Chapter 5

Applying Newton's Laws

PowerPoint® Lectures for
University Physics, Twelfth Edition
– Hugh D. Young and Roger A. Freedman

Lectures by James Pazun

Goals for Chapter 5

- To use and apply Newton's Laws
- Connect these laws to Kinematics
- To study friction and fluid resistance
- To consider forces in circular motion

First in Equilibrium (Newton's First Law)
Then, in non-equilibrium (Second Law)

Using Newton's First Law when forces are in equilibrium

Problem-Solving Strategy 5.1 Newton's First Law: Equilibrium of a Particle

IDENTIFY *the relevant concepts:* You must use Newton's first law for any problem that involves forces acting on a body in equilibrium—that is, either at rest or moving with constant velocity. For example, a car is in equilibrium when it's parked, but also when it's traveling down a straight road at a steady speed.

If the problem involves more than one body and the bodies interact with each other, you'll also need to use Newton's *third* law. This law allows you to relate the force that one body exerts on a second body to the force that the second body exerts on the first one.

Be certain that you identify the target variable(s). Common target variables in equilibrium problems include the magnitude of one of the forces, the components of a force, or the direction (angle) of a force.

SET UP *the problem* using the following steps:

1. Draw a very simple sketch of the physical situation, showing dimensions and angles. You don't have to be an artist!
2. Draw a free-body diagram for each body that is in equilibrium. For the present, we consider the body as a particle, so you can represent it as a large dot. In your free-body diagram, *do not* include the other bodies that interact with it, such as a surface it may be resting on, or a rope pulling on it.
3. Ask yourself what is interacting with the body by touching it or in any other way. On your free-body diagram, draw a force vector for each interaction and label each force with a symbol representing the *magnitude* of the force. If you know the angle at which a force is directed, draw the angle accurately and label it. Include the body's weight, except in cases where the body has negligible mass (and hence negligible weight). If the mass is given, use $w = mg$ to find the weight. A surface in contact with the body exerts a normal force perpendicular to the surface and possibly a friction force parallel to the surface. A rope or chain exerts a pull (never a push) in a direction along its length.
4. *Do not* show in the free-body diagram any forces exerted *by* the body on any other body. The sums in Eqs. (5.1) and (5.2) include only forces that act *on* the body. For each force on the body, ask yourself "What other body causes that force?" If you can't answer that question, you may be imagining a force that isn't there.
5. Choose a set of coordinate axes and include them in your free-body diagram. (If there is more than one body in the problem, choose axes for each body separately.) Label the positive direction for each axis. If a body rests or slides on a plane surface, it usually simplifies the solution to take the axes in the directions parallel and perpendicular to this surface, even when the plane is tilted.

EXECUTE *the solution* as follows:

1. Find the components of each force along each of the body's coordinate axes. Draw a wiggly line through each force vector that has been replaced by its components, so you don't count it twice. Remember that while the *magnitude* of a force is always positive, the *component* of a force along a particular direction may be positive or negative.
2. Set the algebraic sum of all x-components of force equal to zero. In a separate equation, set the algebraic sum of all y-components equal to zero. (*Never* add x- and y-components in a single equation.)
3. If there are two or more bodies, repeat all of the above steps for each body. If the bodies interact with each other, use Newton's third law to relate the forces they exert on each other.
4. Make sure that you have as many independent equations as the number of unknown quantities. Then solve these equations to obtain the target variables.

EVALUATE *your answer:* Look at your results and ask whether they make sense. When the result is a symbolic expression or formula, try to think of special cases (particular values or extreme cases for the various quantities) for which you can guess what the results ought to be. Check to see that your formula works in these particular cases.

Netwon's laws problems

1. **Draw the free body diagram (only forces ON the object, not the ones exerted by the object)**

2. **Decompose the forces along X and Y directions**

3. **Write down Newton's 2nd laws for each direction and each object**

4. **If more than one object determine their relation (tension forces, acceleration, etc.)**

1-D equilibrium

Consider an athlete hanging on a massless rope.

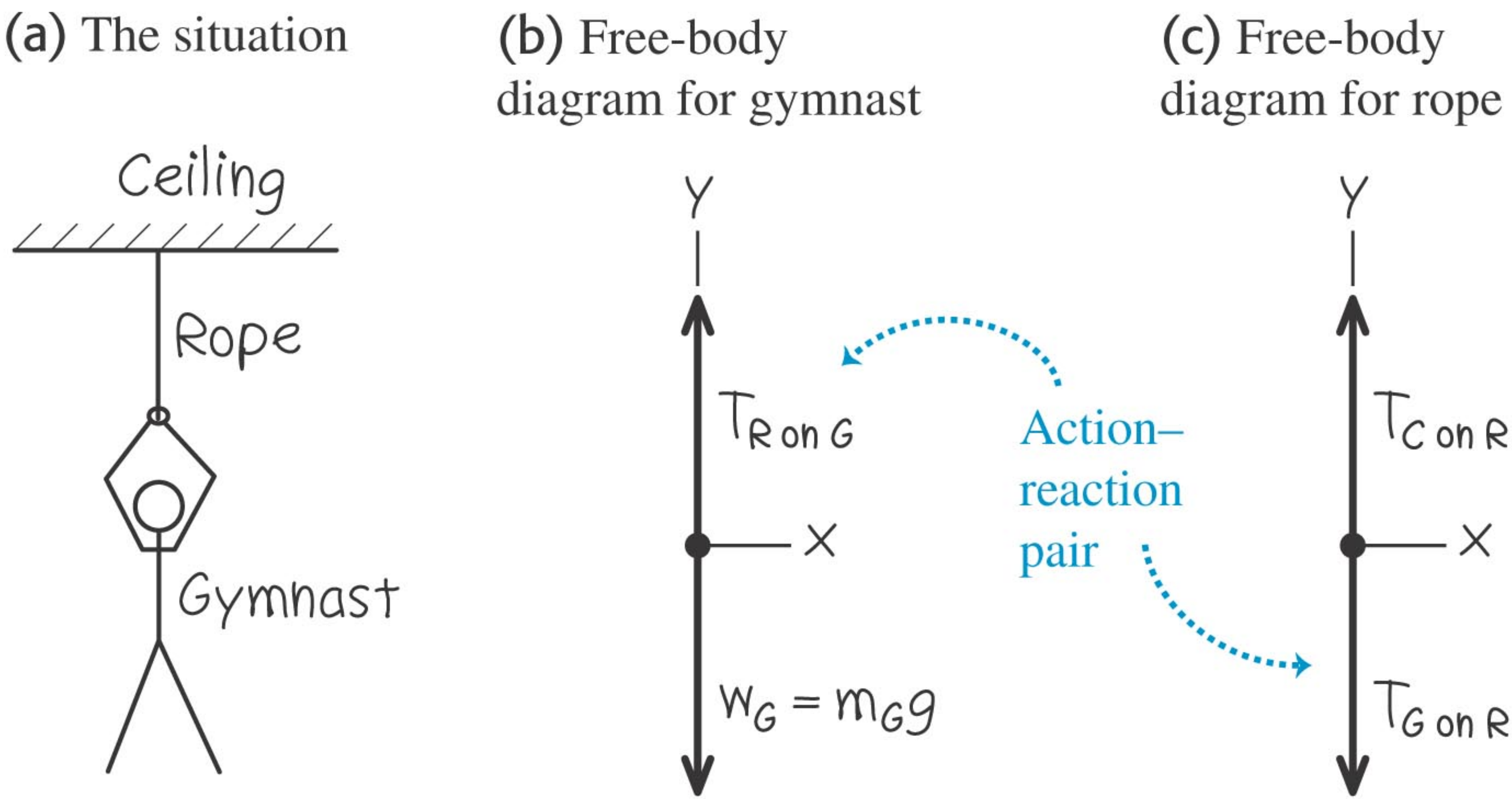
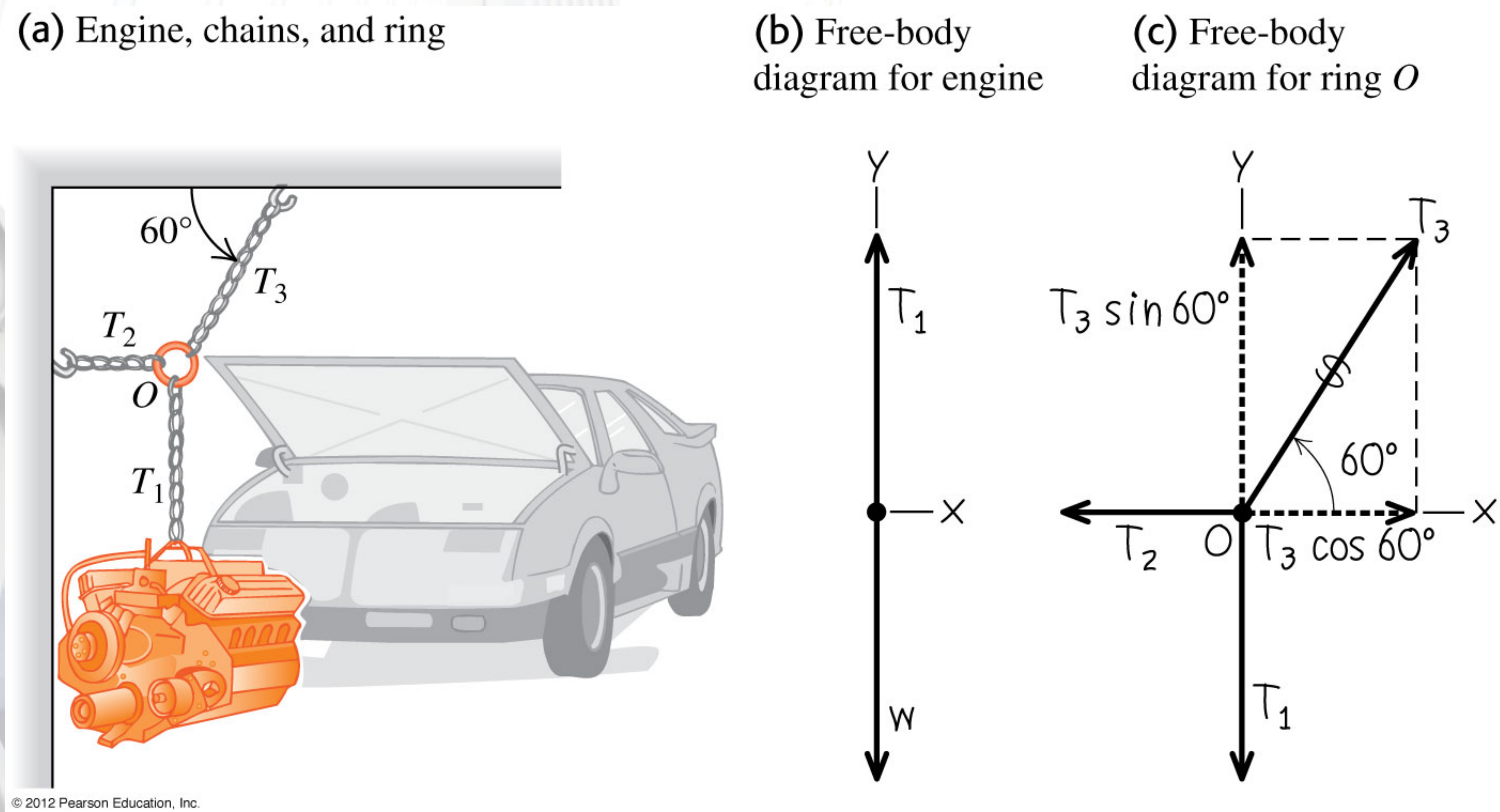


Figure 5.3



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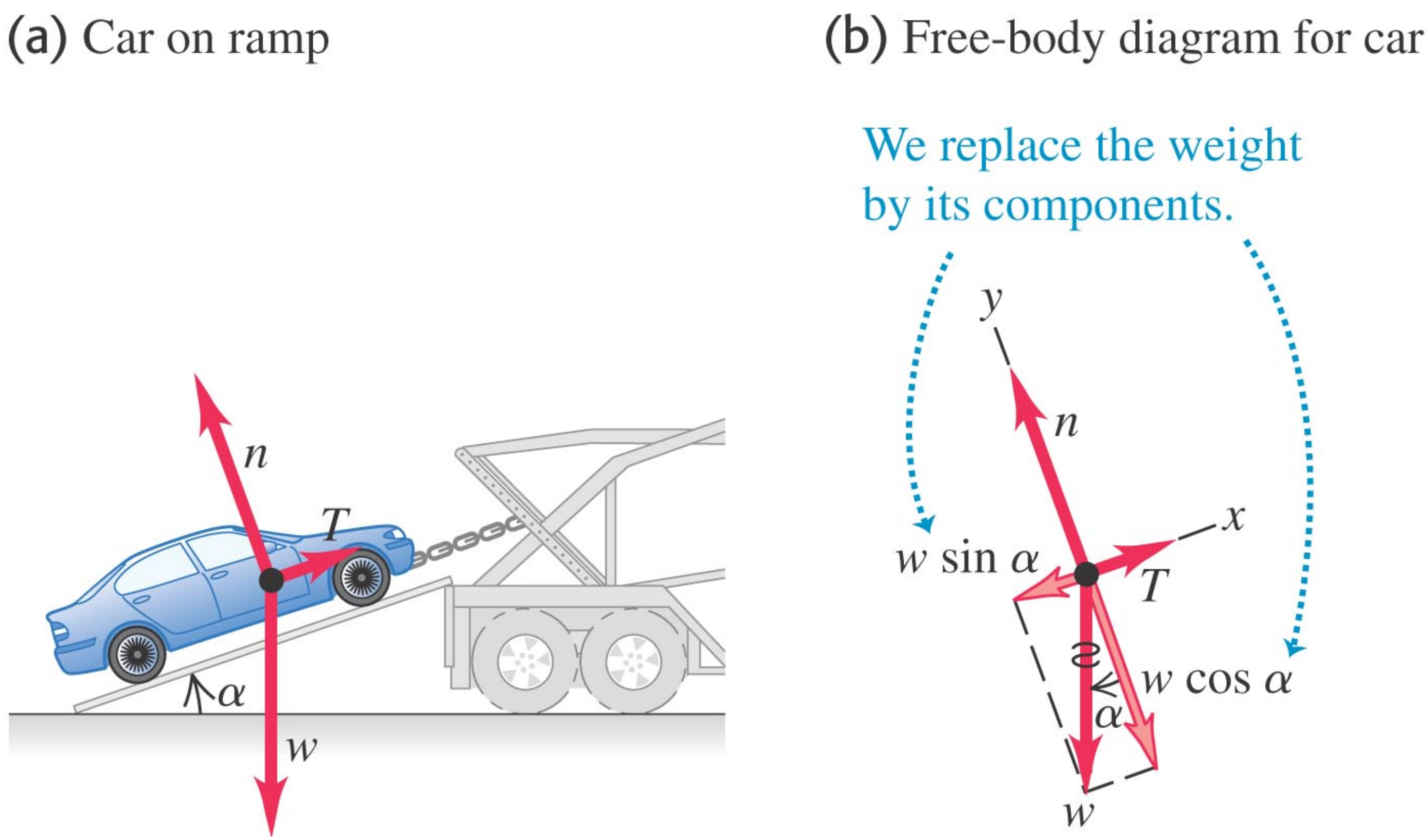
A crate on an inclined plane

An object on an inclined plane will have components of force in *x* and *y* space.



Person in an elevator

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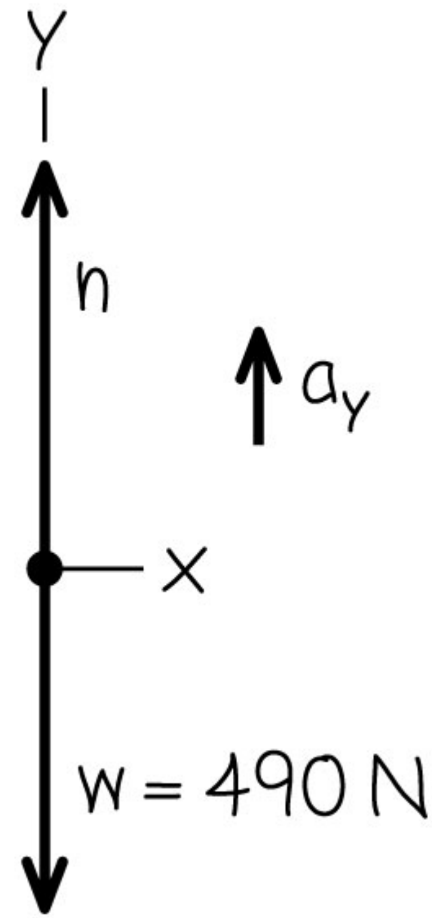
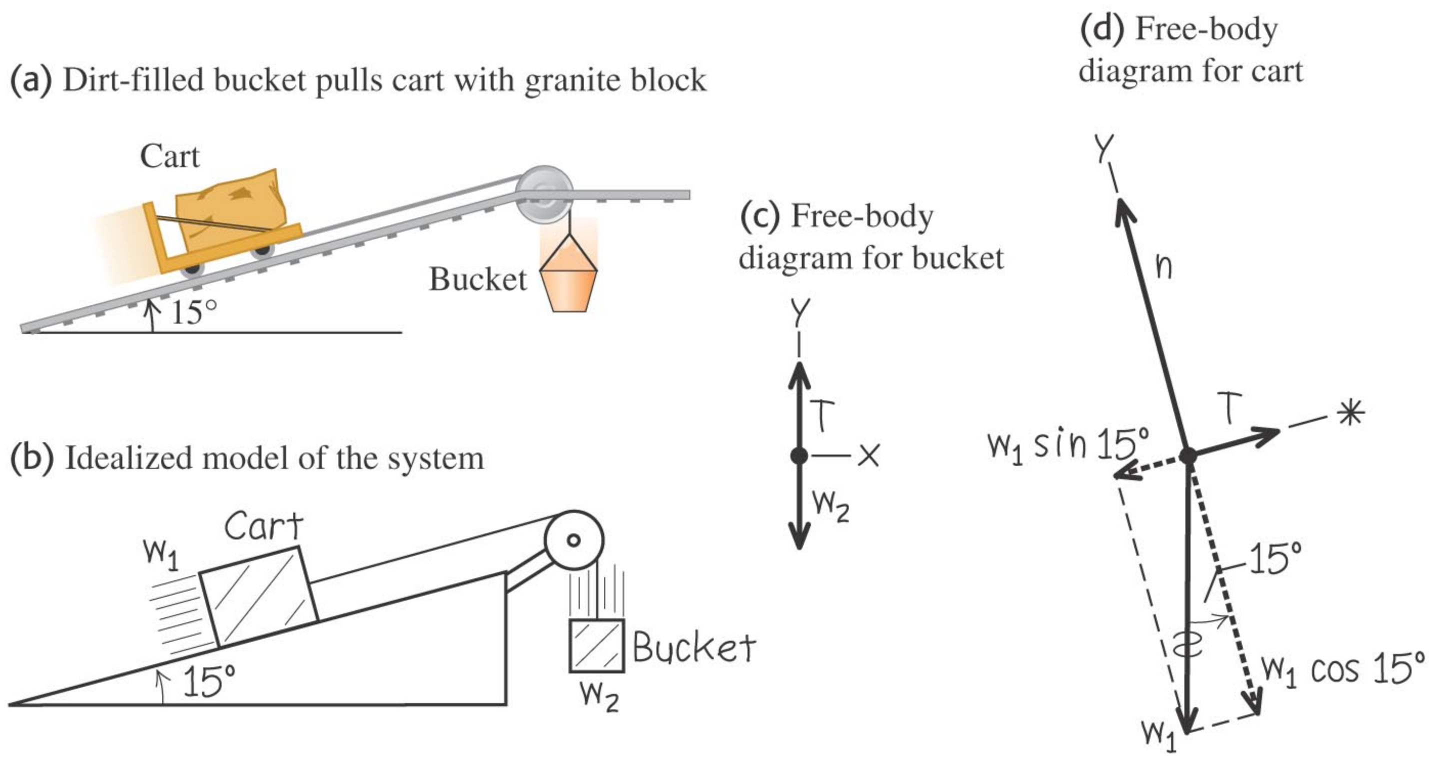
Moving in an arbitrary direction

(b) Free-body diagram for woman



Connected - Two bodies with same acceleration magnitude

Draw the two-free body diagrams. The tension from the mass hanging is the same force that draws the cart up the ramp.



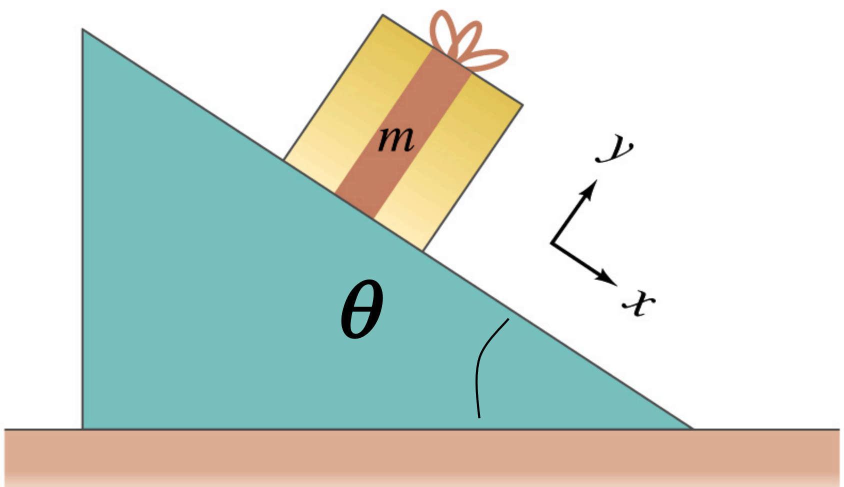
Box on an inclined plane

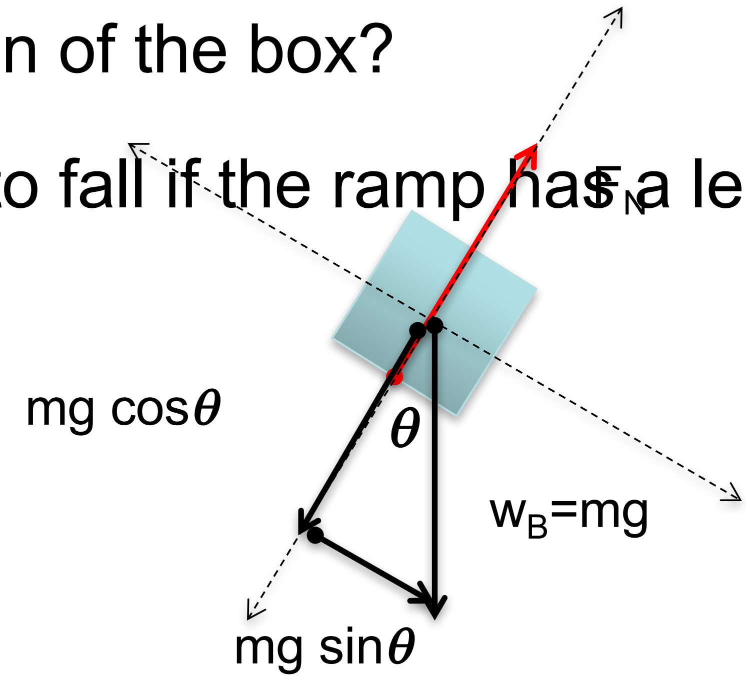
A box with mass *m* is placed on a frictionless incline with angle θ and is allowed to slide down.

a) What is the normal force?

b) What is the acceleration of the box?

c) How long does it take to fall if the ramp has a length L?





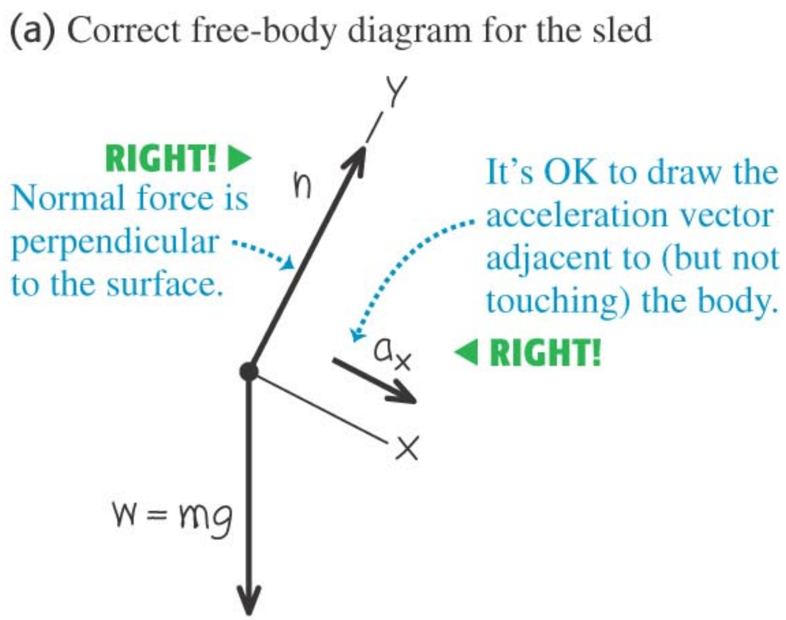
$$x: \quad mg\sin\theta = ma_x$$

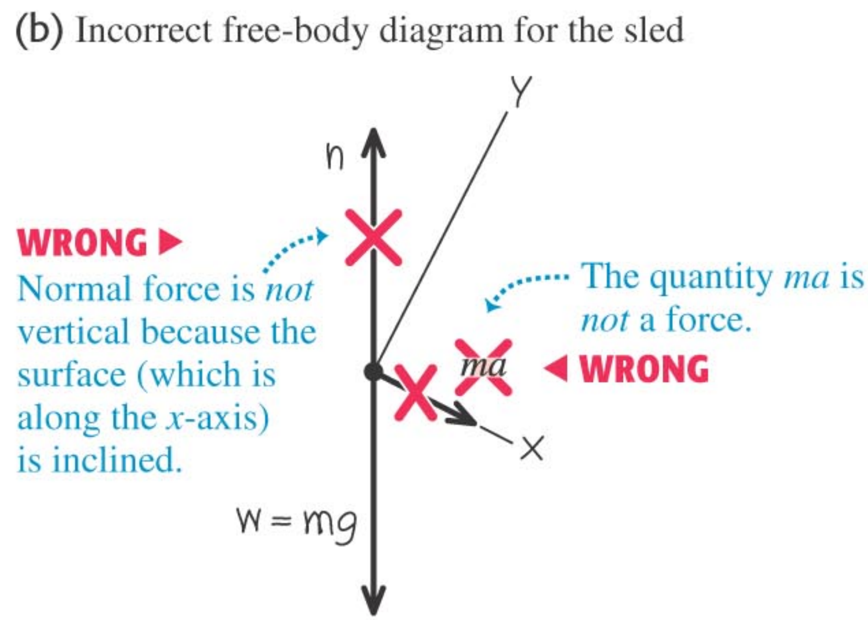
$$y: \quad F_N - mg\cos\theta = 0$$

$$a_x = g\sin\theta$$

Watch for this common error

A good "road sign" is to be sure that the normal force comes out perpendicular to the surface.





Friction

Two types of friction:

1. *Kinetic:* The friction force that slows things down

2. *Static:* The force that makes it hard to even get things moving

Refrigerator

If you push a refrigerator when there is no friction what happens?

In the real world what happens? Especially when it's fully loaded and on a sticky kitchen floor?

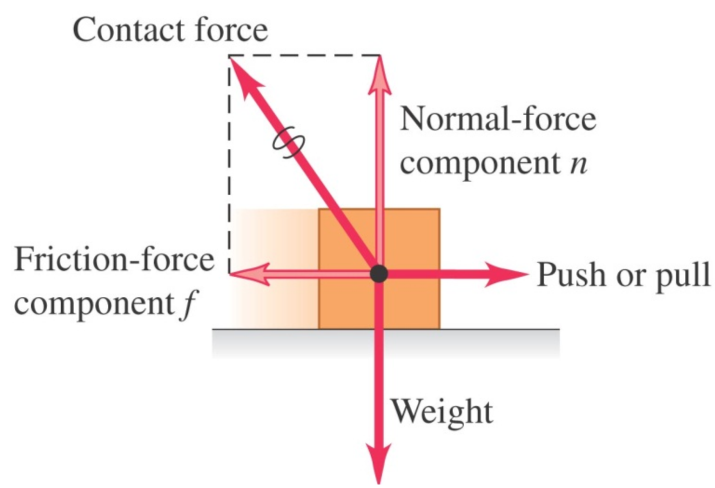
- When does static friction kick in?
- When does kinetic friction kick in?

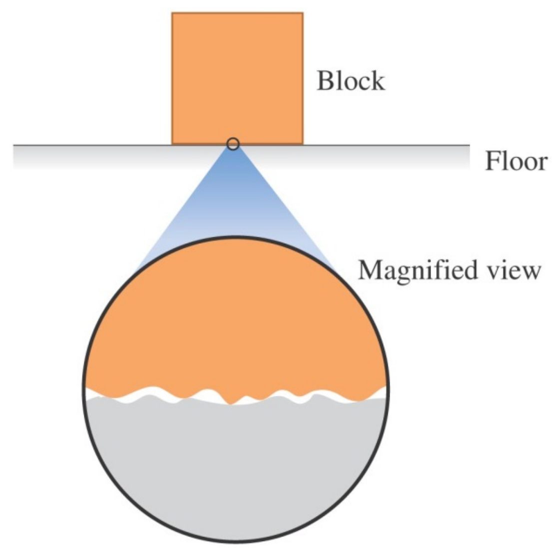
Frictional forces, kinetic and static—Figures 5.17 and 5.18

Friction can keep an object from moving or slow its motion from what we last calculated on an ideal, frictionless surface.

Microscopic imperfections cause nonideal motion.

The friction and normal forces are really components of a single contact force.

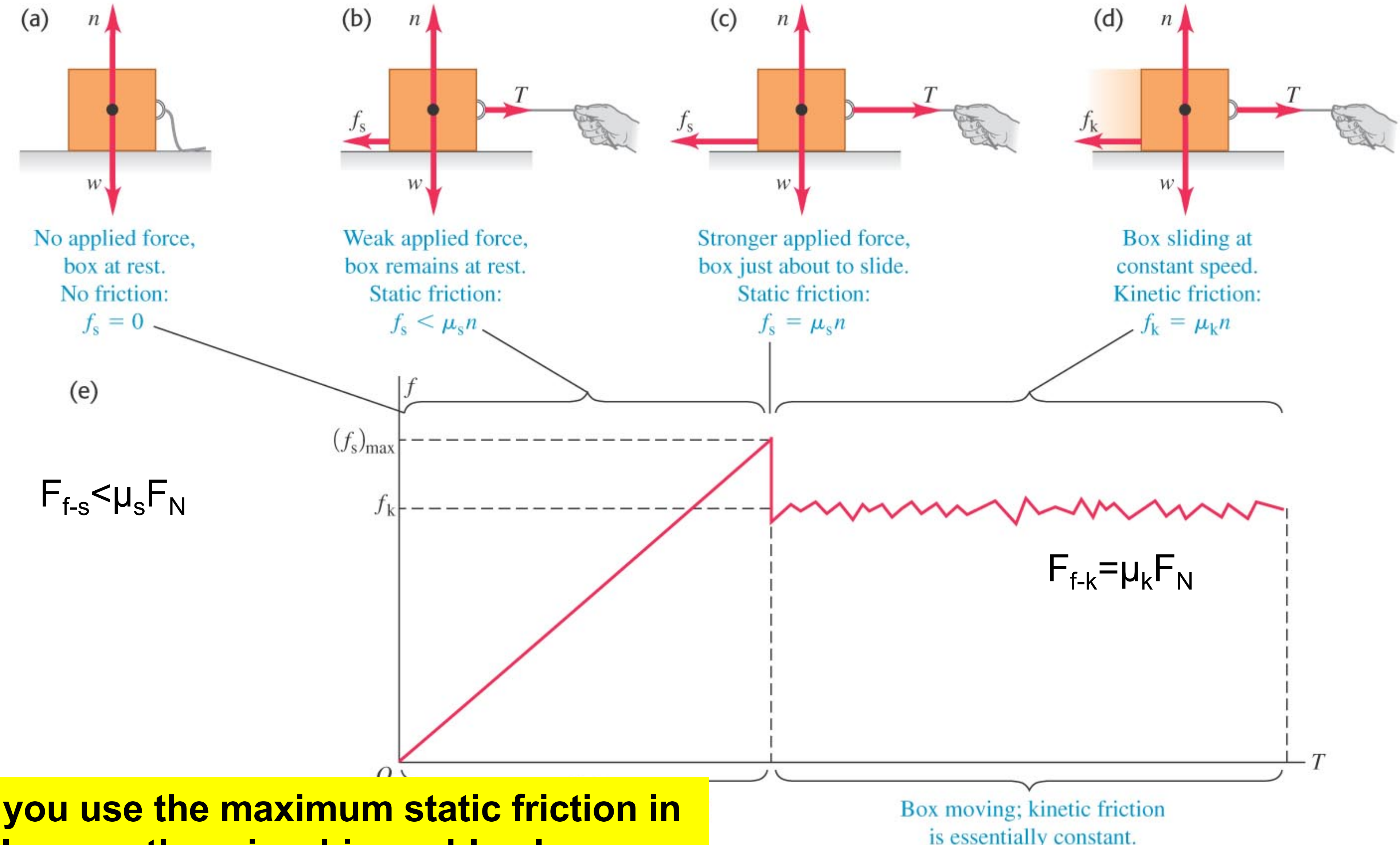




On a microscopic level, even smooth surfaces are rough; they tend to catch and cling.

Applied force is proportional until the object moves—Figure 5.19

Notice the transition between static and kinetic friction.



$F_{f\text{-}s} < \mu_s F_N$

$F_{f\text{-}k} = \mu_k F_N$

If you use the maximum static friction in all cases, there is a big problem!

Static Friction

This is more complicated

For static friction, the friction force can vary

$$F_{Friction} \leq \mu_{Static} F_{Normal}$$

Example of the refrigerator:

- If I don't push, what is the static friction force?
- What if I push a little?

Kinetic Friction

For kinetic friction, it turns out that the larger the Normal Force the larger the friction. We can write

$$F_{Friction} = \mu_{Kinetic} F_{Normal}$$

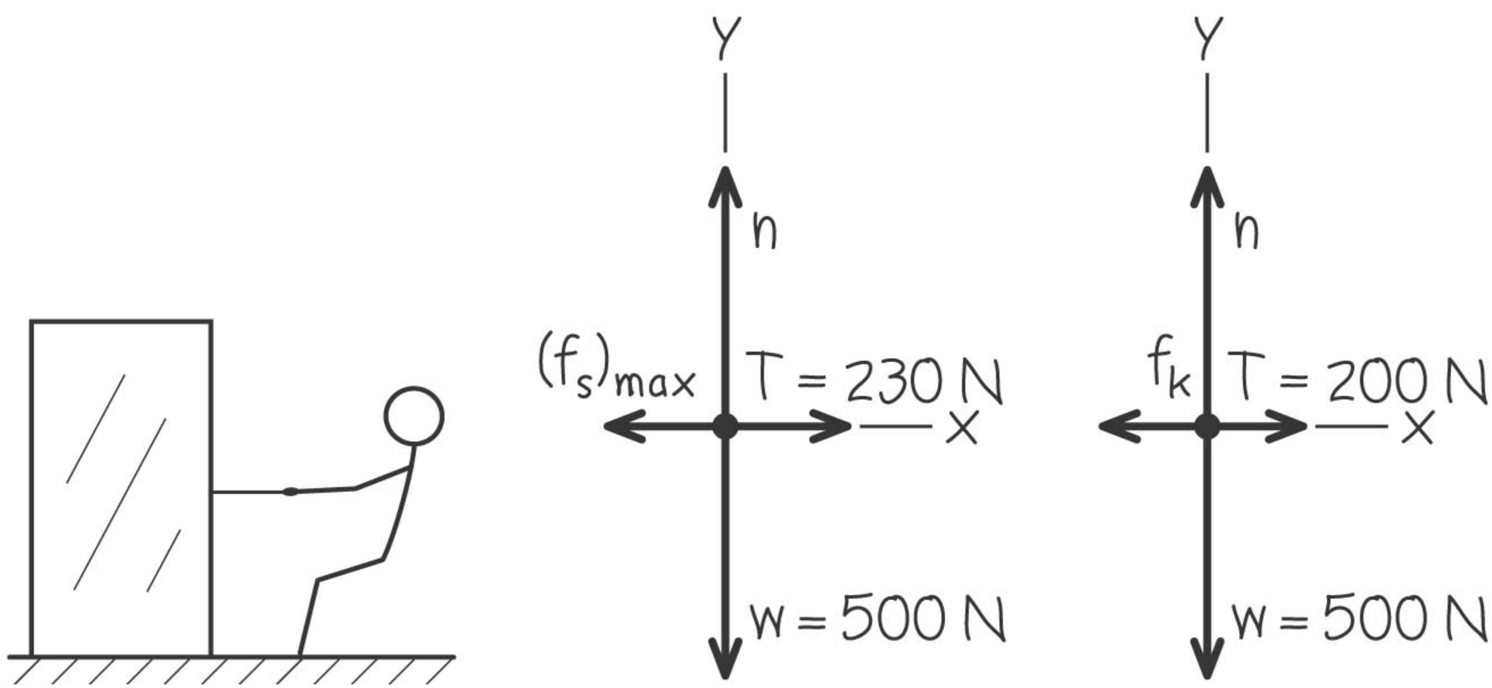
Here μ is a constant

Warning:

- THIS IS NOT A VECTOR EQUATION!

Notice the effect of friction in horizontal motion

Moving a 500 N crate has two parts: getting the motion to begin and then the effect of friction on constant velocity motion.



(a) Pulling a crate

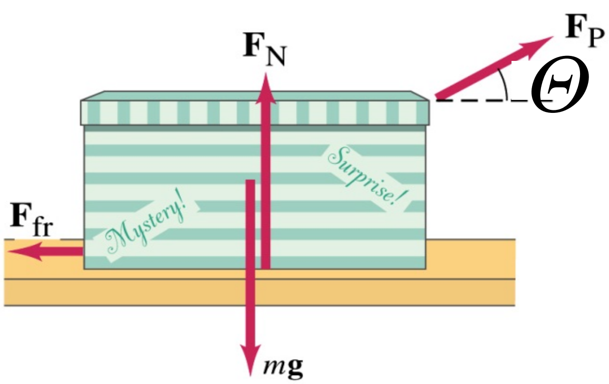
(b) Free-body diagram for crate just before it starts to move

(c) Free-body diagram for crate moving at constant speed

Pulling Against Friction

A box of mass *m* is on a surface with coefficient of kinetic friction *mu*. You pull with constant force F_P at angle *Q*. The box does not leave the surface and moves to the right.

1. What is the acceleration?
2. What angle maximizes the acceleration?



$$x: \quad F_P \cos\theta - \mu_K F_N = ma_x$$

$$y: \quad F_N + F_P \sin\theta - mg = 0$$

$$\Rightarrow \quad F_N = mg - F_P \sin\theta$$

$$x: \quad F_P \cos\theta - \mu_K (mg - F_P \sin\theta) = ma_x$$

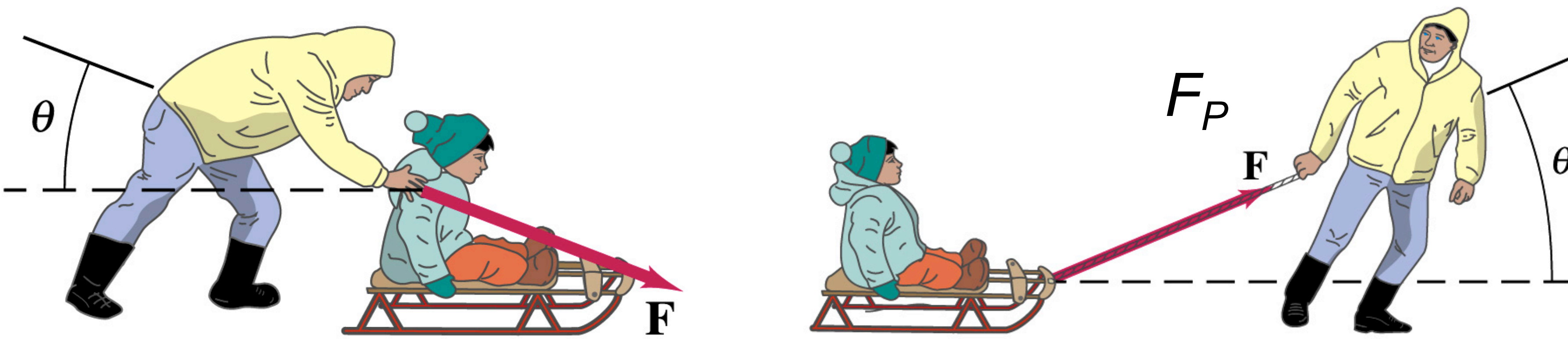
$$a_x = \frac{F_P}{m}\cos\theta - \mu_K g + \mu_K \frac{F_P}{m}\sin\theta$$

$$\left.\frac{d(a_x)}{d\theta}\right|_{\theta\,\max} = -\frac{F_P}{m}\sin\theta + \mu_K \frac{F_P}{m}\cos\theta = 0 \quad \Rightarrow \theta_{\max} = \tan^{-1}\mu_K$$

Is it better to push or pull a sled?

You can pull or push a sled with the same force magnitude, F_P, but different angles *Q*, as shown in the figures.

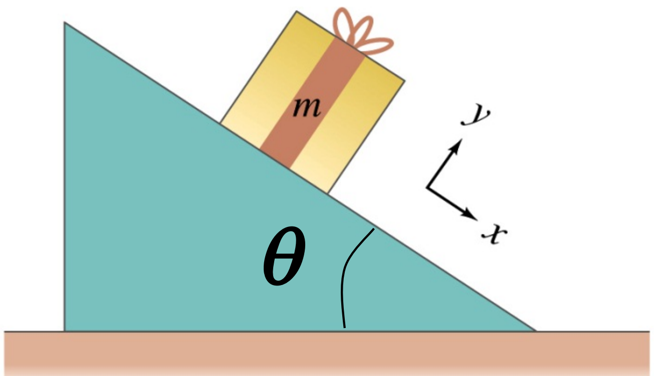
Assuming the sled doesn't leave the ground and has a constant coefficient of friction, *m*, which is better?

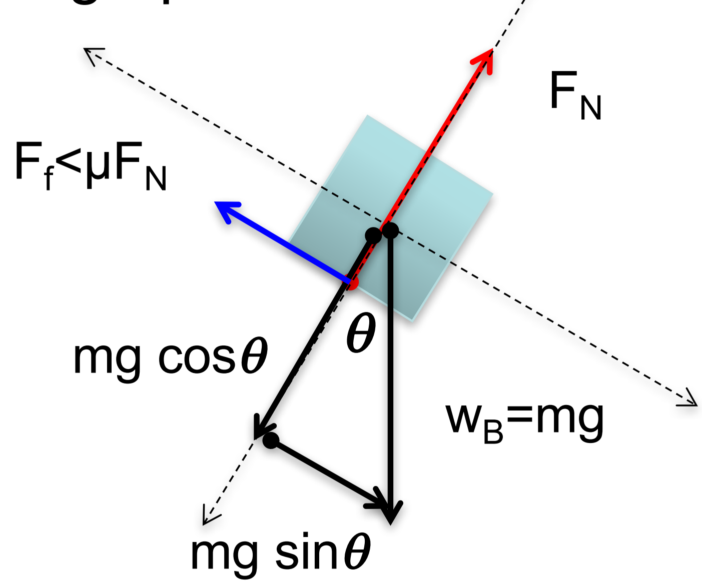


Box on an inclined plane 2

Same problem as before, but now friction is not negligible and the coefficient of friction is μ. The inclined plane is adjustable and we change θ from 0 to 90 degrees. Mass is known and is equal to **m**. Calculate and draw a graph of:

- Friction force as a function of θ
- Acceleration of the box as a function of θ





If static

$$x: \quad mg\sin\theta - F_f = 0 \quad \Rightarrow F_f = mg\sin\theta$$

$$y: \quad F_N - mg\cos\theta = 0$$

$$\mu_s F_N = mg\sin\theta_{\max}$$

$$\mu_s mg\cos\theta_{\max} = mg\sin\theta_{\max}$$

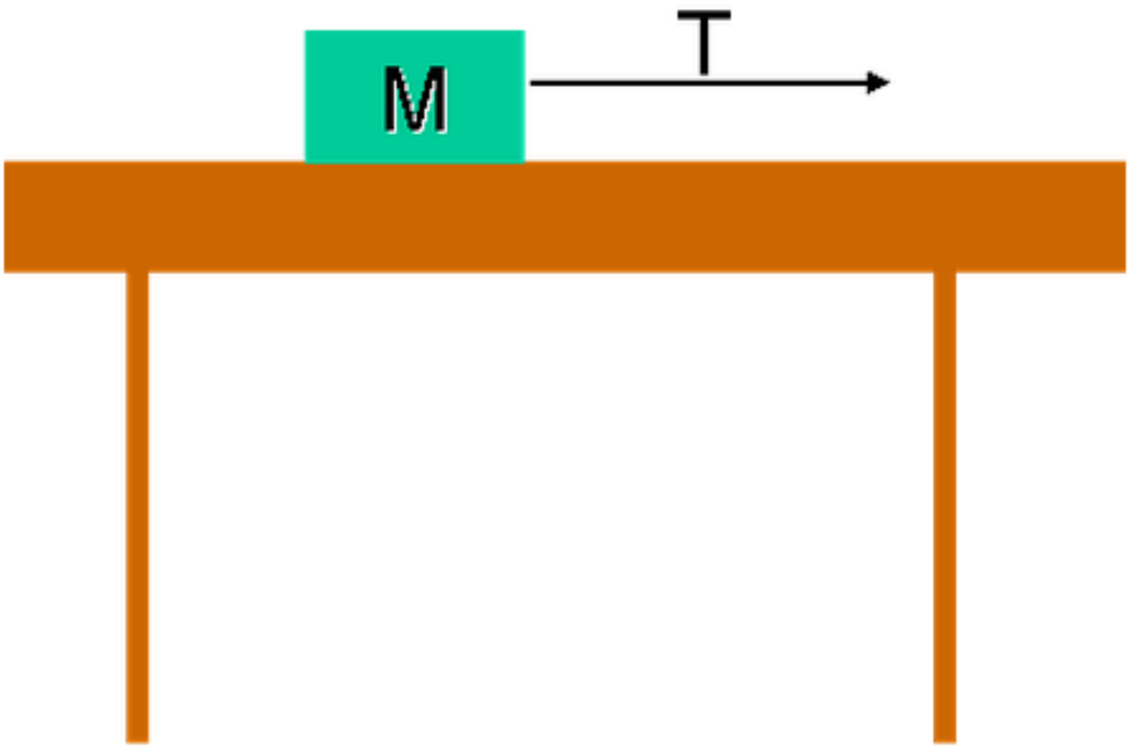
$$\tan\theta_{\max} = \mu_s$$

If $\theta > \theta_{max}$

$$x: \quad mg\sin\theta - \mu_K F_N = ma_x$$

$$y: \quad F_N - mg\cos\theta = 0 \quad \Rightarrow \quad mg\sin\theta - \mu_k mg\cos\theta = ma_x$$

Friction



A box sits on a horizontal table. A string with tension T pulls to the right, but static friction between the box and the table prevents the box from moving.

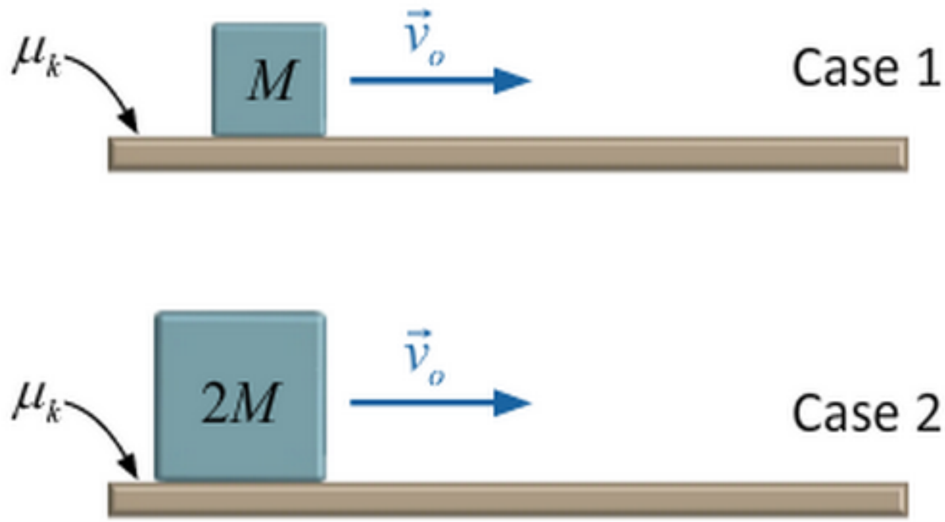
1) What is the magnitude of the static frictional force acting on the box?

- Mg
- μMg
- T
- 0

Friction

In both cases shown a box is sliding across a floor with the same kinetic coefficient of friction and the same initial velocity. The only difference between the two cases is the mass of the box.

In which case will the box slide the furthest before coming to rest?

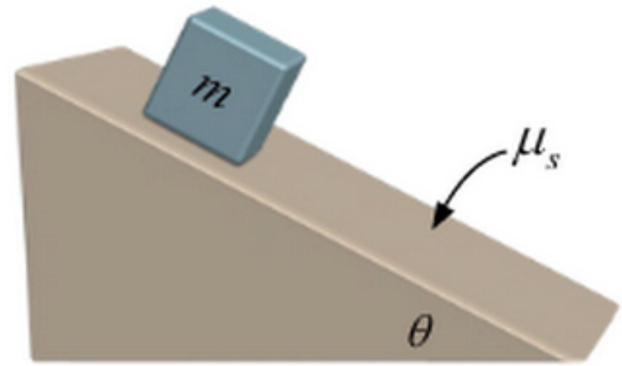


- Case 1
- Case 2
- Same

Friction

A box of mass m sits at rest on an inclined plane that makes and angle θ with the horizontal. It is prevented from sliding by static friction. The coefficient of static friction between the box and the ramp is μ_s.

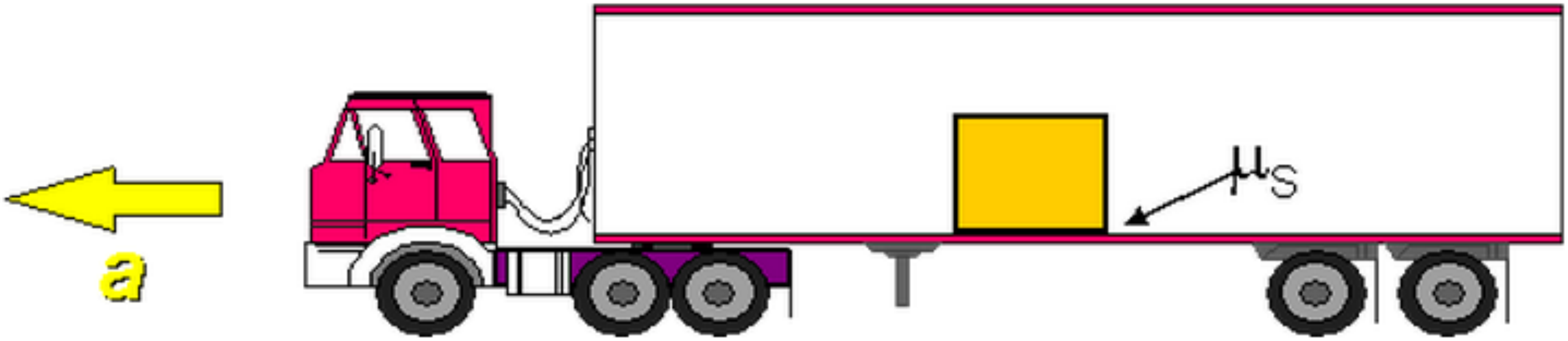
What is the magnitude of the static frictional force acting on the box?



- $\mu_s mg$
- $\mu_s mg \cos\theta$
- $mg\sin\theta$

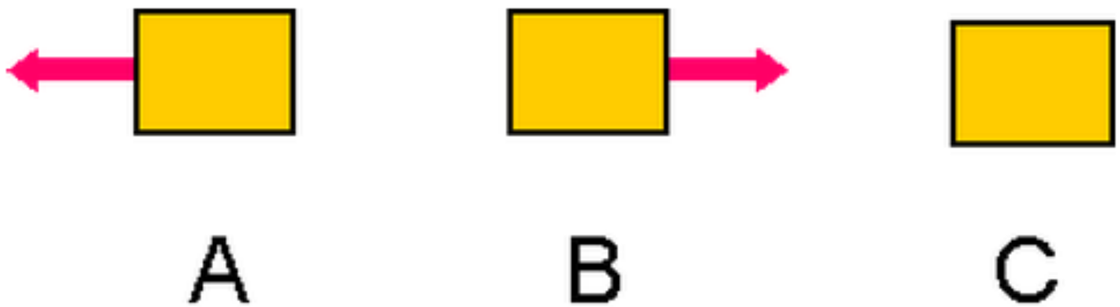
Submit

Friction



A box sits on the horizontal bed of a moving truck. Static friction between the box and the truck keeps the box from sliding as the truck accelerates to the left as shown.

1) Which of the following diagrams best describes the static frictional force acting on the box?



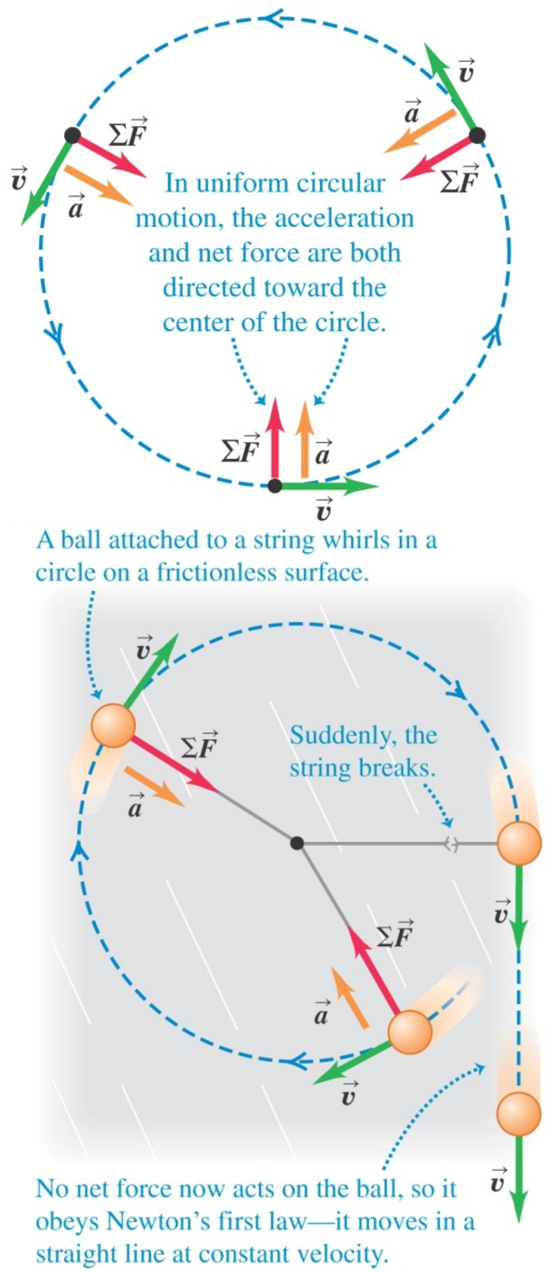
- A
- B
- C

The dynamics of uniform circular motion

In uniform circular motion, both the acceleration and force are centripetal.

When going in a circle the choice of coordinates is NOT optional. One of the axis has to point towards the center and in this case

$$\sum F_r = ma_c = m\frac{v^2}{R}$$



Netwon’s laws problems

1. Draw the free body diagram (only forces ON the object, not the ones exerted by the object)

2. Choose coordinates (chose one along the direction of motion if going straight) for each object. Choose + in the direction of motion. IF there is circular motion ONE of the axis has to point towards the center (+ towards center). Decompose the forces that are not along the coordinates

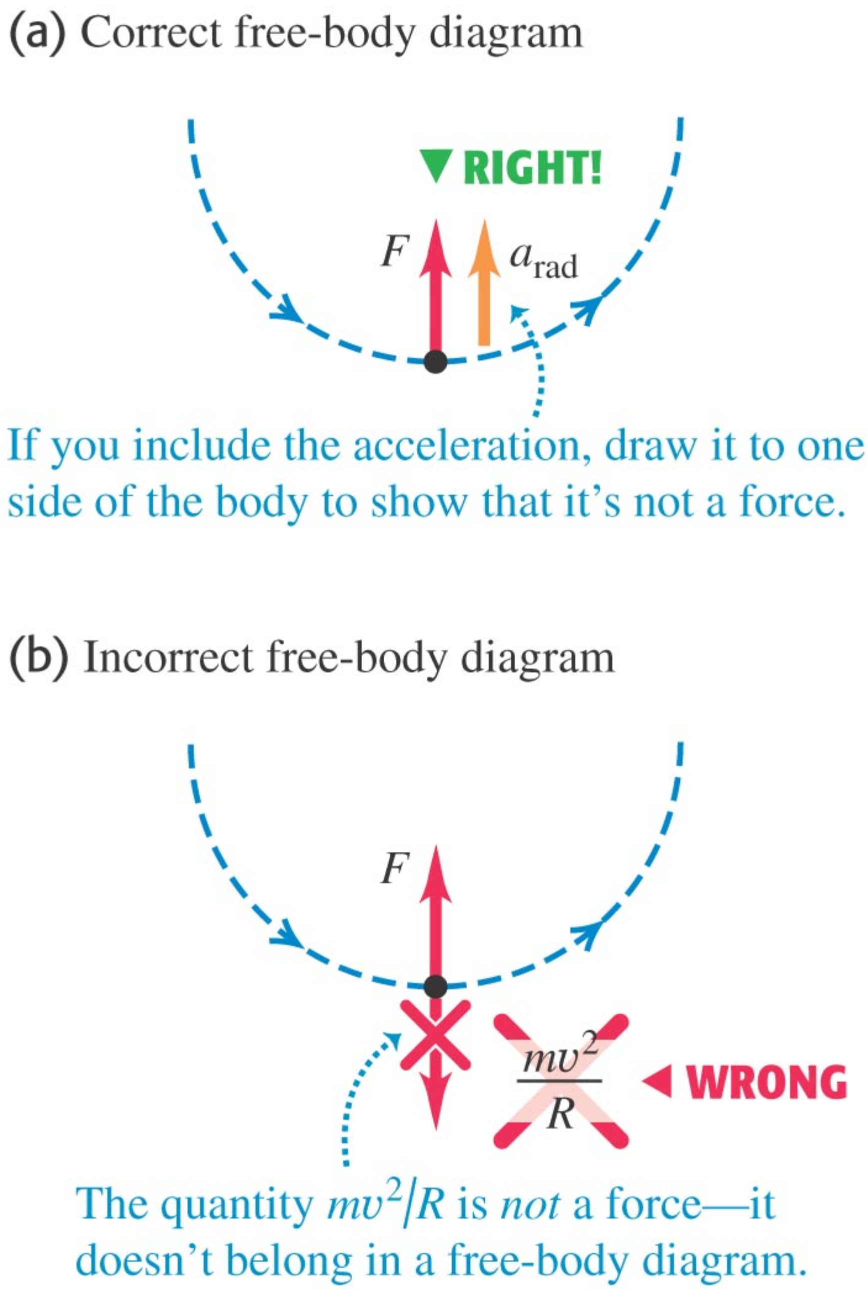
3. Write down Newton’s 2nd laws for each direction and each object. For the one going around a circle the acceleration is $a_c=v^2/R$.

4. If more than one object determine their relation (force, acceleration, etc.)

Examining a misnomer

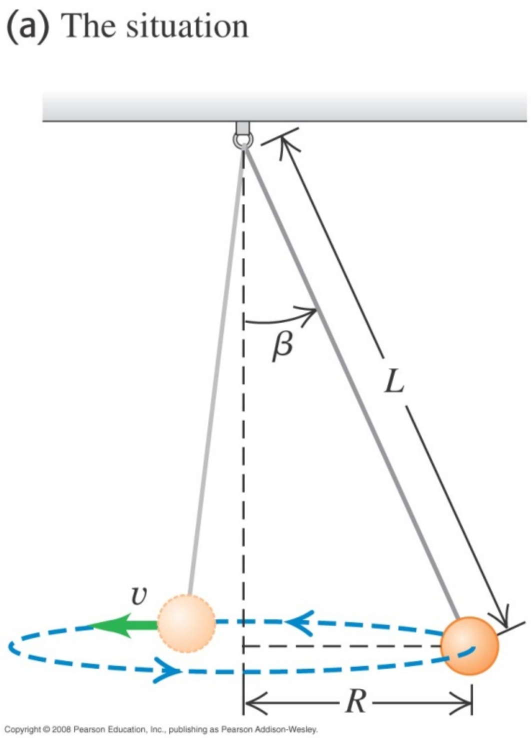
People have adopted the pop-culture use of "centrifugal force" but it really results from reference frames.

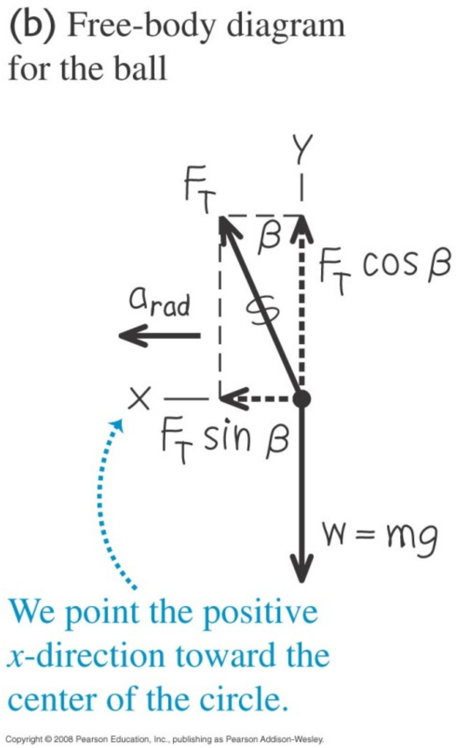
It is fictional and results from a car turning while a person continues in straight-line motion (for example).



Hanging ball going on circles

For the situation below, if only L and the angle are known,
(a) What is the tension in the cord?
(b) What is the time it takes the ball to go around once?





$$\sum F_r = F_T \sin\beta = m\frac{v^2}{R} = m\frac{v^2}{L\sin\beta}$$

$$\sum F_y = F_T \cos\beta - mg = 0$$

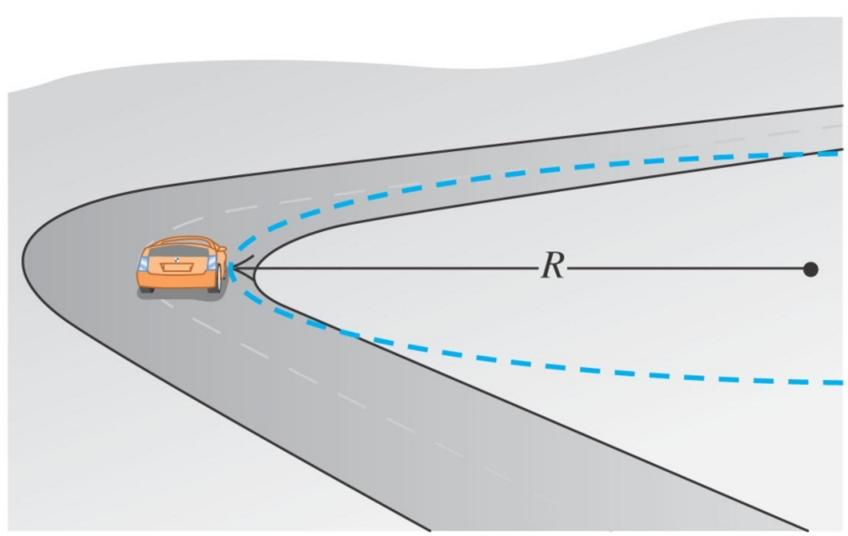
$$F_T = \frac{mg}{\cos\beta} \Rightarrow \frac{mg}{\cos\beta}\sin\beta = m\frac{4\pi^2 L\sin\beta}{T^2}$$

$$T = 2\pi\sqrt{\frac{L\cos\beta}{g}}$$

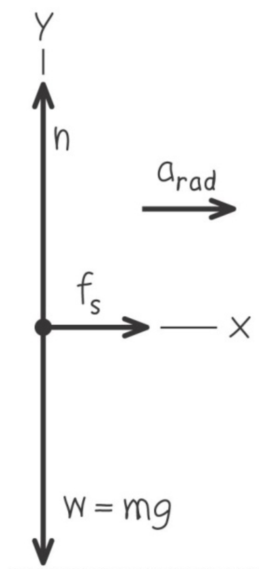
Rounding unbanked curve: maximum speed

Given a coefficient of static friction, μ_s, what is the maximum speed the car can go around the curve without skidding?

(a) Car rounding flat curve



(b) Free-body diagram for the car



$$\sum F_r = F_f = m\frac{v^2}{R}$$

$$\sum F_y = F_N - mg = 0$$

$$F_{f-\max} = \mu_s F_N$$

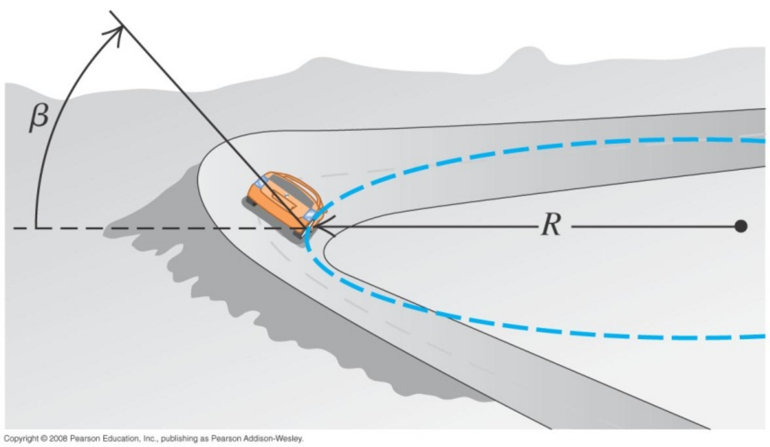
$$\Rightarrow \mu_s F_N = m\frac{v_{\max}^2}{R}$$

$$\Rightarrow v_{\max} = \sqrt{\mu_s g R}$$

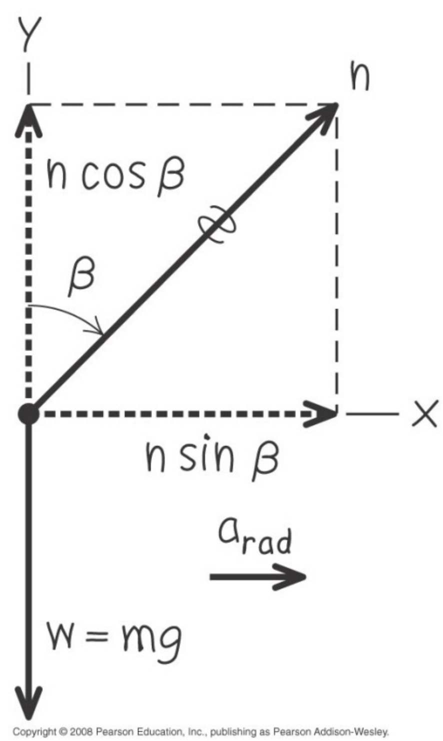
Rounding banked curve: maximum speed

What is the angle you need to go around the curve at speed v without friction?

(a) Car rounding banked curve



(b) Free-body diagram for the car



$$\sum F_r = F_N \sin\beta = m\frac{v^2}{R}$$

$$\sum F_r = F_N \cos\beta - mg = 0$$

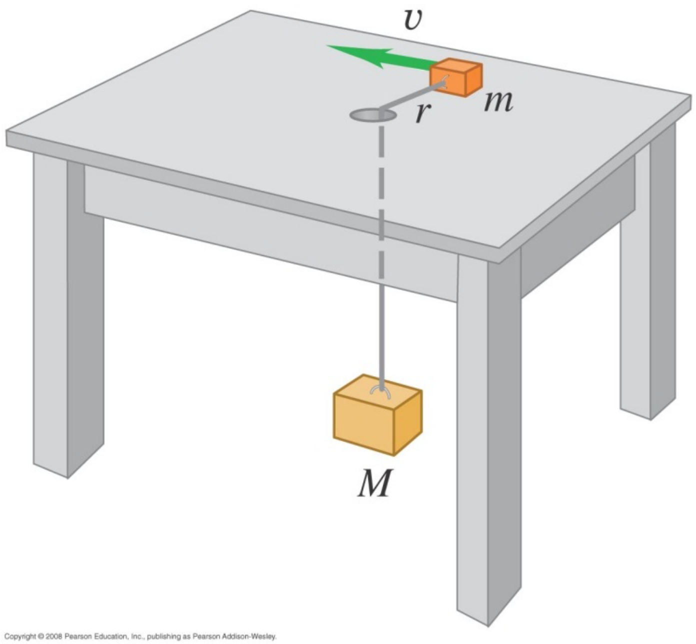
$$F_N = \frac{mg}{\cos\beta}$$

$$\Rightarrow \frac{mg}{\cos\beta}\sin\beta = mg\tan\beta = m\frac{v^2}{R}$$

$$\Rightarrow v = \sqrt{gR\tan\beta}$$

Circular and linear motion (2 Objects)

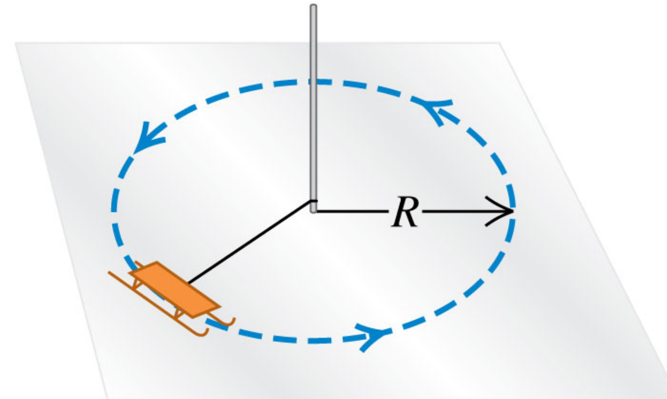
The table is frictionless. What must the velocity be for the hanging mass ***M*** (2 kg) to remain stationary? Radius is 20 cm. The small mass ***m*** is 1 kg.



Q5.11

A sled moves on essentially frictionless ice. It is attached by a rope to a vertical post set in the ice. Once given a push, the sled moves around the post at constant speed in a circle of radius *R*.

If the rope breaks,



A. the sled will keep moving in a circle.

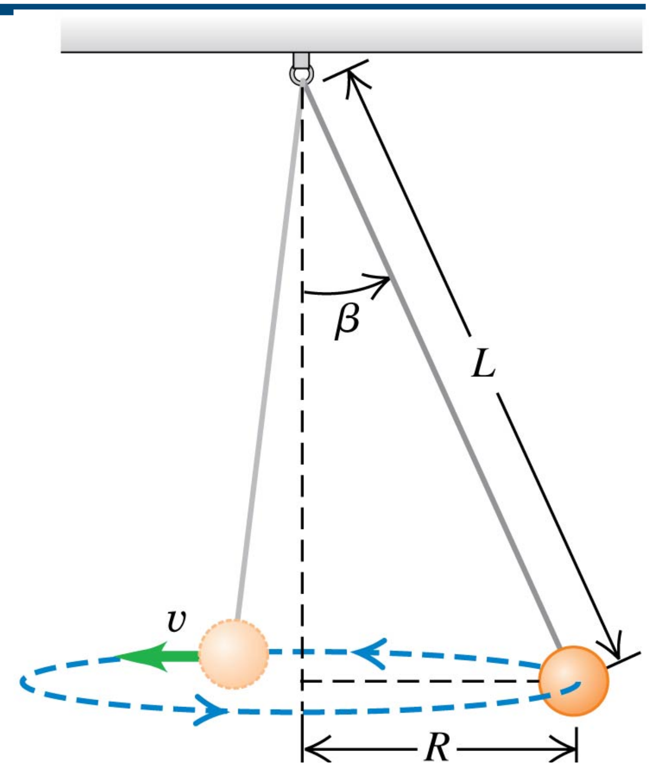
B. the sled will move on a curved path, but not a circle.

C. the sled will follow a curved path for a while, then move in a straight line.

D. the sled will move in a straight line.

Q5.12

A pendulum bob of mass *m* is attached to the ceiling by a thin wire of length *L*. The bob moves at constant speed in a horizontal circle of radius *R*, with the wire making a constant angle   with the vertical. The tension in the wire



A. is greater than *mg.*

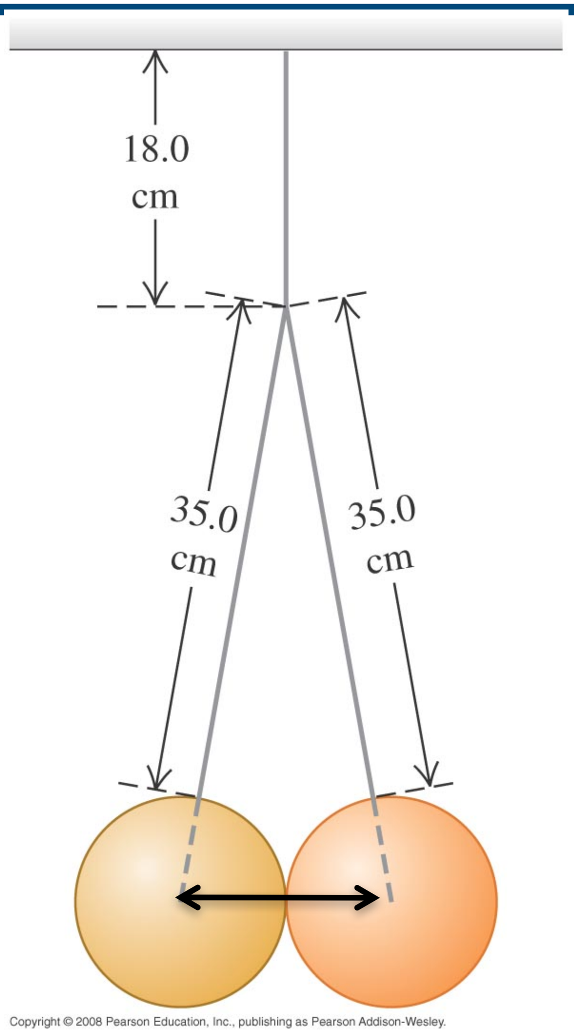
B. is equal to *mg.*

C. is less than *mg.*

D. could be two of the above, depending on the values of *m*, *L*, *R*, and *.*

E. could be all three of the above, depending on the values of *m*, *L*, *R*, and *.*

Hanging balls



25 cm

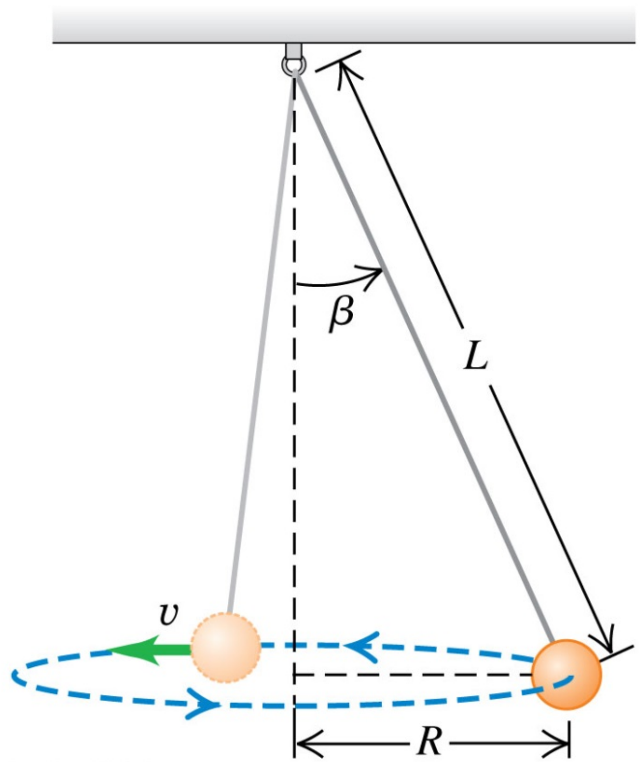
What is the tension on each string and the force that the balls exert on each other? The mass of each mass is 15 kg and the diameter 25 cm.

This example was worked out in class

Try to do an example with different masses, e.g., one is 10 Kg and the other 20 Kg.

Q5.12

A pendulum bob of mass *m* is attached to the ceiling by a thin wire of length *L*. The bob moves at constant speed in a horizontal circle of radius *R*, with the wire making a constant angle β with the vertical. The tension in the wire



A. is greater than *mg.*

B. is equal to *mg.*

C. is less than *mg.*

D. is any of the above, depending on the bob's speed *v.*

Q5.13

A pendulum of length *L* with a bob of mass *m* swings back and forth. At the low point of its motion (point *Q*), the tension in the string is (3/2)*mg*. What is the speed of the bob at this point?

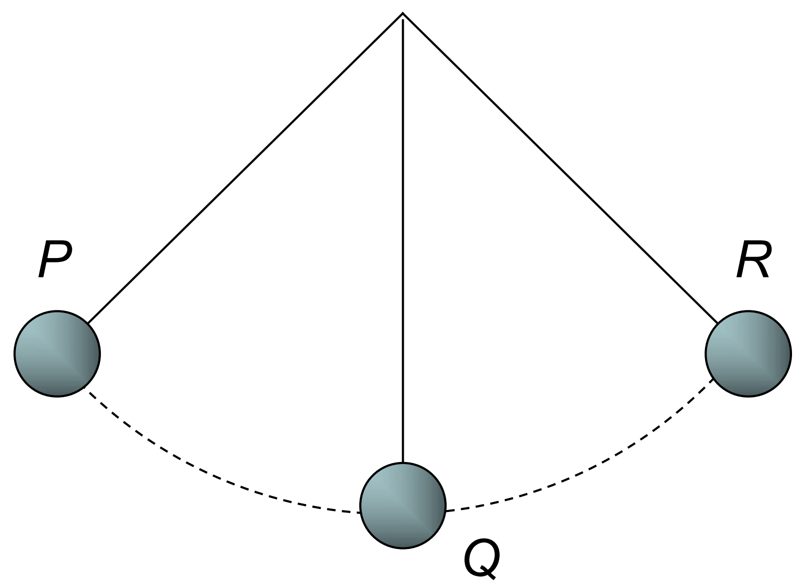
A. $2\sqrt{gL}$

B. $\sqrt{2gL}$

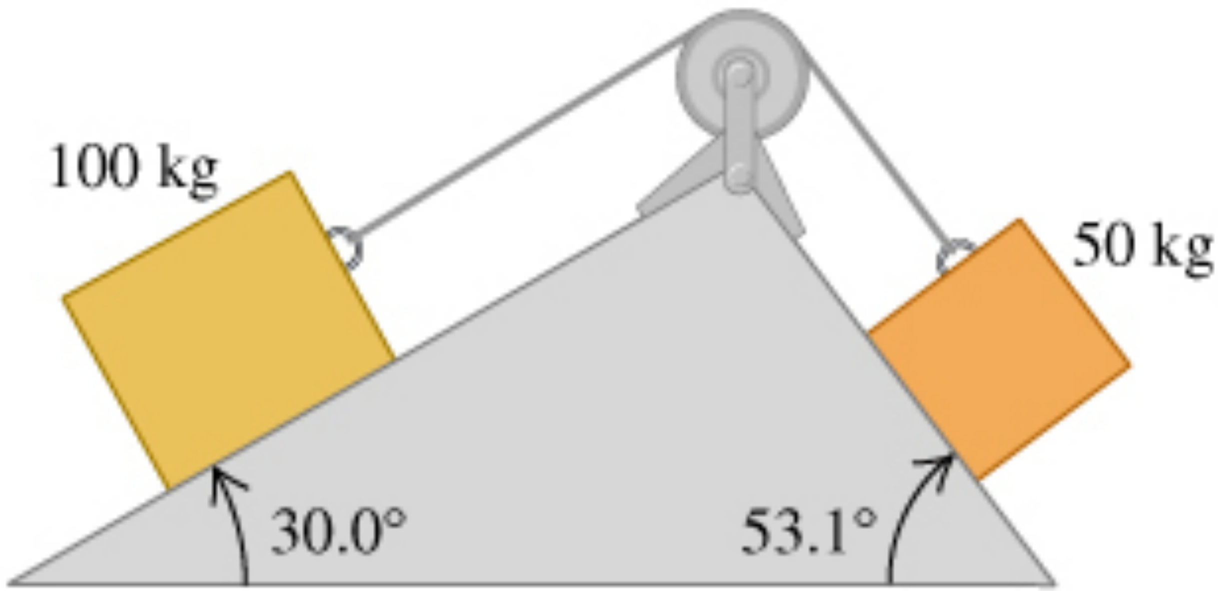
C. $\sqrt{gL}$

D. $\sqrt{\frac{gL}{2}}$

E. $\frac{\sqrt{gL}}{2}$



Forces



Assume no friction. Which way will it move?

a) Left
b) Right
c) Stays balanced and will not move

Q5.5

A lightweight crate (*A*) and a heavy crate (*B*) are side by side on a frictionless horizontal surface. You are applying a horizontal force *F* to crate *A*. Which of the following forces *should* be included in a free-body diagram for crate *B?*

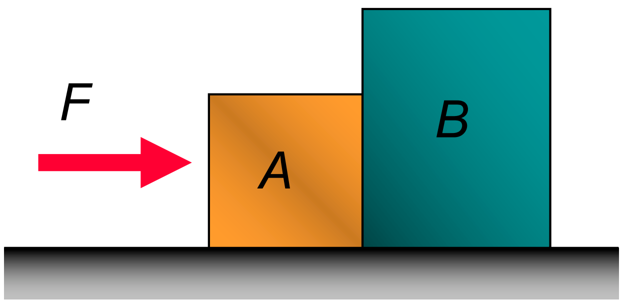
A. the weight of crate *B*

B. the force of crate *B* on crate *A*

C. the force *F* that you exert

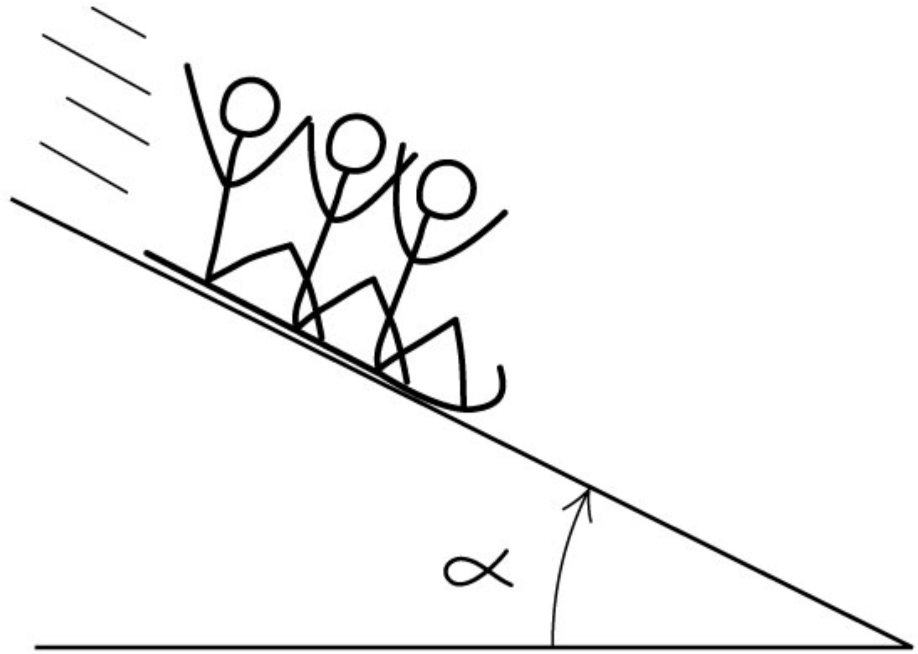
D. the acceleration of crate *B*

E. more than one of the above



Q5.6

A toboggan of weight w (including the passengers) slides down a hill of angle α at a constant speed. Which statement about the normal force on the toboggan (magnitude n) is *correct?*



A. $n = w$

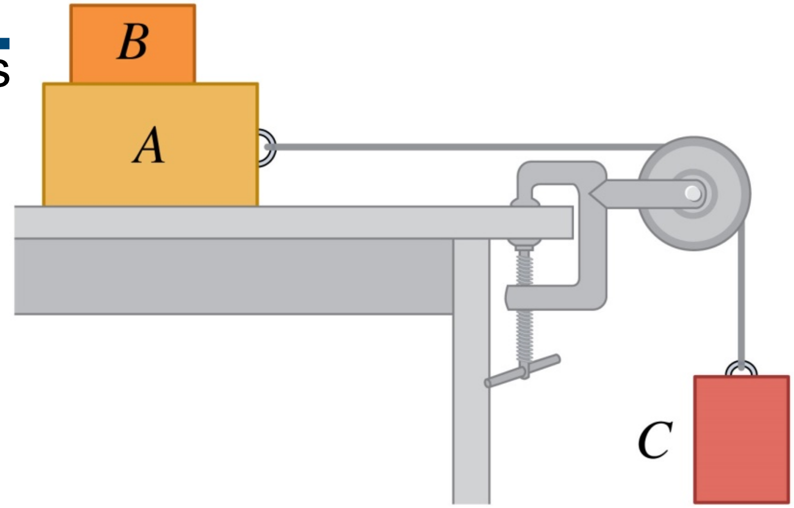
B. $n > w$

C. $n < w$

D. not enough information given to decide

Q5.9

Blocks *A* and *C* are connected by a string as shown. When released, block *A* accelerates to the right and block *C* accelerates downward.



There is friction between blocks *A* and *B*, but not enough to prevent block *B* from slipping. If you stood next to the table during the time that block *B* is slipping on top of block *A*, you would see

A. block *B* accelerating to the right.

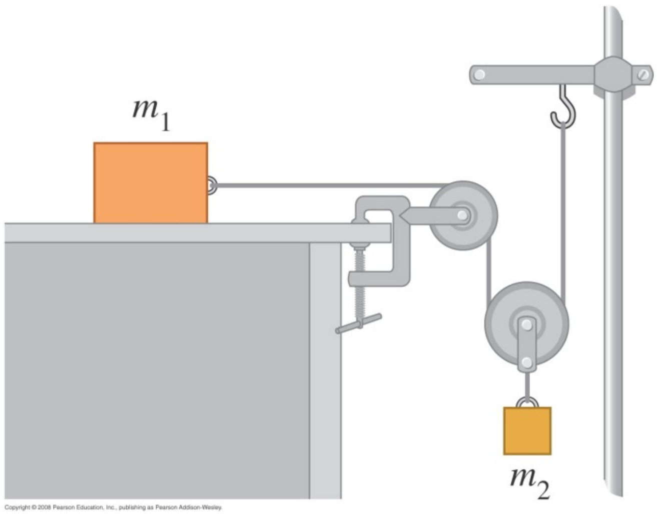
B. block *B* accelerating to the left.

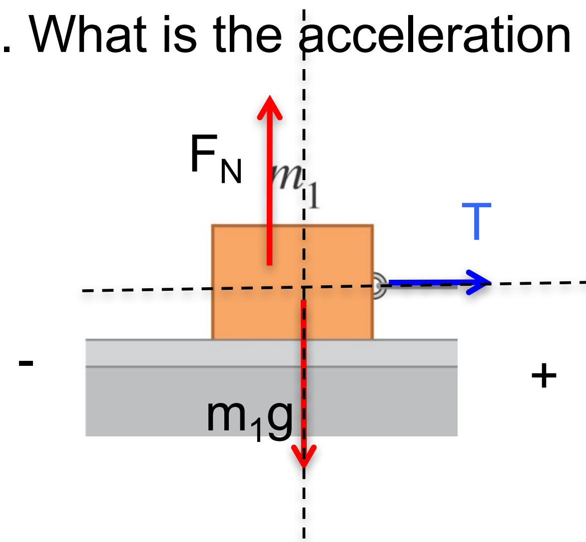
C. block *B* moving at constant speed to the right.

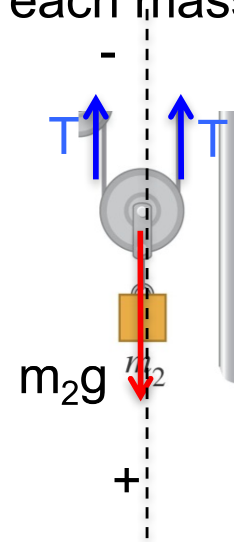
D. block *B* moving at constant speed to the left.

A more complicated pulley problem

Here there is no friction. What is the acceleration of each mass?







$$x: \sum F_x = T = m_1 a_1$$

$$y: \sum F_y = F_N - m_1 g = 0$$

$$x: 0 = 0$$

$$y: \sum F_y = m_2 g - 2T = m_2 a_2$$

The next key thing to notice is that a_1 is twice a_2: this is because the length of the cord is conserved and if object 1 moves 1 meter to the left then object 2 moves 1/2 a meter down. Then:

$$T = m_1 a_1$$

$$m_2 g - 2T = m_2 \frac{a_1}{2}$$

$$\Rightarrow m_2 g - 2m_1 a_1 = m_2 \frac{a_1}{2}$$

$$\Rightarrow a_1 = \frac{m_2 g}{2m_1 + (m_2/2)} \quad \text{and } a_2 = \frac{m_2 g}{4m_1 + m_2}$$