the ramp, and the ramp itself rises at 25.0° above the horizontal.

a. Draw a free-body diagram for the car.

b. Find the tension in the cable.

c. How hard does the surface of the ramp push on the car?



Solution #3

A free-body diagram for each object use vectors to show all the forces applied *to that object only*. One must also choose directions for the coordinate axes, preferably so that motion only occurs along one axis. In this problem, the 3 forces acting on the car are the normal force, tension, and gravity. We choose the x axis up the ramp:

$$\Sigma F_x = T \cos 31° - mg \sin 25° = 0$$

$$\Sigma F_y = n + T \sin 31° - mg \cos 25° = 0$$

These 2 equations can be solved for the 2 unknowns:

$$T = (mg \sin 25°)/\cos 31° = 5{,}460 \text{ N}$$

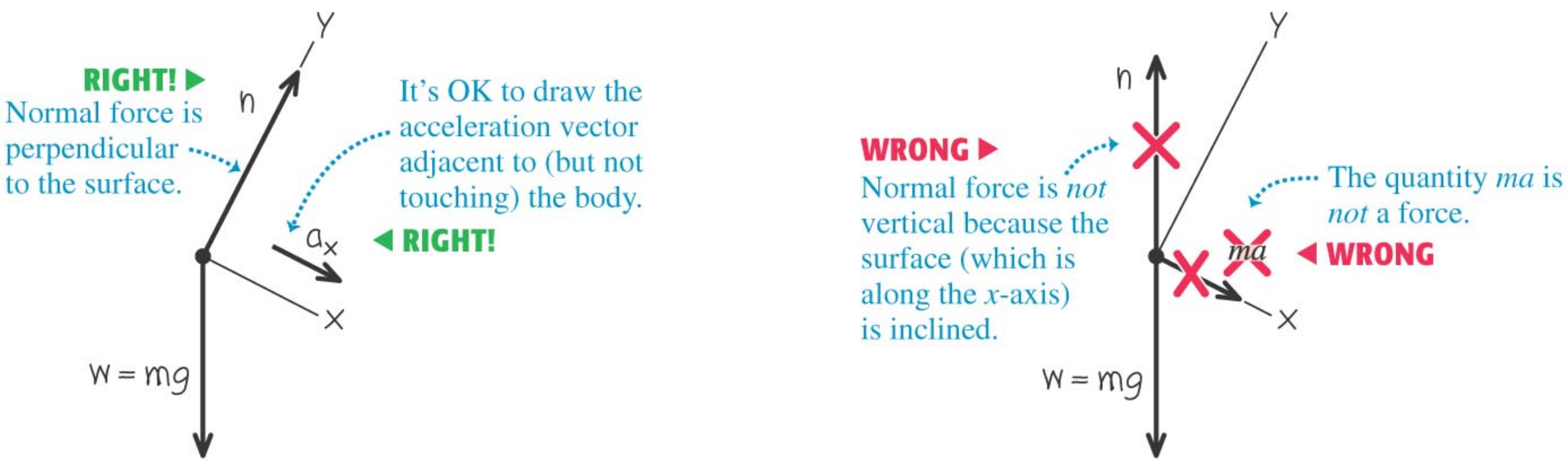
$$n = -T \sin 31° + mg \cos 25° = 7{,}220 \text{ N}$$

Two common free-body diagram errors

- The normal force must be perpendicular to the surface. It's not always down, opposite to gravity.
- There is no "***ma*** force." The sum of the forces are equal to ***ma*** which is not itself a force.

(a) Correct free-body diagram for the sled

(b) Incorrect free-body diagram for the sled



Using Newton’s Second Law: Dynamics of Particles

- If the forces do not sum to zero:

  $$\Sigma \boldsymbol{F}_i \neq 0$$

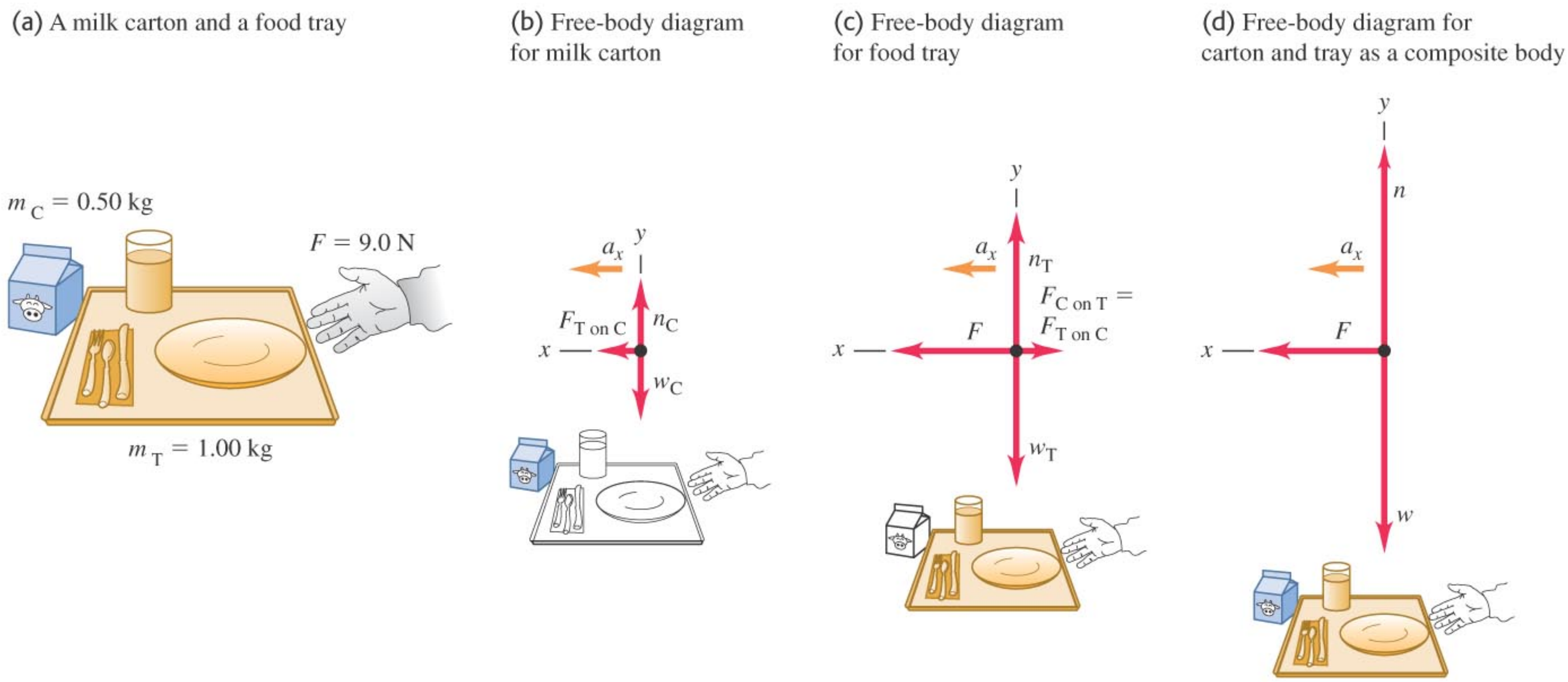
  the object is not in equilibrium. We must use Newton’s 2nd law:

  $$\Sigma \boldsymbol{F}_i = m\boldsymbol{a}$$

  to determine the nonzero acceleration $\boldsymbol{a}$.

Two bodies with the same acceleration

If two objects experience the same acceleration, we can apply Newton's 2nd law to each separately or to both collectively.

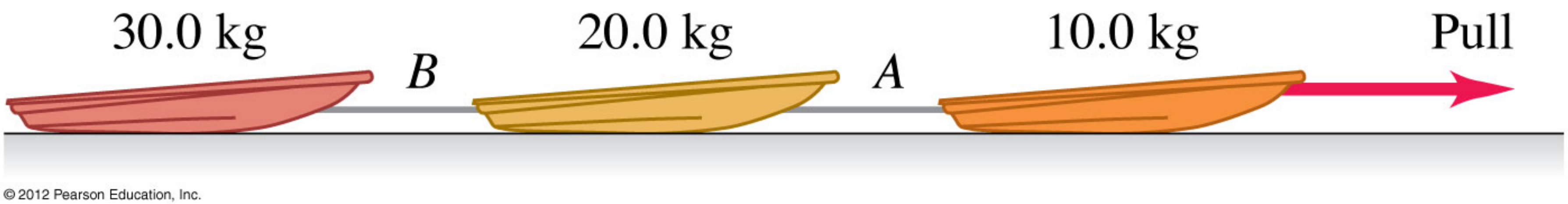


Example #4

Three sleds are being pulled horizontally on frictionless horizontal ice using horizontal ropes. The pull has a magnitude of 190 N.

a. Find the acceleration of the system.

b. Find the tension in ropes *A* and *B.*



Solution #4

a. Motion is to the right which we define to be the x direction. First let's consider all 3 sleds together:

$$\Sigma F_x = P = (m_1 + m_2 + m_3)a_x \Longrightarrow$$

$$a_x = (190\ \text{N})/(60.0\ \text{kg}) = 3.17\ \text{m/s}^2$$

b. Since all 3 sleds experience the same acceleration, we can apply Newton's 2nd law to parts of the system. First consider the red and yellow boats together:

$$\Sigma F_x = T_A = (m_1 + m_2)a_x = (50.0\ \text{kg})(3.17\ \text{m/s}^2) = 158\ \text{N}$$

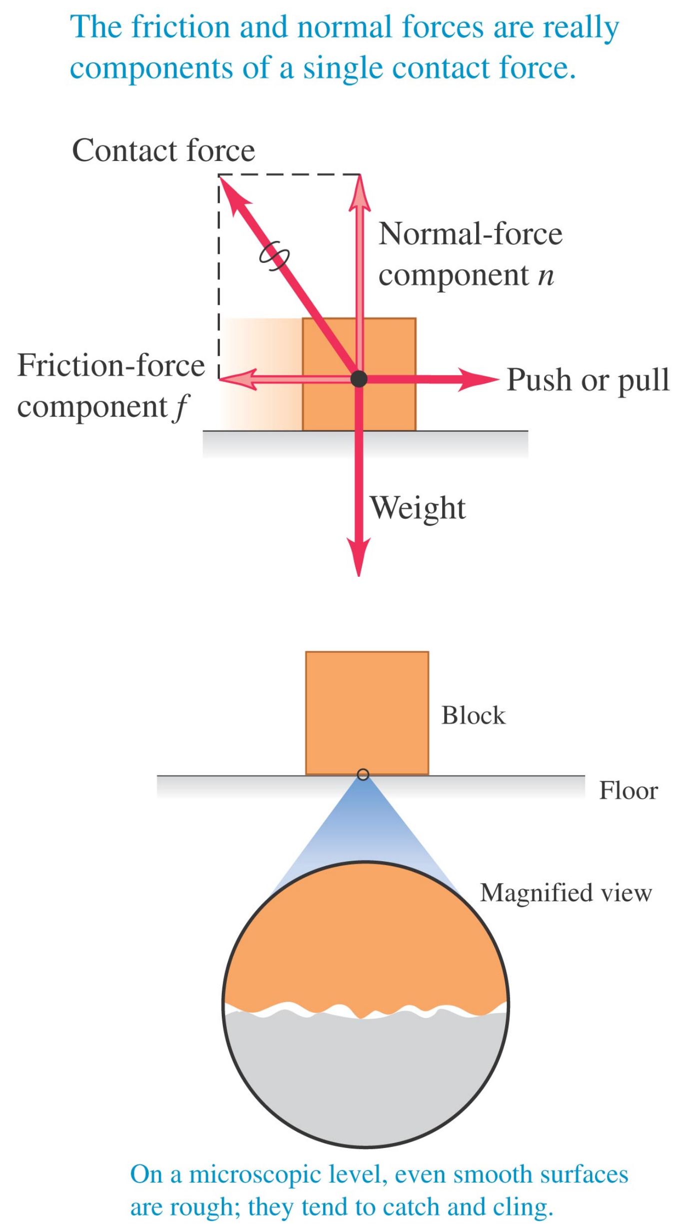
Now consider just the red boat:

$$\Sigma F_x = T_B = m_1 a_x = (30.0\ \text{kg})(3.17\ \text{m/s}^2) = 95\ \text{N}$$

This is ½ the total force since the red boat has ½ the mass.

Frictional forces

- When a body rests or slides on a surface, the *friction force* is parallel to the surface.
- Friction between two surfaces arises from interactions between molecules on the surfaces.

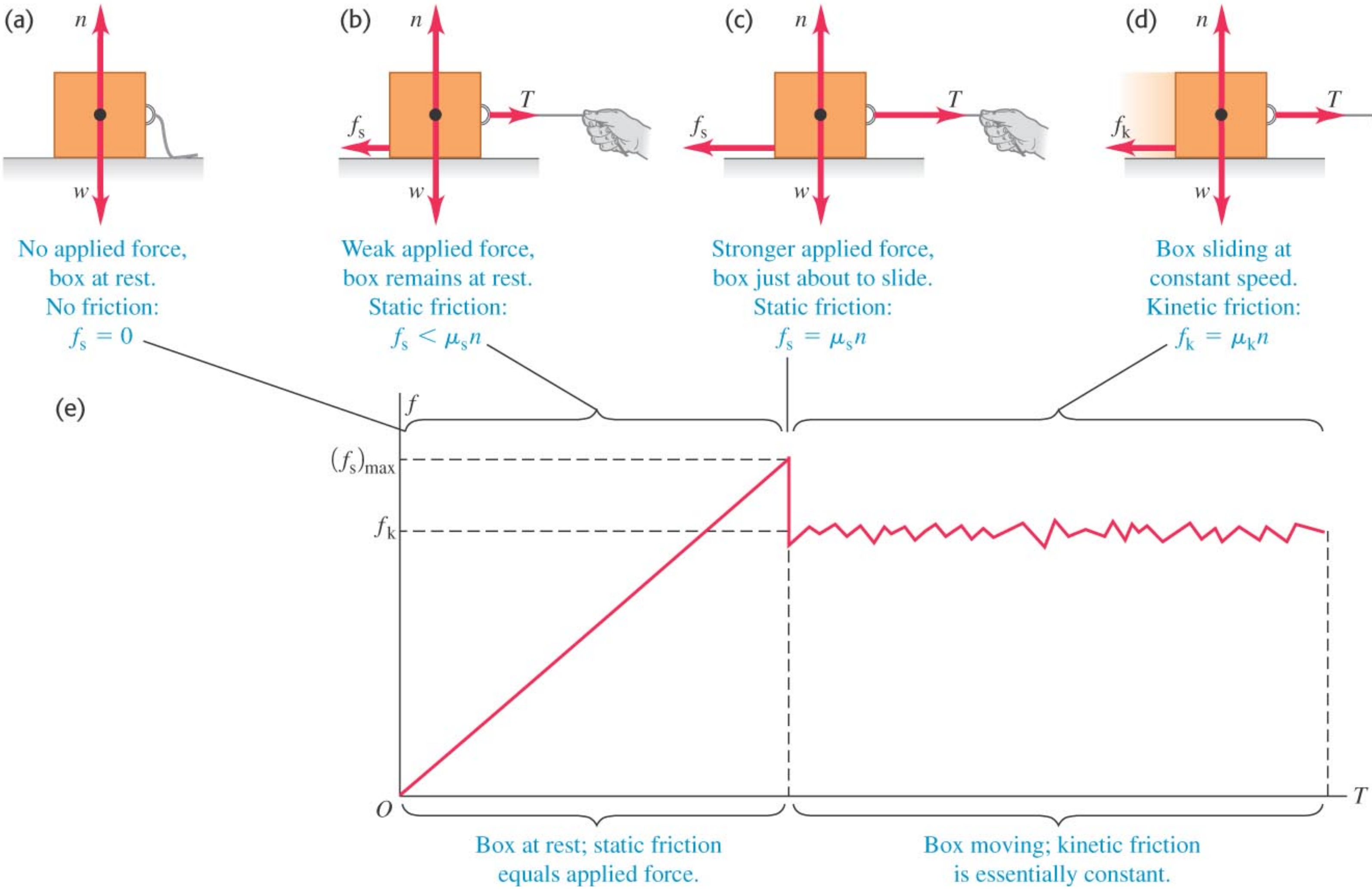


Kinetic and static friction

- *Kinetic friction* acts when a body slides over a surface.
- The *kinetic friction force* is $f_k = \mu_k n$.
- *Static friction* acts when there is no relative motion between bodies.
- The *static friction force* can vary between zero and its maximum value: $f_s \leq \mu_s n$.

Static friction followed by kinetic friction

- Before the box slides, static friction acts. But once it starts to slide, kinetic friction acts.



Some approximate coefficients of friction

Table 5.1 Approximate Coefficients of Friction

Materials	Coefficient of Static Friction, μ_s	Coefficient of Kinetic Friction, μ_k
Steel on steel	0.74	0.57
Aluminum on steel	0.61	0.47
Copper on steel	0.53	0.36
Brass on steel	0.51	0.44
Zinc on cast iron	0.85	0.21
Copper on cast iron	1.05	0.29
Glass on glass	0.94	0.40
Copper on glass	0.68	0.53
Teflon on Teflon	0.04	0.04
Teflon on steel	0.04	0.04
Rubber on concrete (dry)	1.0	0.8
Rubber on concrete (wet)	0.30	0.25

Example #6

A large crate of mass *m* rests on a horizontal floor. The coefficients of friction between the crate and floor are μ_s and μ_k. A woman pushes downward with a force ***F*** on the crate at an angle θ that below the horizontal.

a. What magnitude of force *F* is required to keep the crate moving at constant velocity?

b. If μ_s is greater than some critical value, the woman cannot start the crate moving no matter how hard she pushes. Calculate this critical value of $\mu_{s.}$

Solution #6

a. If the box is moving at constant velocity, Newton's 1st law tells us that the forces sum to zero:

$\Sigma F_x = F\cos\theta - \mu_k n = 0 \quad \Sigma F_y = n - mg - F\sin\theta = 0 \Longrightarrow$

$F = \mu_k mg/(\cos\theta - \mu_k \sin\theta)$

b. If the box is at rest, static friction applies ($\mu_k \rightarrow \mu_s$):

$F = \mu_s mg/(\cos\theta - \mu_s \sin\theta)$

If $\mu_s \rightarrow \cot\theta$, $F \rightarrow \infty$ and the box cannot be moved. F is minimized when

$dF/d\theta = \mu_s mg(\sin\theta + \mu_s\cos\theta)/(\cos\theta - \mu_s\sin\theta)^2 = 0 \Longrightarrow$

$\theta = -\tan^{-1}\mu_s \Longrightarrow \sin\theta = -\mu_s(1 + \mu_s^2)^{-1/2}, \quad \cos\theta = (1 + \mu_s^2)^{-1/2} \Longrightarrow$

$F = \mu_s mg/(1 + \mu_s^2)^{1/2}$

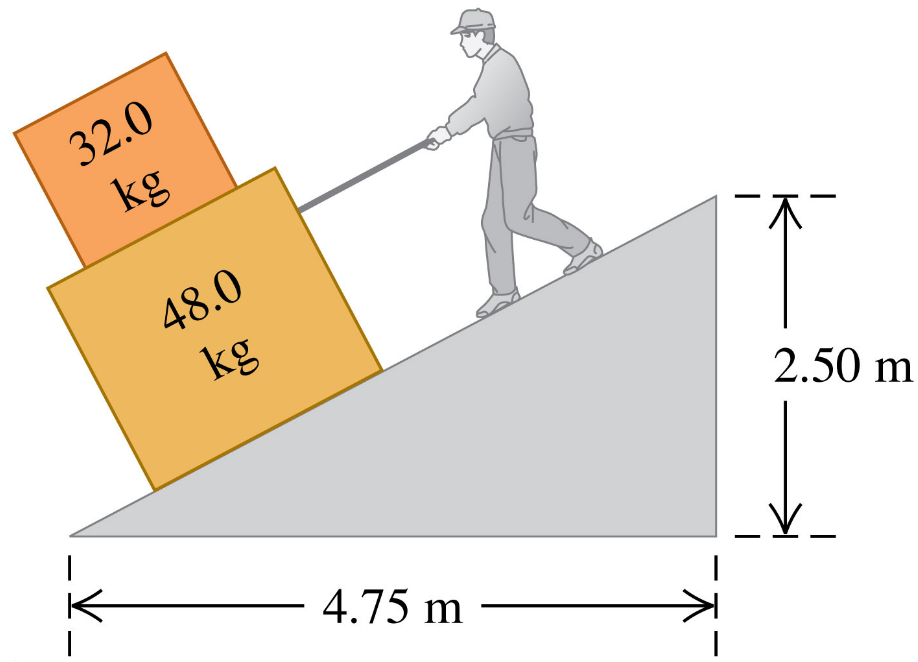
In the limit $\mu_s \rightarrow \infty$, $F \rightarrow mg$ and $\theta \rightarrow -90° \Longrightarrow$ Carry the box!

Example #6

You are lowering two boxes, one on top of the other, down a ramp by pulling on a rope parallel to the surface of the ramp. Both boxes move together at a constant speed of 15.0 cm/s. The coefficient of kinetic friction between the ramp and the lower box is 0.444 and the coefficient of static friction between the two boxes is 0.800.

a. What force do you need to accomplish this?

b. What are the magnitude and direction of the friction force on the upper box?



Solution #6

The two boxes have the same acceleration, so we can consider them as a composite system. Apply Newton's 2nd law:

$$\Sigma \boldsymbol{F}_i = \boldsymbol{w} + \boldsymbol{f} + \boldsymbol{T} + \boldsymbol{n} = 0$$

Choosing the x direction to point up the ramp:

$$\Sigma F_x = \mu_k n + T - mg \sin\theta = 0 \qquad \Sigma F_y = n - mg \cos\theta = 0$$

$$T = mg(\sin\theta - \mu_k \cos\theta)$$
$$= (80.0 \text{ kg})(9.8 \text{ m/s}^2)[2.5 \text{ m} - (0.444)(4.75 \text{ m})]/(5.37 \text{ m}) = 57.1 \text{ N}$$

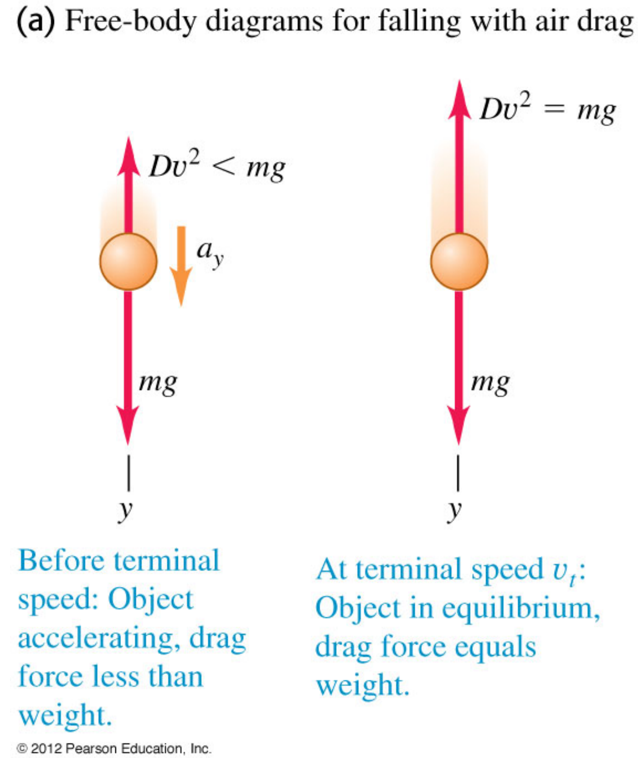
Calculate the x component of the Newton's 2nd law for top box:

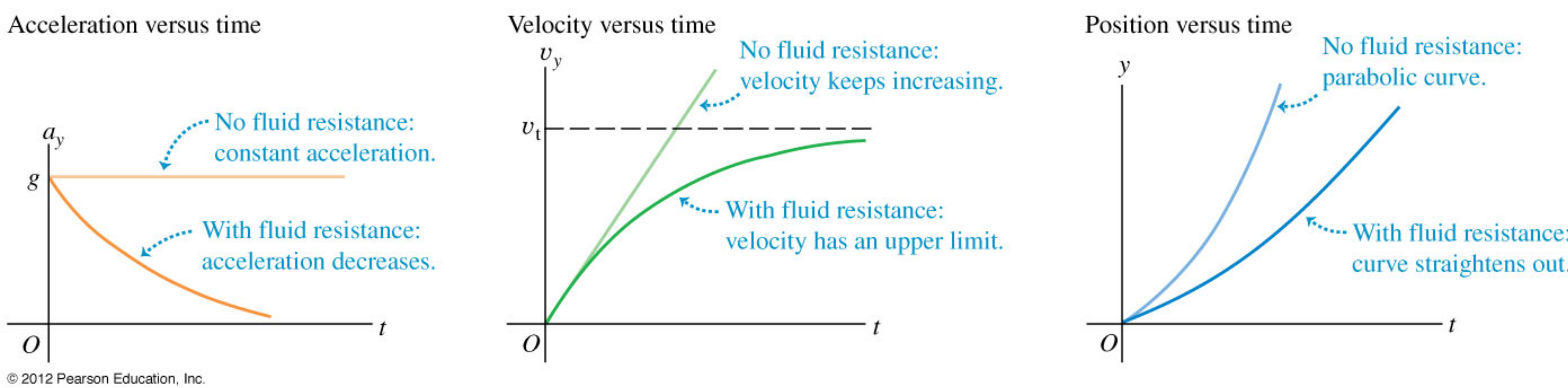
$$\Sigma F_x = f - mg \sin\theta = 0 \Longrightarrow$$

$$f = (32.0 \text{ kg})(9.8 \text{ m/s}^2)(2.5\text{m})/(5.37 \text{ m}) = 146 \text{ N}$$

Fluid resistance and terminal speed

- The *fluid resistance* on a body depends on the speed of the body, unlike friction between surfaces.
- A falling body reaches its *terminal speed* when the resisting force equals the weight of the body.
- The figures at the right illustrate the effects of air drag.





Example #7

a. What value of the drag coefficient D is required for a 50 kg skydiver to achieve a terminal velocity of 42 m/s?

b. If the skydiver's daughter, whose mass is 40 kg, has the same drag coefficient as her father, what is her terminal velocity?

(b) A skydiver falling at terminal speed

Solution #7

a. At the terminal velocity, the velocity is constant so Newton's 1st law tells us the forces sum to zero:

$$\Sigma F_y = Dv^2 - mg = 0 \Longrightarrow$$

$$D = mg/v^2 = (50\text{ kg})(9.8\text{ m/s}^2)/(42\text{ m/s})^2 = 0.28\text{ kg/m}$$

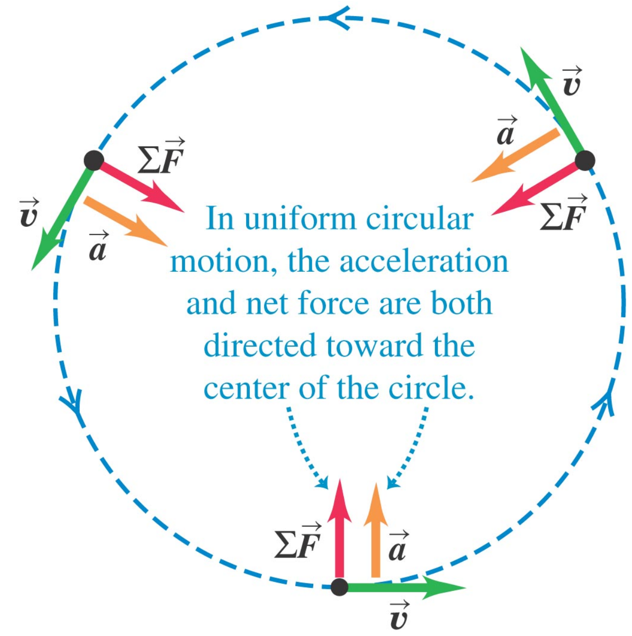
b. The daughter's terminal velocity will be:

$$v = (mg/D)^{1/2} = [(40\text{ kg})(9.8\text{ m/s}^2)/(0.28\text{ kg/m})]^{1/2} = 38\text{ m/s}$$

The daughter's lesser weight balances a smaller drag force and this smaller velocity. This is why denser objects fall faster in the atmosphere.

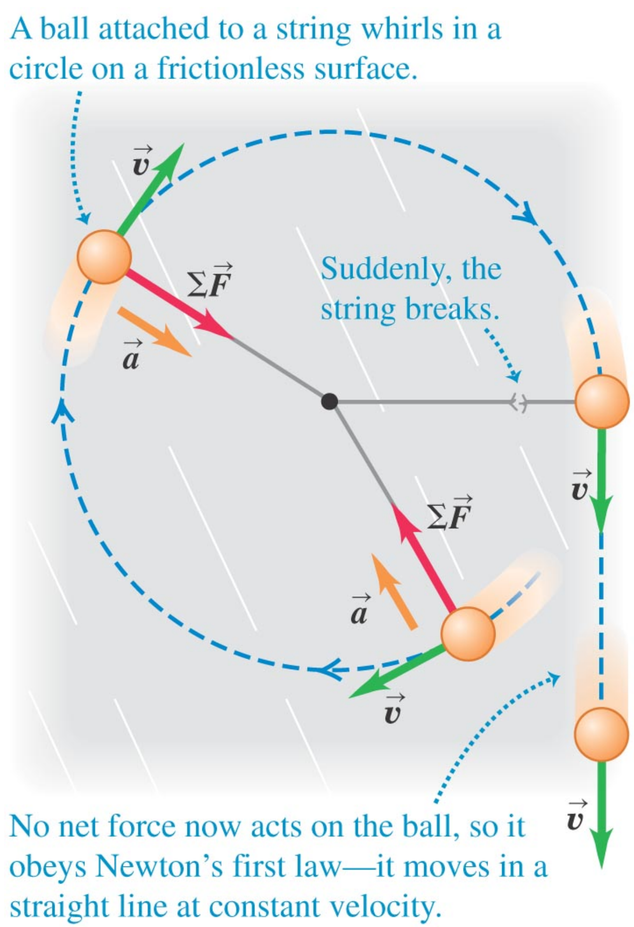
Dynamics of circular motion

- If a particle is in uniform circular motion, both its acceleration and the net force on it are directed toward the center of the circle.
- The magnitude of the net force on the particle is $F_{net} = mv^2/R$.



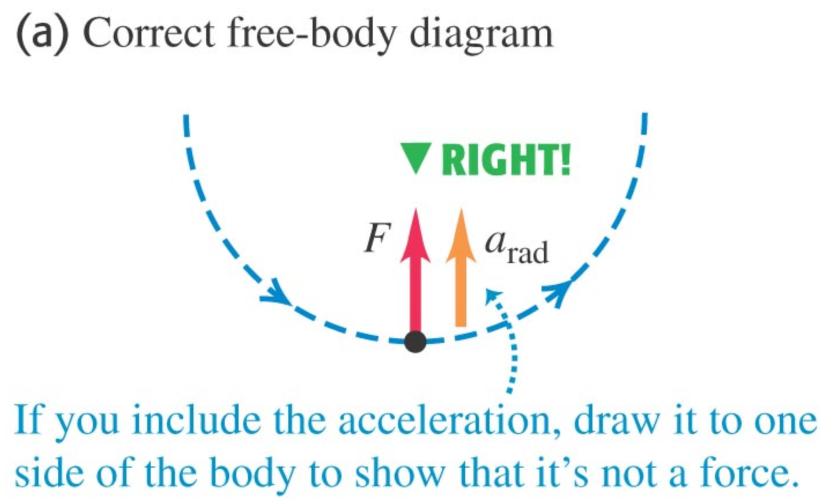
What if the string breaks?

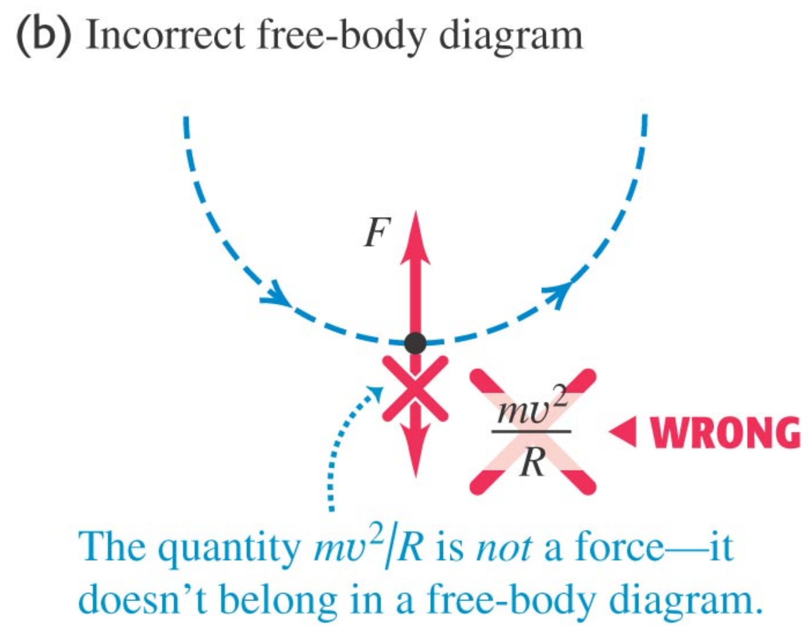
- If the string breaks, no net force acts on the ball, so it obeys Newton's first law and moves in a straight line.



Avoid using "centrifugal force"

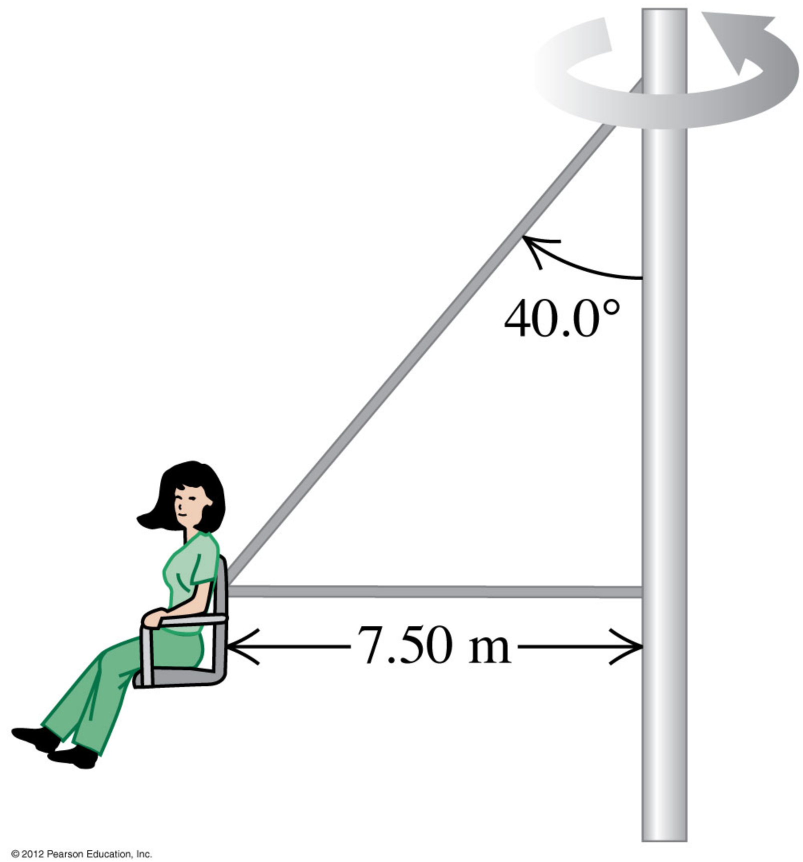
- Figure (a) shows the correct free-body diagram for a body in uniform circular motion.
- Figure (b) shows a common error. The force on the object is inwards.
- Only in a non-inertial reference frame is there a "centrifugal force." We will not use such frames in this course.





Example #8

In a "Giant Swing" ride at an amusement park, a person swings in a horizontal circle at 28.0 rpm. If the seat weighs 255 N and an 825 N person is sitting in it, find the tension in each cable.



Solution #8

The woman is in uniform circular motion and thus experiencing a centripetal acceleration. Applying Newton's 2nd law:

$\Sigma F_x = T_1 + T_2 \sin\theta = 4\pi^2 mR/P^2 \quad \Sigma F_y = T_2 \cos\theta - mg = 0 \Longrightarrow$

$T_2 = mg/\cos\theta = (1080\text{ N})/(\cos 40.0°) = 1{,}410\text{ N}$

$T_1 = 4\pi^2 mR/P^2 - T_2 \sin\theta$

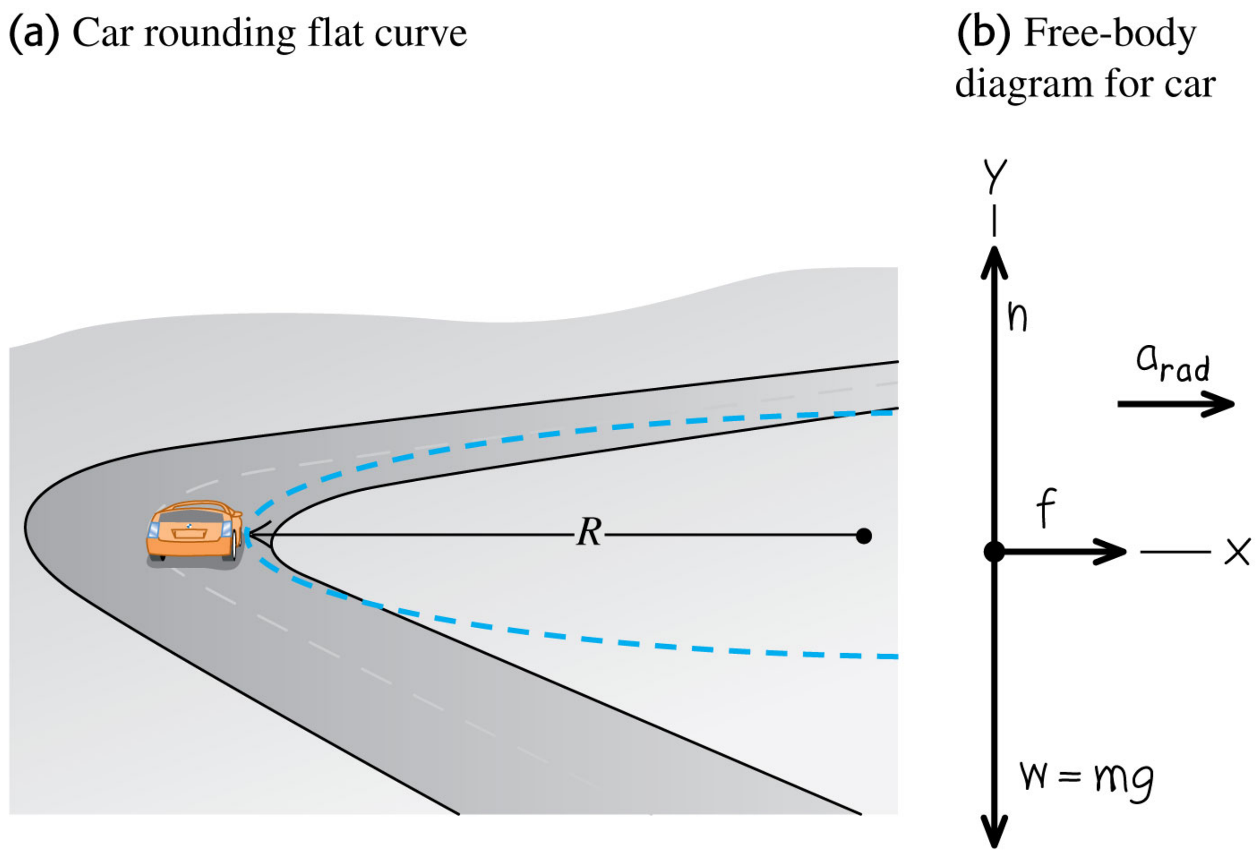
$= 4\pi^2(1080\text{ N})(7.5\text{ m})[(28.0\text{ rpm})/(60\text{ s/min})]^2/(9.8\text{ m/s}^2)$

$- (1410\text{ N})\sin 40.0° = 6{,}200\text{ N}$

A car rounds a flat curve

- A car rounds a flat unbanked curve. What is its maximum speed?

$$\Sigma F_x = f = \mu_s n = \mu_s mg = mv^2/R \Longrightarrow v = (\mu_s gR)^{1/2}$$



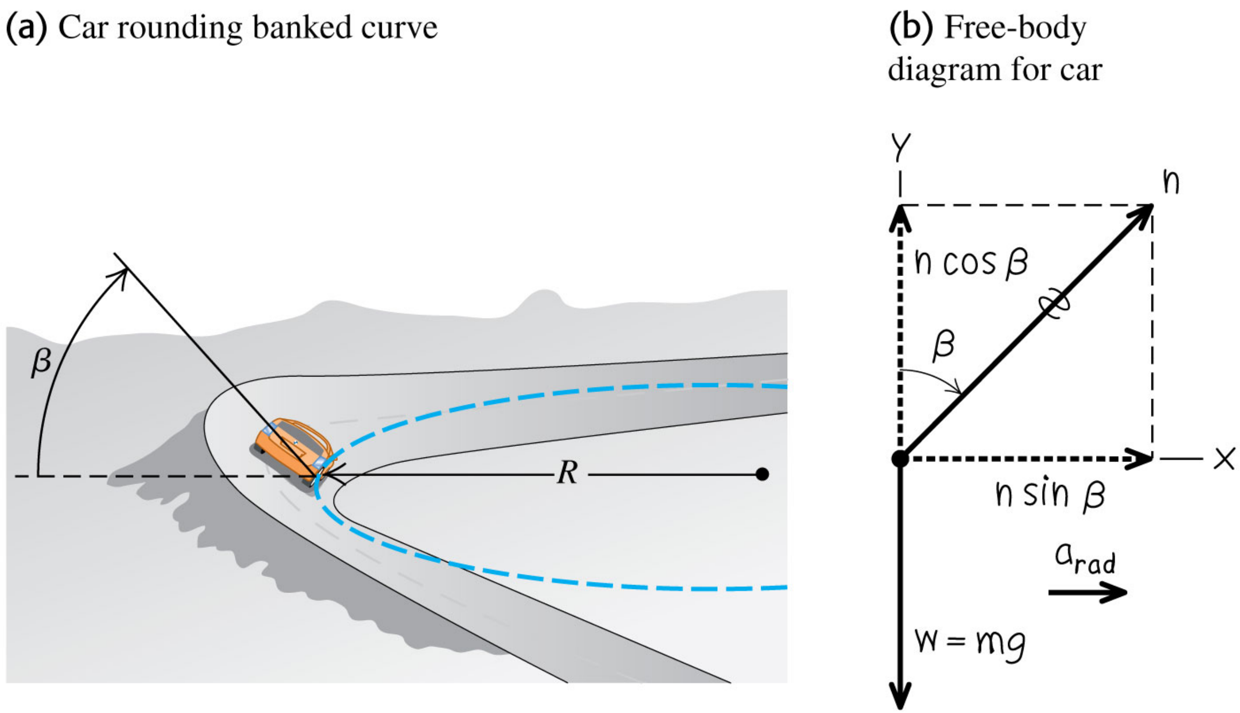
A car rounds a banked curve

- At what angle should a curve be banked so a car can make the turn even with no friction?

$\Sigma F_y = n \cos\beta - mg = 0$ $\qquad$ $\Sigma F_x = n \sin\beta = mv^2/R \implies$

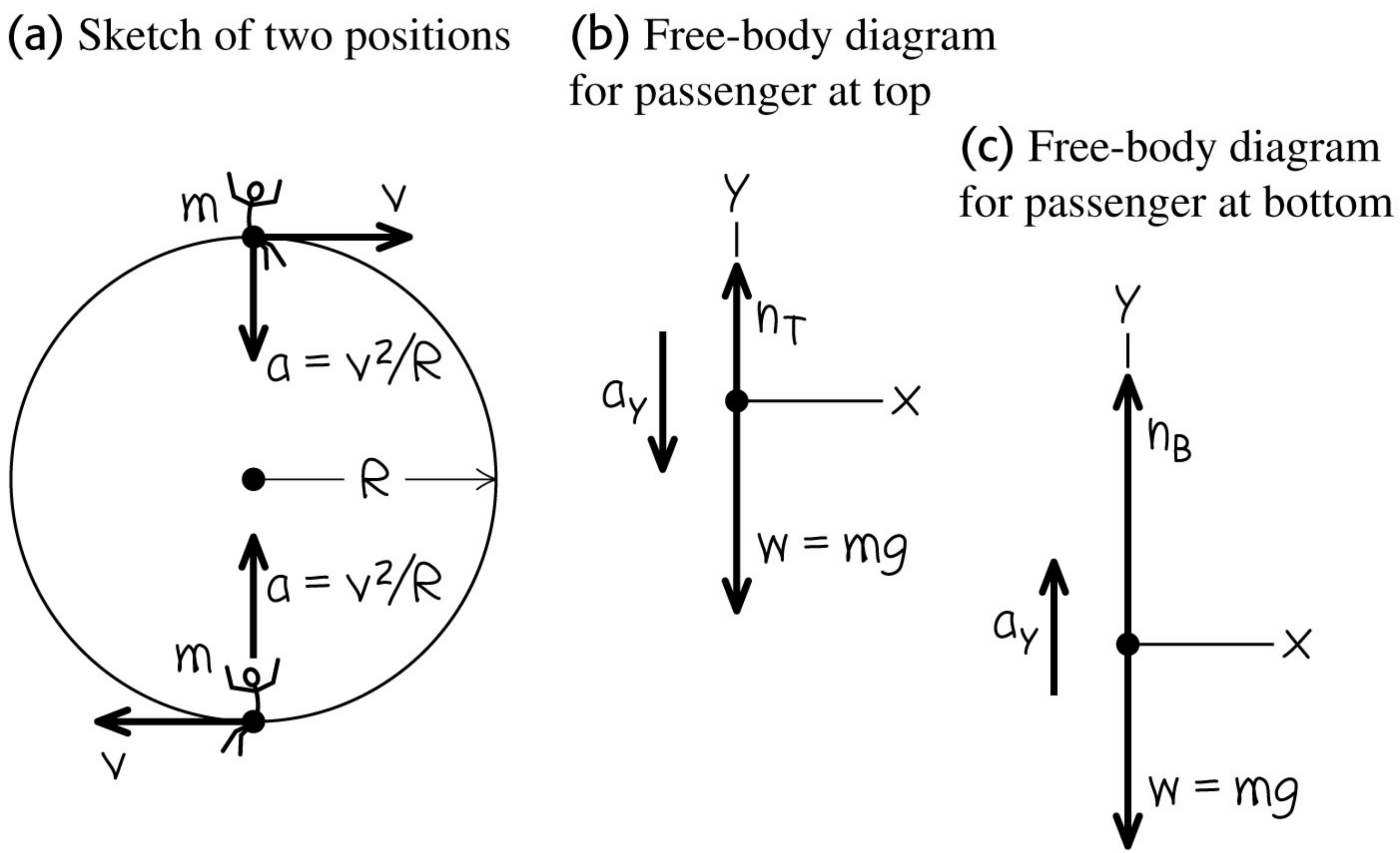
$v = (\mu_s g \tan\beta)^{1/2}$ compare with $v = (\mu_s g R)^{1/2}$

The horizontal component of normal force takes the place of friction!



Uniform motion in a vertical circle

- A person on a Ferris wheel moves in a vertical circle.

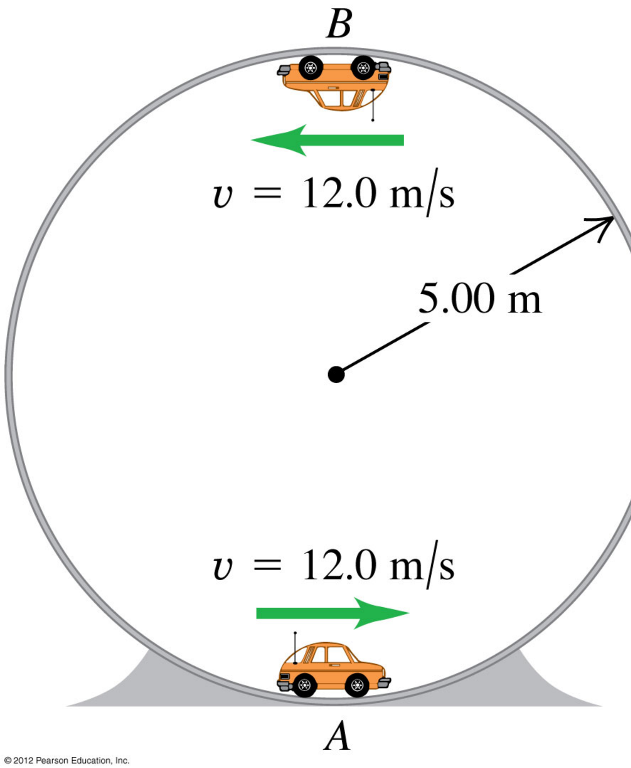


Example #9

A small remote-controlled car with mass 1.60 kg moves at constant speed 12.0 m/s in a track formed by a vertical circle inside a hollow metal cylinder that has a radius of 5.00 m. What is the magnitude of the normal force exerted on the car by the walls of the cylinder at

a. point *A* (bottom of the track)

b. point *B* (top of the track)



Solution #9

If the car moves at constant speed, it is uniform circular motion with $a = v^2/R$ directed towards the center of the circle. If we choose the y axis to point upwards:

a. At point A: $\Sigma F_y = n - mg = ma \Longrightarrow$

$n = m(g + a) = m(g + v^2/R)$

$= (1.6\ \text{kg})[9.8\ \text{m/s}^2 + (12.0\ \text{m/s})^2/(5.00\ \text{m})] = 61.8\ \text{N}$

b. At point B: $\Sigma F_y = -n - mg = -ma \Longrightarrow$

$n = m(a - g) = m(v^2/R - g)$

$= (1.6\ \text{kg})[(12.0\ \text{m/s})^2/(5.00\ \text{m}) - 9.8\ \text{m/s}^2] = 30.4\ \text{N}$

The fundamental forces of nature

- According to current understanding, all forces are expressions of four distinct *fundamental* forces:
- *gravitational interactions*
- *electromagnetic interactions*
- the *strong interaction*
- the *weak interaction*
- Physicists have taken steps to unify all interactions into a *theory of everything*.