Chapter 4

Forces and Newton's Laws of Motion

continued

Clicker Question 4.11

There are two ropes and each applies a force of +40 N on mass of 20 kg. However, the mass exhibits an acceleration of –10 m/s². What other force (magnitude and direction) acts on the object?

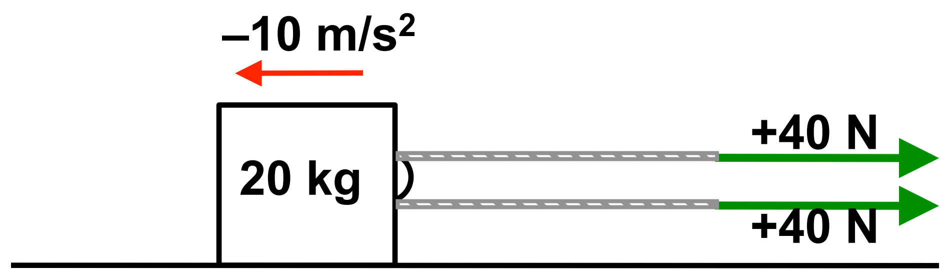
a) $F_3 = 200\ \text{N}$

b) $F_3 = 80\ \text{N}$

c) $F_3 = -280\ \text{N}$

d) $F_3 = -100\ \text{N}$

e) $F_3 = -80\ \text{N}$



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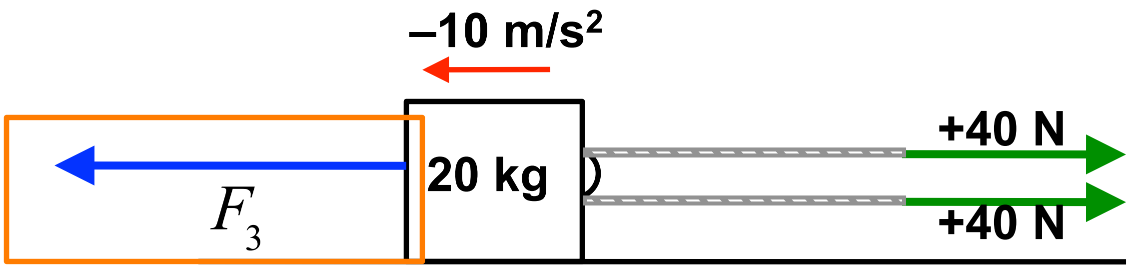
e) $F_3 = -80\text{ N}$



$$F_{Net} = ma = (20\,\text{kg})(-10\,\text{m/s}^2)$$
$$= -200\,\text{N}$$
$$= F_3 + 80\text{ N}$$
$$F_3 = F_{Net} - 80\text{ N}$$
$$= -280\text{ N}$$

Example:

Acting on a ball are two forces, each with a magnitude of 20 N, acting at 45° with the respect to the vertical direction. What single force will make the Net Force acting on the ball equal to zero?

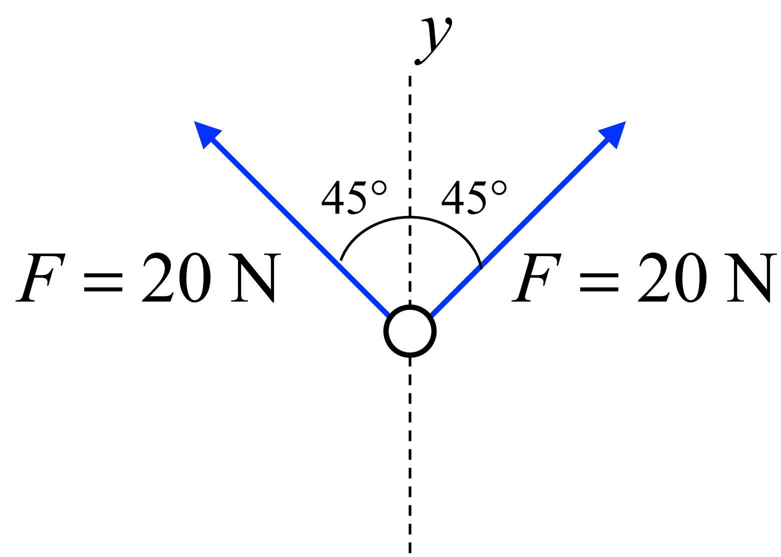
a) -40 N

b) -14 N

c) -32 N

d) -18 N

e) -28 N



Example:

Acting on a ball are two forces, each with a magnitude of 20 N, acting at 45° with the respect to the vertical direction. What single force will make the Net Force acting on the ball equal to zero?

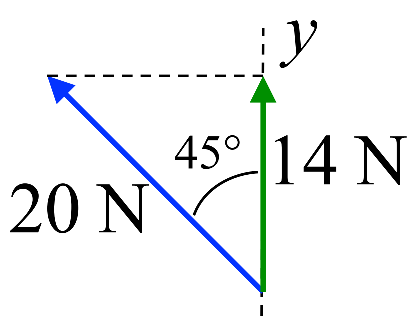
a) – 40 N

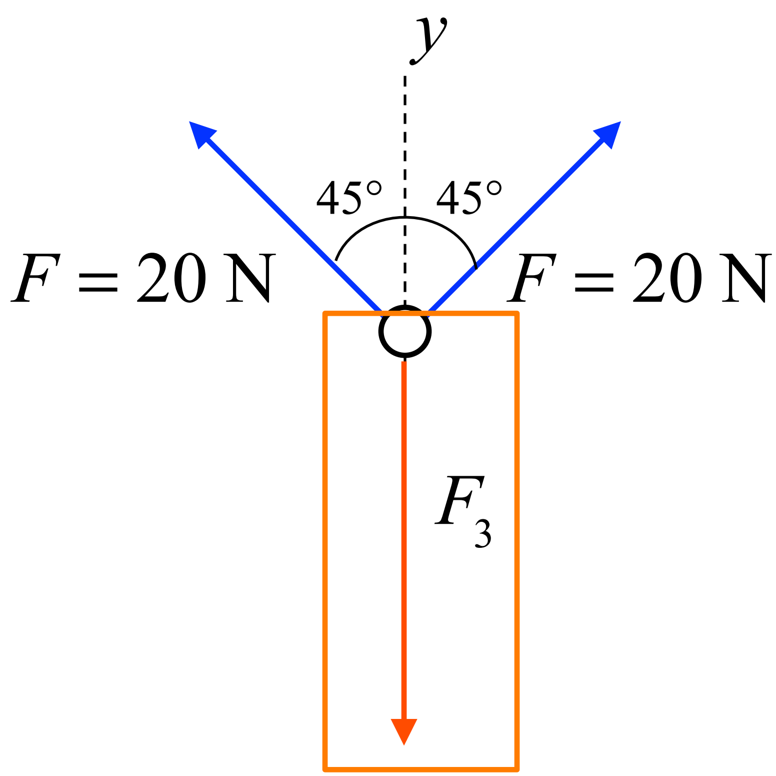
b) – 14 N

c) – 32 N

d) – 18 N

e) – 28 N





$$y : F_{Net} = 0 = 2\left(F\cos 45°\right) + F_3$$

$$F_3 = -2\left(F\cos 45°\right) = -28\,\text{N}$$

4.2 Newton's Laws of Motion (Gravity and the Body)

The ONLY thing a person can feel is a stretch or compression of your body parts, mostly at a point of contact. If your body is not stretched or compressed, you will feel like you are floating.

Gravity ALONE will not stretch or compress your body.

Hanging from the board, the board also pulls up on your arms. Newton's 3rd law!

Standing on the ground, the ground also pushes up on the bottom of your feet. Newton's 3rd law!

While falling, the earth pulls on you and you pull on the earth. Gravity requires no contact. YOU CANNOT FEEL GRAVITY.

4.2 Newton's Laws of Motion (Gravity and the Body)

Can you feel gravity (the gravitational force) ?

Most people would say yes!

Consider standing on the concrete floor.

Gravity pulls down on you and compresses your body. You feel most of the compression in your legs, because most of your body mass is above them.

A) In your arms

B) In your legs

Consider hanging by your hands from a 100 m high diving board.

Gravity pull down on you and stretches your body. You feel most stretching in your arms, because most body mass is below them.

A) In your arms

B) In your legs

Let go of the 100 m high diving board.

While gravity accelerates you downward, what do you feel ?

You don't feel stretched, and you don't feel compressed.

You feel "weightless", yes, but your weight is still $W = mg$.

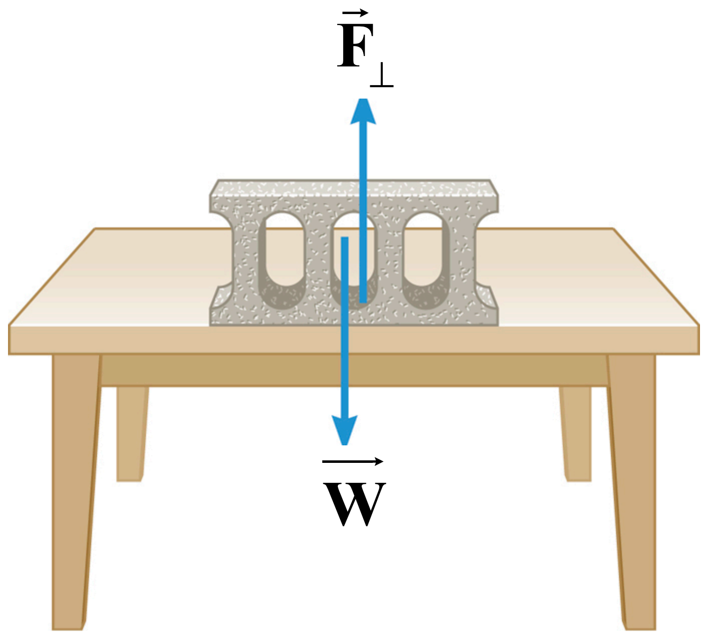
A) Stretched & compressed

B) Weightless

Definition of the Normal Force

The normal force is one component of the force that a surface exerts on an object with which it is in contact – namely, the component that is perpendicular to the surface.

$\vec{\mathbf{F}}_{\perp}$ sometimes written as $\vec{\mathbf{n}}$



4.3 Applications Newton's Laws (Normal Forces)

A block with a weight of 15 N sits on a table. It is pushed down with a force of 11 N or pulled up with a force of 11 N. Calculate the normal force in each case.

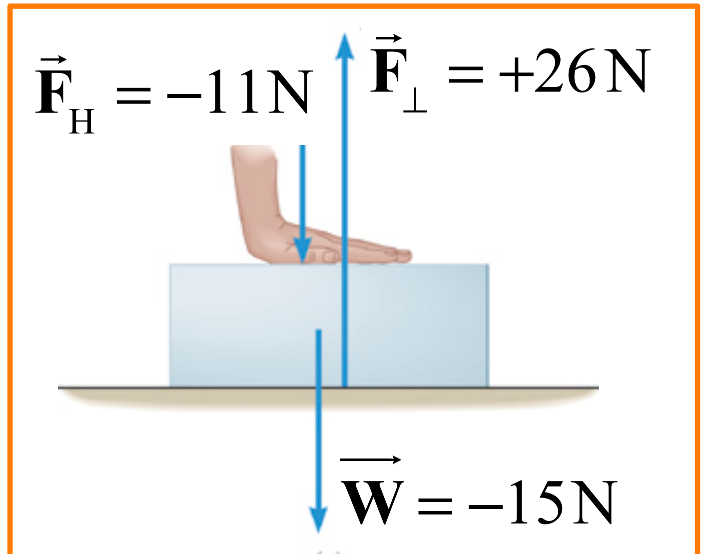
$$\vec{\mathbf{a}} = 0 \quad \Rightarrow \quad \vec{\mathbf{F}}_{\text{Net}} = 0$$

$$\vec{\mathbf{F}}_{\text{Net}} = \vec{\mathbf{F}}_{\perp} + \vec{\mathbf{F}}_{\text{H}} + \overrightarrow{\mathbf{W}} = 0$$

$$\vec{\mathbf{F}}_{\perp} = -\vec{\mathbf{F}}_{\text{H}} - \overrightarrow{\mathbf{W}}$$

$$= -\left(-11\,\text{N}\right) - \left(-15\,\text{N}\right)$$

$$= +26\ \text{N}$$



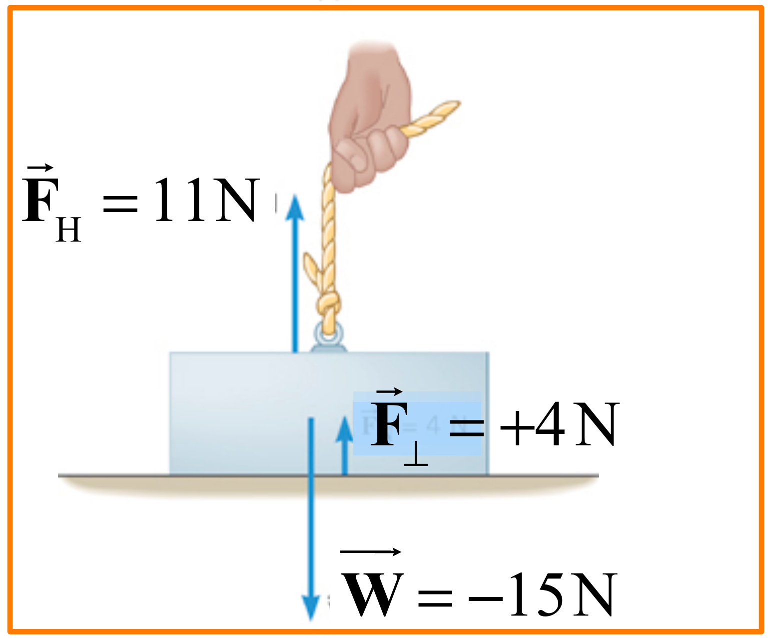
(a)

$$\vec{\mathbf{F}}_{\text{Net}} = \vec{\mathbf{F}}_{\perp} + \vec{\mathbf{F}}_{H} + \overrightarrow{\mathbf{W}} = 0$$

$$\vec{\mathbf{F}}_{\perp} = -\vec{\mathbf{F}}_{H} - \overrightarrow{\mathbf{W}}$$

$$= -(11\,\text{N}) - \left(-15\,\text{N}\right)$$

$$= +4\,\text{N}$$



(b)

4.3 Newton's Laws of Motion (Elevators)

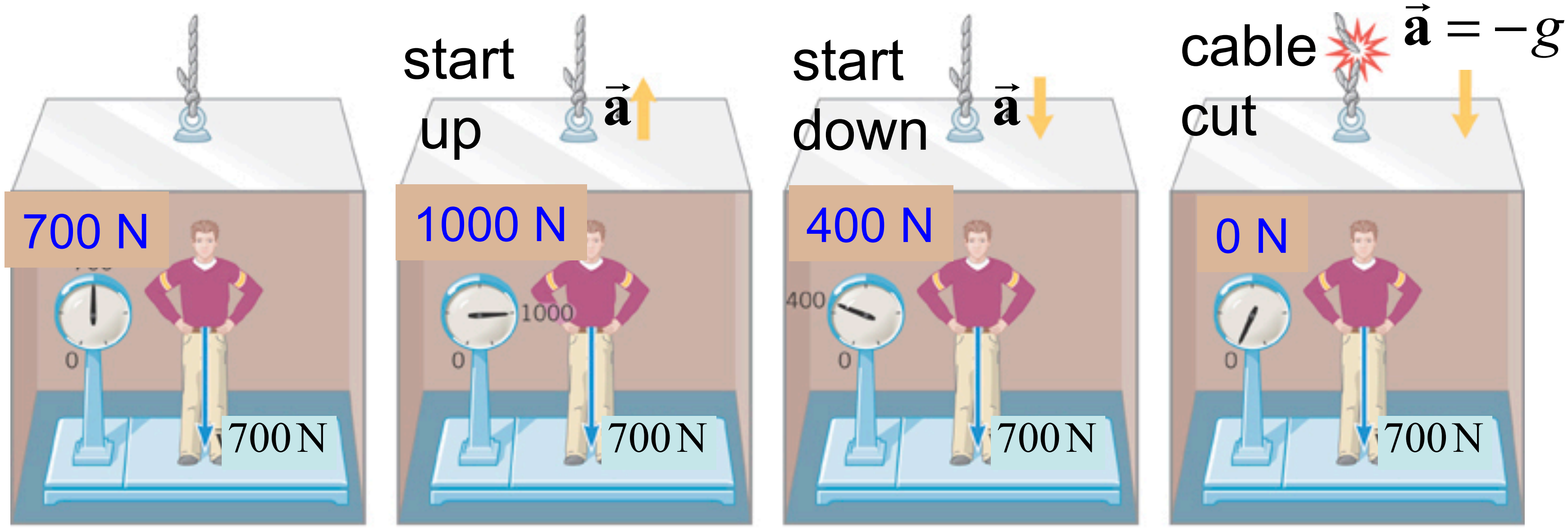
Apparent Weight = Normal force acting on an object

The Apparent Weight of an object is the value the scale reads.

Apparent Weight = normal force of the scale on the person.

Also, by Newton's 3rd law

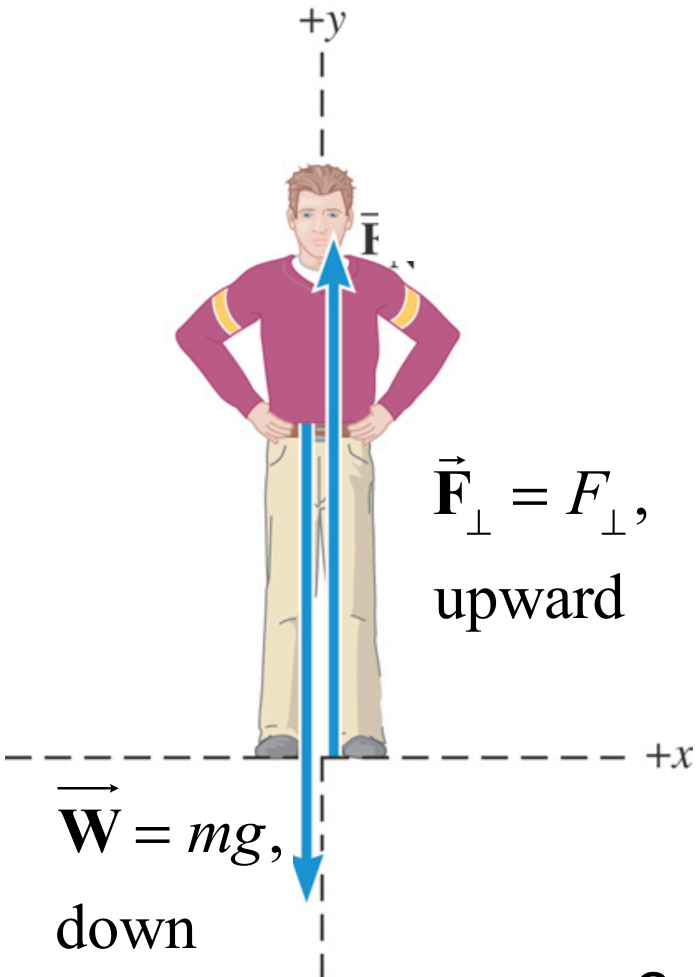
Apparent Weight = normal force of the person on the scale.



v constant up/down/zero	accelerating a, upward	accelerating a, downward	Free fall $a = g$, downward

4.3 Newton's Laws of Motion (Normal Forces)

For the person being accelerated (a)



$$\sum F_y = F_\perp + W = ma_y$$

$$F_\perp = -W + ma_y$$

$$F_\perp = mg + ma_y$$

apparent weight ($F_\perp$) — true weight (mg)

a_y is up: apparent weight > true weight

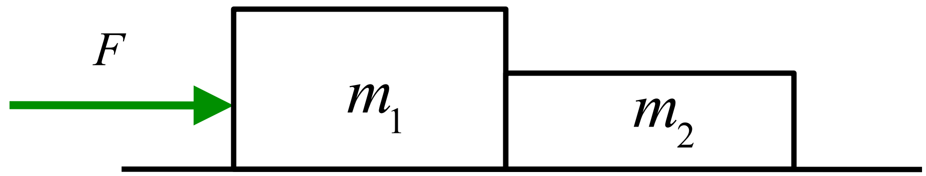
a_y is down: apparent weight < true weight

$a_y = 0$, constant velocity: apparent weight = true weight

4.3 Newton's Laws of Motion (Normal Forces)

Example:

On a frictionless surface, two boxes with the masses in the ratio of $m_1/m_2 = 3/2$, shown are pushed together by a force with magnitude F. What is the force that the smaller mass block exerts on the larger mass block?



Hint: the masses have the same acceleration!

a) $(1/3)F$

b) $(1/5)F$

c) $(2/3)F$

d) $(3/2)F$

e) $(2/5)F$

4.3 Newton's Laws of Motion (Normal Forces)

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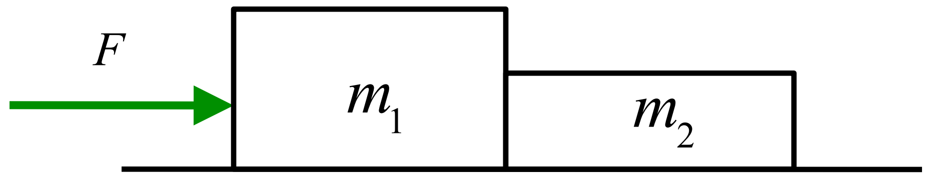
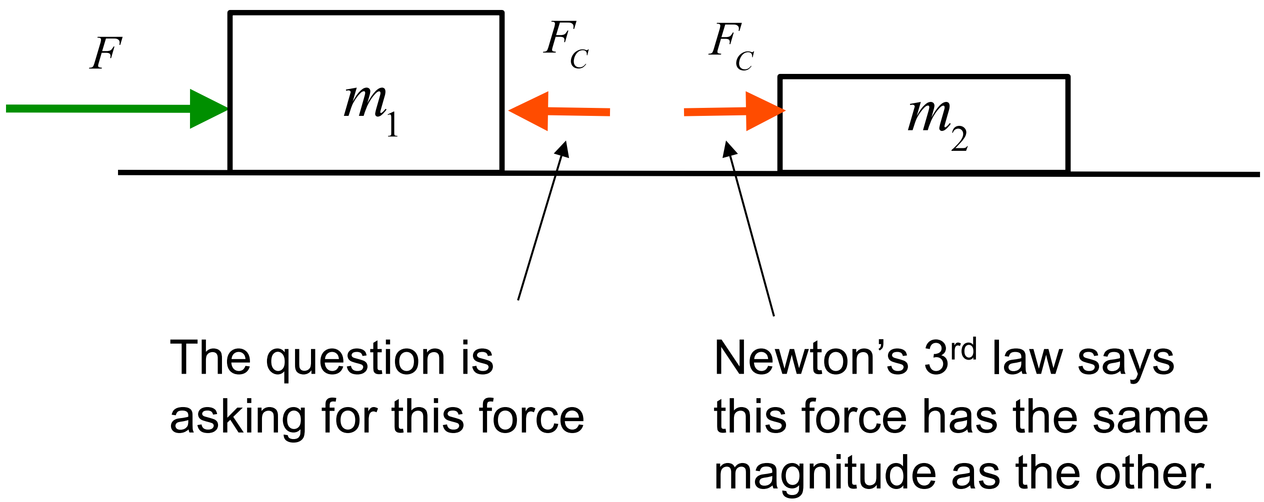


Hint: the masses have the same acceleration!

Step 1) Realize that Contact forces, F_C of Newton's 3rd law apply between the masses (show them)!



4.3 Newton's Laws of Motion (Normal Forces)

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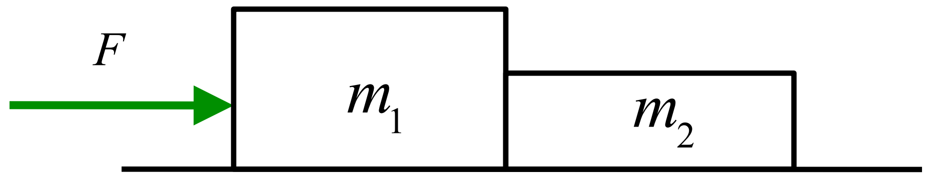

a) $(1/3)F$

b) $(1/5)F$

c) $(2/3)F$

d) $(3/2)F$

e) $(2/5)F$

Hint: the masses have the same acceleration!

Step 2) Determine the acceleration of the mass pair

2nd Law for total mass

$$F = ma = (m_1 + m_2)a \quad \Rightarrow \quad a = \frac{F}{(m_1 + m_2)}$$

4.3 Newton's Laws of Motion (Normal Forces)

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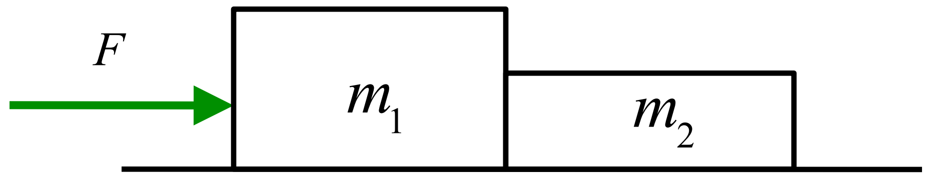


a) $(1/3)F$

b) $(1/5)F$

c) $(2/3)F$

d) $(3/2)F$

e) $(2/5)F$

Hint: the masses have the same acceleration!

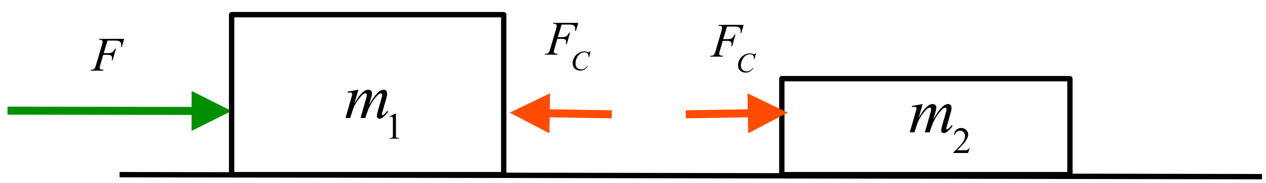
Step 2) Determine the acceleration of the mass pair

2nd Law for total mass

$$F = ma = (m_1 + m_2)a \quad \Rightarrow \quad a = \frac{F}{(m_1 + m_2)}$$

Step 3) Determine the contact forces using this acceleration

Both masses have the acceleration of the total mass

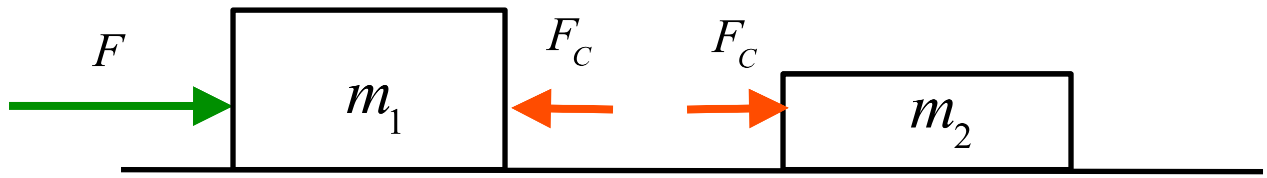


2nd Law for mass m_2

$$F_C = m_2 a = \frac{m_2}{m_1 + m_2} F = \frac{F}{(m_1/m_2 + 1)} = \frac{F}{5/2} = (2/5)F$$

4.3 Newton's Laws of Motion (Normal Forces)

Step 4) Prove you could have used m_1 to get F_C



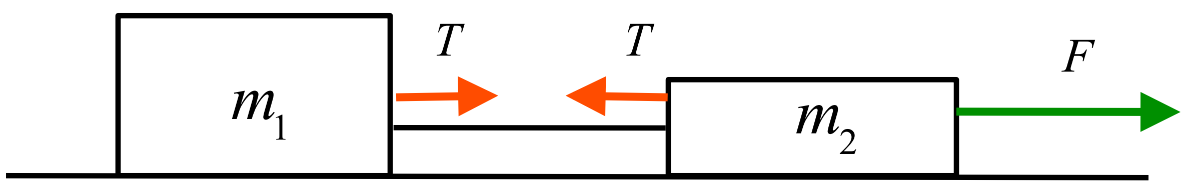
2nd Law for mass m_1

$$F_{\text{Net}} = F - F_C = m_1 a = \frac{m_1}{m_1 + m_2} F$$

$$F_C = \left[1 - \frac{m_1}{m_1 + m_2}\right] F = \left[\frac{m_2}{m_1 + m_2}\right] F = \frac{1}{m_1/m_2 + 1} F = (2/5) F$$

Answer is the same as using m_2

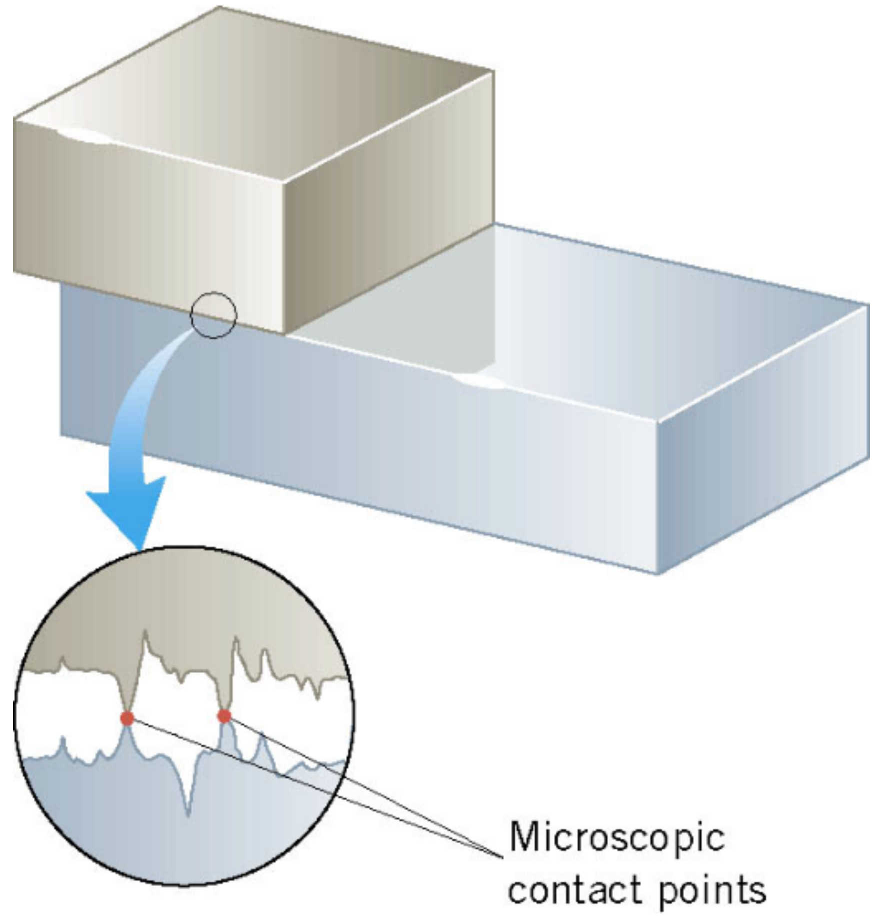
Problems with a rope between masses are solved the same way.



Tension of stretched (massless) rope acts like an action-reaction pair of forces

4.4 Static and Kinetic Frictional Forces

When an object is in contact with a surface forces can act on the objects. The component of this force acting on each object that is parallel to the surface is called the ***frictional force***.



4.4 Static and Kinetic Frictional Forces

When the two surfaces are not sliding (at rest) across one another the friction is called ***static friction***.

Block is at rest. Net force is zero on block

$$\sum \mathbf{F} = \vec{\mathbf{F}}_{\mathrm{R}} + \vec{\mathbf{f}}_S = 0$$

$$+F_{\mathrm{R}} + (-f_S) = 0 \text{ (opposite direction)}$$

$$F_{\mathrm{R}} = f_S \text{ (same magnitude)}$$

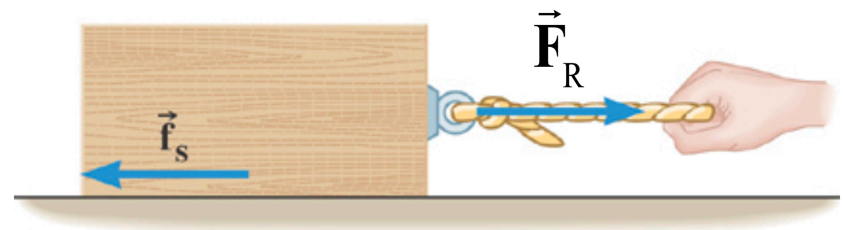
The harder the person pulls on the rope the larger the static frictional force becomes.

Until the static frictional force f_S reaches its maximum value, f_S^{Max}, and the block begins to slide.

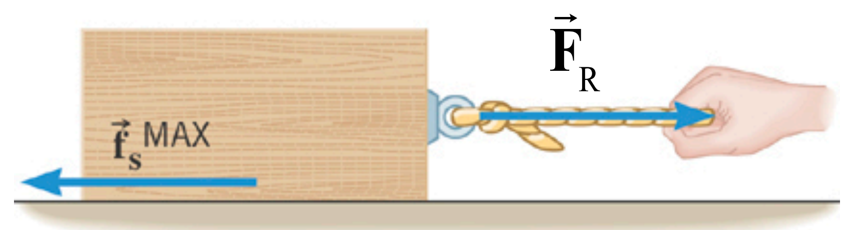
$\vec{\mathbf{F}}_{\mathrm{R}}$ = rope force

No movement

$\vec{\mathbf{f}}_S$ = static friction force



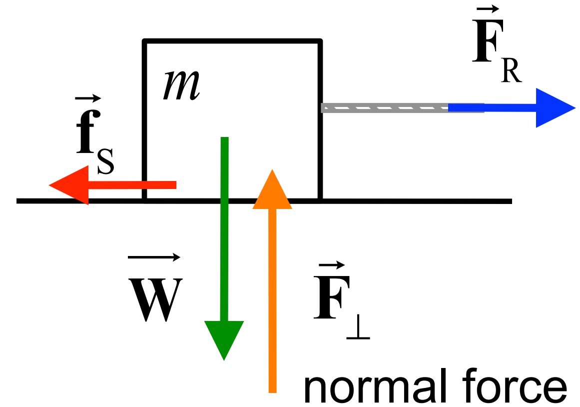
No movement
(b)



When movement just begins
(c)

4.4 Static and Kinetic Frictional Forces

The magnitude of the static frictional force can have any value from zero up to a maximum value, f_S^{Max}



Friction equations are for MAGNITUDES only.

$$f_S \le f_S^{Max} \text{ (object remains at rest)}$$

$$f_S^{MaX} = \mu_S F_\perp,$$

$$0 < \mu_S < 1$$

Vertical forces only

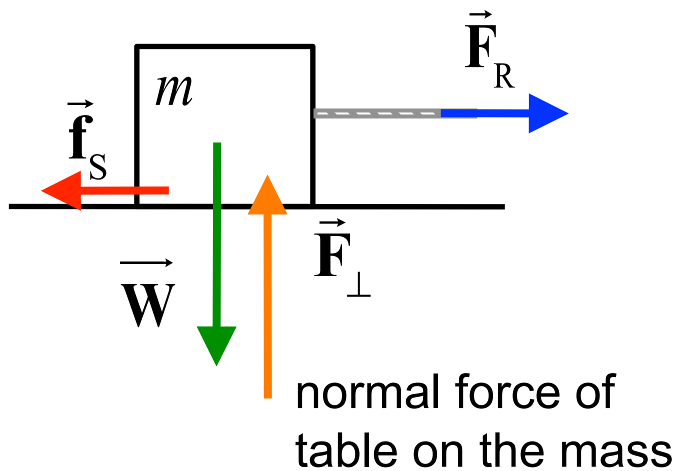
$$F_\perp = W = mg$$

μ_S , coefficient of static friction.

Example: It takes a horizontal force of at least 10,000 N to begin to move a 5,000 kg mass on flat road. What is the coefficient of friction between the two surfaces?

$$W = mg = 49{,}000\text{N}$$

$$f_S^{\text{Max}} = 10{,}000 \text{ N.}$$



$$f_S^{\text{Max}} = \mu_S F_\perp = \mu_S W$$

$$\Rightarrow \quad \mu_S = f_S^{\text{Max}} / W = \underline{0.20}$$

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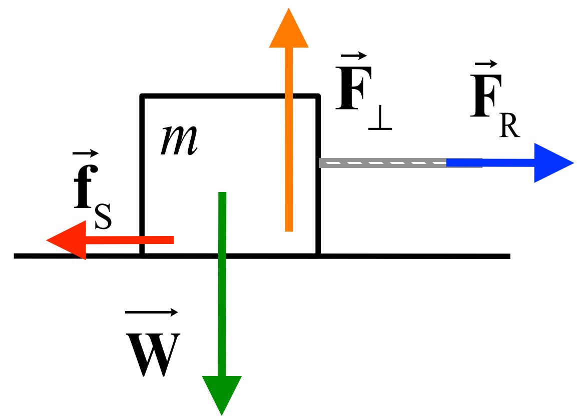

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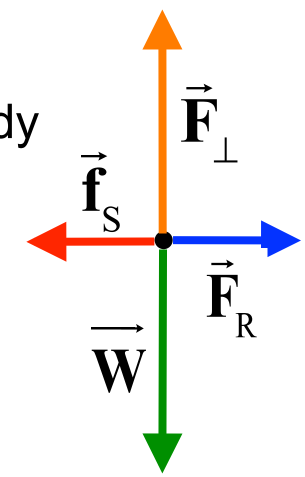


$$f_S^{\text{Max}} = \mu_S F_\perp = \mu_S W$$

$$\Rightarrow \quad \mu_S = f_S^{\text{Max}} \big/ W = \underline{0.20}$$

Clicker Question 4.12

$$f_S^{\mathrm{MaX}} = \mu_S F_\perp$$

A 50.0 kg mass is at rest on a table, where the coefficient of friction, $\mu_S = 0.50$. What is the lowest horizontal force that will get the mass to begin to move?

a) 25 N

b) 49 N

c) 245 N

d) 490 N

e) 980 N

Clicker Question 4.12

A 50.0 kg mass is at rest on a table, where the coefficient of friction, $\mu_S = 0.50$. What is the lowest horizontal force that will get the mass to begin to move?

a) 25 N

b) 49 N

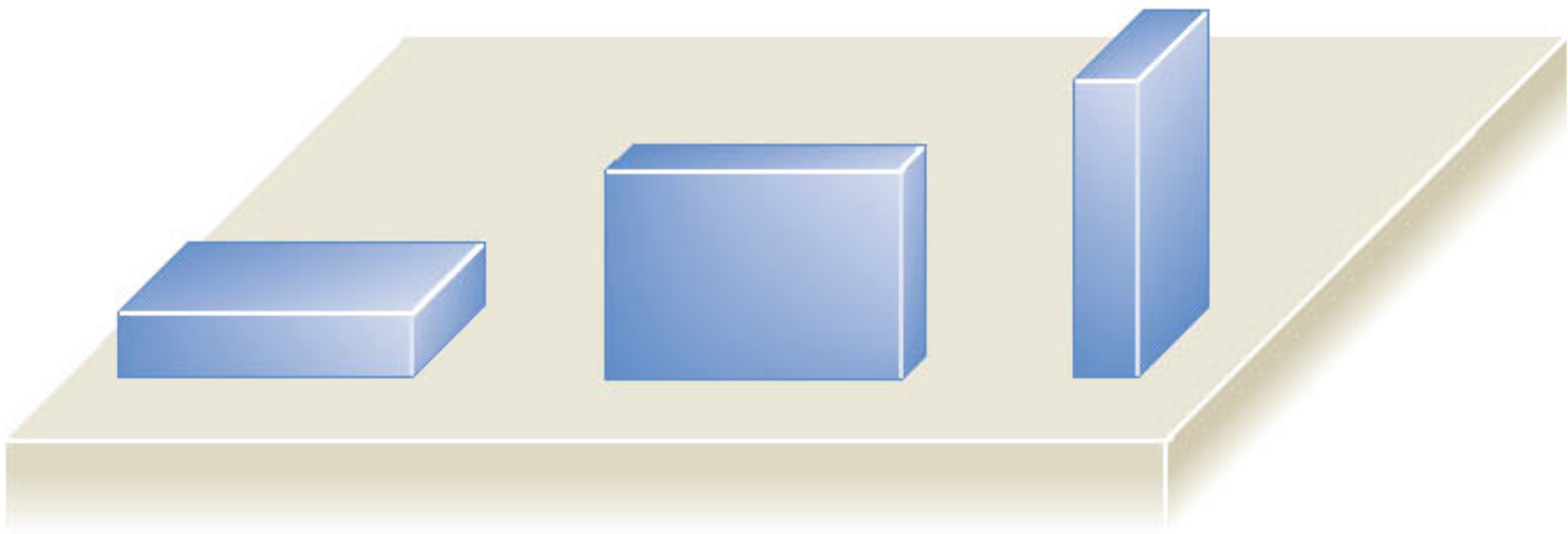
c) 245 N

d) 490 N

e) 980 N

$$f_S^{Max} = \mu_S F_\perp = \mu_S W$$
$$= 0.50(mg) = 0.50(50.0\,\text{kg})(9.81\text{ m/s}^2)$$
$$= 245\text{ N}$$

Note that the magnitude of the frictional force does not depend on the contact area of the surfaces.



4.4 *Static and Kinetic Frictional Forces*

Static friction opposes the *impending* relative motion between two objects.

Kinetic friction opposes the relative sliding motion motions that actually does occur.

Kinetic friction

$$f_k = \mu_k F_\perp$$

Friction equations are for MAGNITUDES only.

$$0 < \mu_k < 1$$

is called the coefficient of kinetic friction.

$\vec{\mathbf{f}}_k$ is a horizontal force.

$\vec{\mathbf{F}}_\perp$ is a vertical force.

OK because friction equations are for MAGNITUDES only.

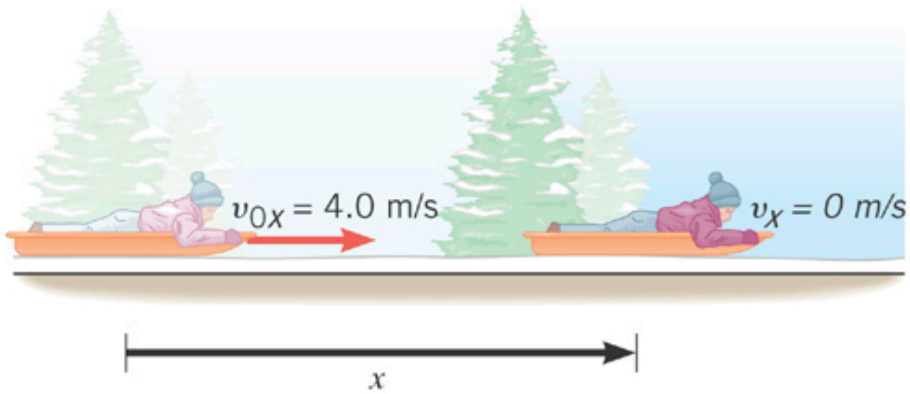
4.4 Static and Kinetic Frictional Forces

Table 4.2 Approximate Values of the Coefficients of Friction for Various Surfaces*

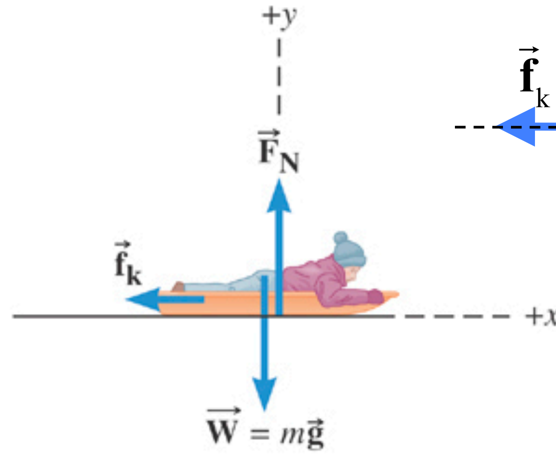
Materials	Coefficient of Static Friction, μ_s	Coefficient of Kinetic Friction, μ_k
Glass on glass (dry)	0.94	0.4
Ice on ice (clean, 0 °C)	0.1	0.02
Rubber on dry concrete	1.0	0.8
Rubber on wet concrete	0.7	0.5
Steel on ice	0.1	0.05
Steel on steel (dry hard steel)	0.78	0.42
Teflon on Teflon	0.04	0.04
Wood on wood	0.35	0.3

*The last column gives the coefficients of kinetic friction, a concept that will be discussed shortly.

4.4 Static and Kinetic Frictional Forces

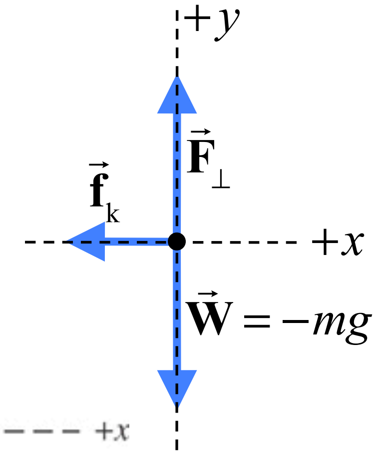


(a)



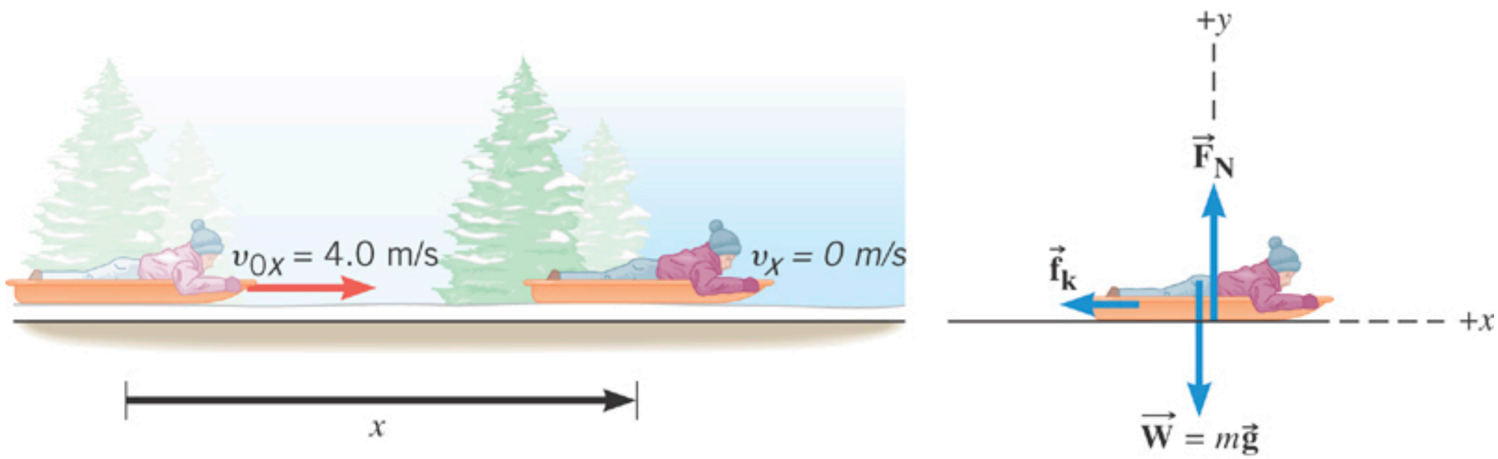
(b) Free-body diagram for the sled and rider

Free Body Diagram



The sled comes to a halt because the kinetic frictional force opposes its motion and causes the sled to slow down.

4.4 Static and Kinetic Frictional Forces



(a)

(b) Free-body diagram for the sled and rider

Suppose the coefficient of kinetic friction is 0.050 and the total mass is 40.0kg. What is the kinetic frictional force?

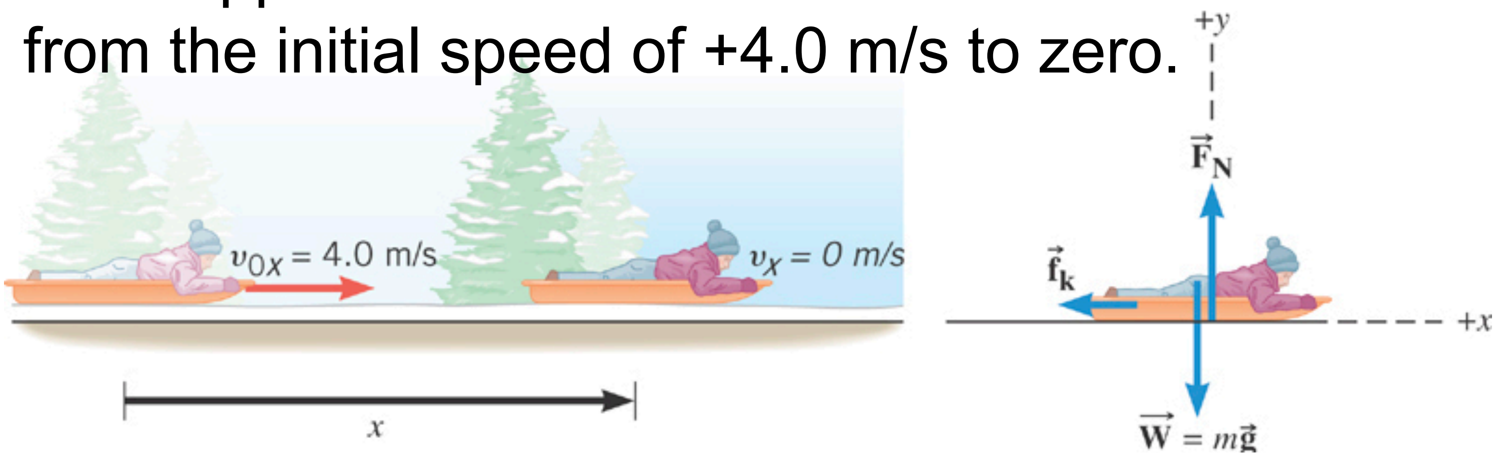
Friction equations are for MAGNITUDES only.

$$f_k = \mu_k F_\perp$$

$$= \mu_k mg = 0.050(40.0\text{kg})(9.81\text{m/s}^2) = 19.6\,\text{N}$$

Clicker Question 4.13

The sled shown comes to a halt because the kinetic frictional force opposes its motion and causes the sled to slow down from the initial speed of +4.0 m/s to zero.



If the magnitude of the kinetic frictional force, $f_k = 20\text{N}$, and the total mass is 40kg, how far does the sled travel?

a) 2m

b) 4m

c) 8m

d) 16m

e) 32m

Hints

vector $f_k = -20\,\text{N}$

use $v^2 = v_{0x}^2 + 2ax$

Clicker Question 4.13

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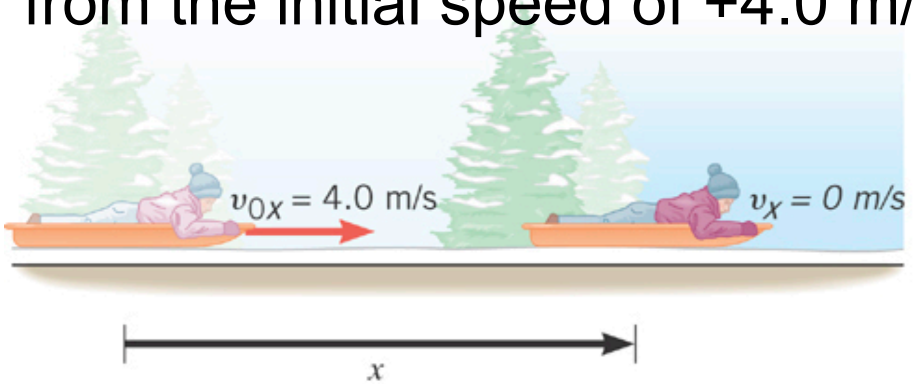

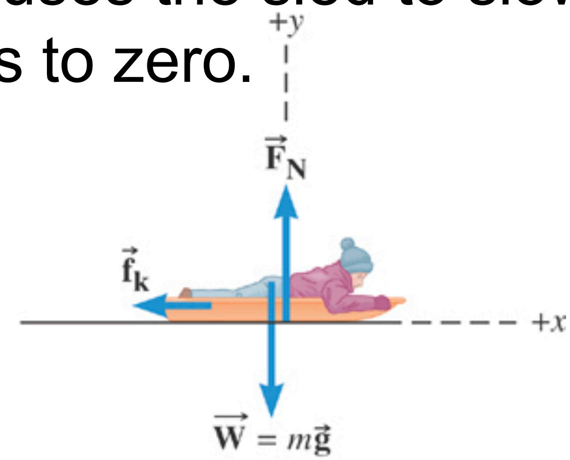

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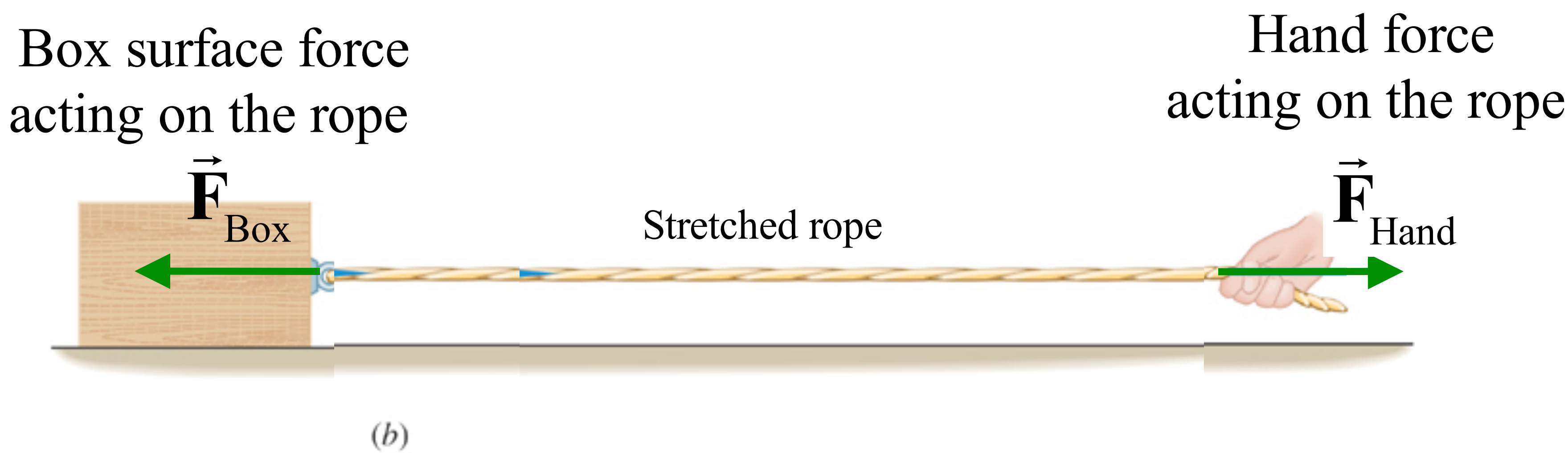
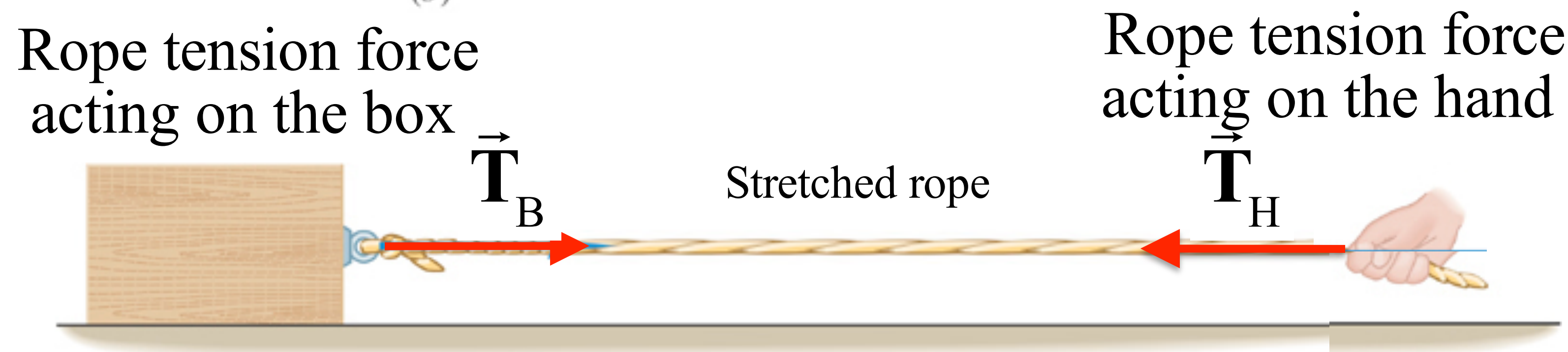
$$a = \frac{f_k}{m} = \frac{-20.0\,\text{N}}{40.0\,\text{kg}} = -0.50\ \text{m/s}^2$$

$$v^2 = v_{0x}^2 + 2ax$$

$$x = \frac{-v_{0x}^2}{2a} = \frac{-16.0\,\text{m}^2/\text{s}^2}{2(-0.50\ \text{m/s}^2)} = +16.0\,\text{m}$$

Cables and ropes transmit forces through ***tension***.

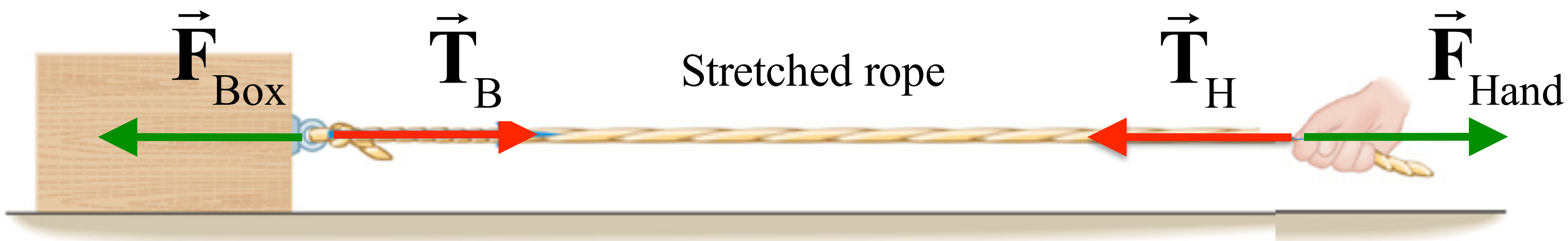




$\left(\vec{\mathbf{F}}_{\text{Box}}, \vec{\mathbf{T}}_{\text{B}}\right)$ These are Newton's 3rd law Action – Reaction pairs $\left(-\vec{\mathbf{T}}_{\text{H}}, \vec{\mathbf{F}}_{\text{Hand}}\right)$

$$F_{\text{Box}} = T_{\text{B}} \qquad T_{\text{B}} = T_{\text{H}} \qquad T_{\text{H}} = F_{\text{Hand}}$$

Hand force stretches the rope that generates tension forces at the ends of the rope



$\left(\vec{F}_{Box}, \vec{T}_B\right)$

These are Newton's 3rd law
Action – Reaction pairs

$\left(\vec{F}_{Hand}, \vec{T}_H\right)$

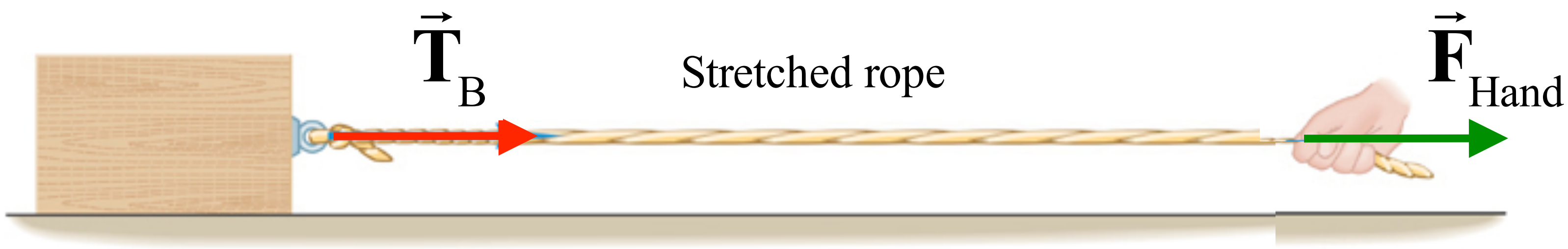
Tension pulls on box

Box pulls on rope

Tension pulls on hand

Hand pulls on rope

Cables and ropes transmit forces through ***tension***.



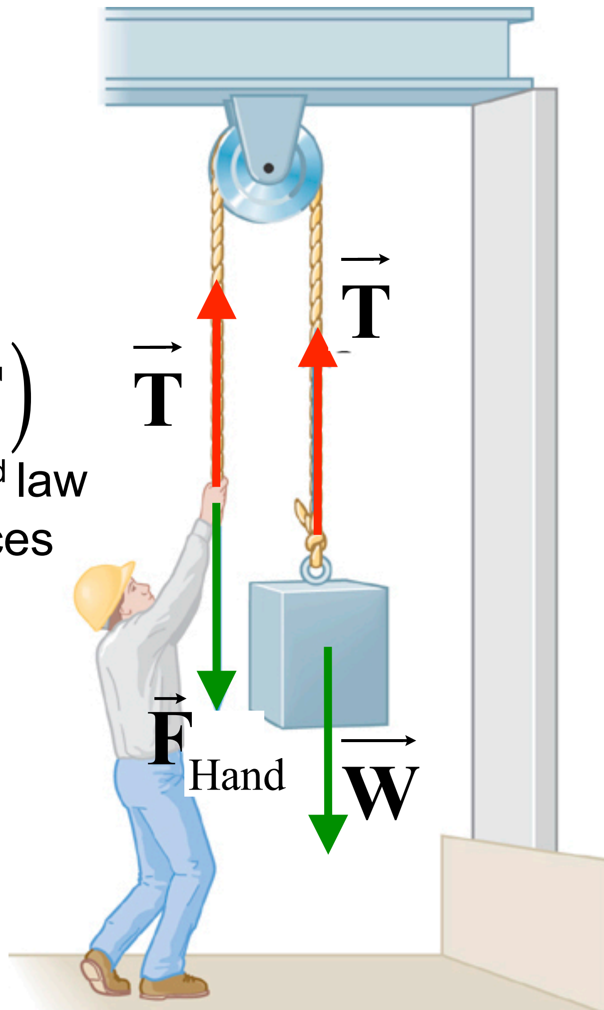
Hand force causes a tension force on the box

Force magnitudes are the same

$$T = F_{\text{Hand}}$$

4.4 The Tension Force

Corrected Figure 4.26



A massless rope will transmit tension magnitude undiminished from one end to the other.

A massless, frictionless pulley, transmits the tension undiminished to the other end.

If the mass is at rest or moving with a constant speed & direction the Net Force on the mass is zero!

$$\sum \mathbf{F} = \vec{\mathbf{W}} + \vec{\mathbf{T}} = 0$$

$$0 = -mg + \vec{\mathbf{T}}$$

$$\vec{\mathbf{T}} = +mg, \text{ and } \mathbf{F}_{\text{Hand}} = -mg$$

Note: the weight of the person must be larger than the weight of the box, or the mass will drop and the tension force will accelerate the person upward.

Clicker Question 4.14

The person is raising a mass *m* at a constant speed of 0.05 m/s. What force must the person apply to the rope to maintain the constant upward speed of the mass.

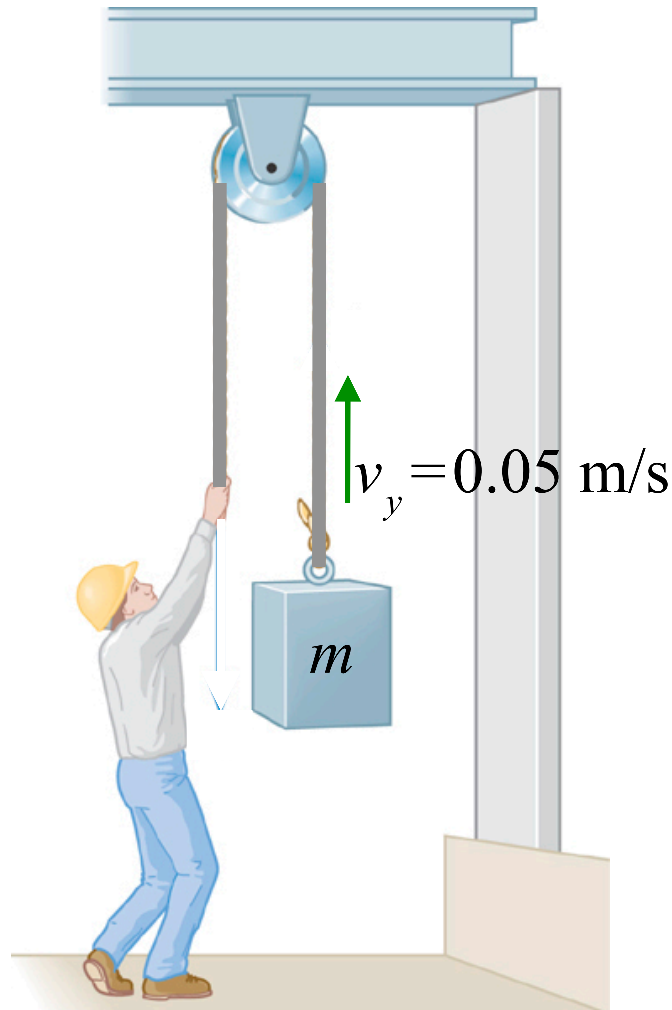
a) mg

b) $> mg$

c) $< mg$

d) $m(0.05 \text{ m/s})$

e) $mg + m(0.05 \text{ m/s})$



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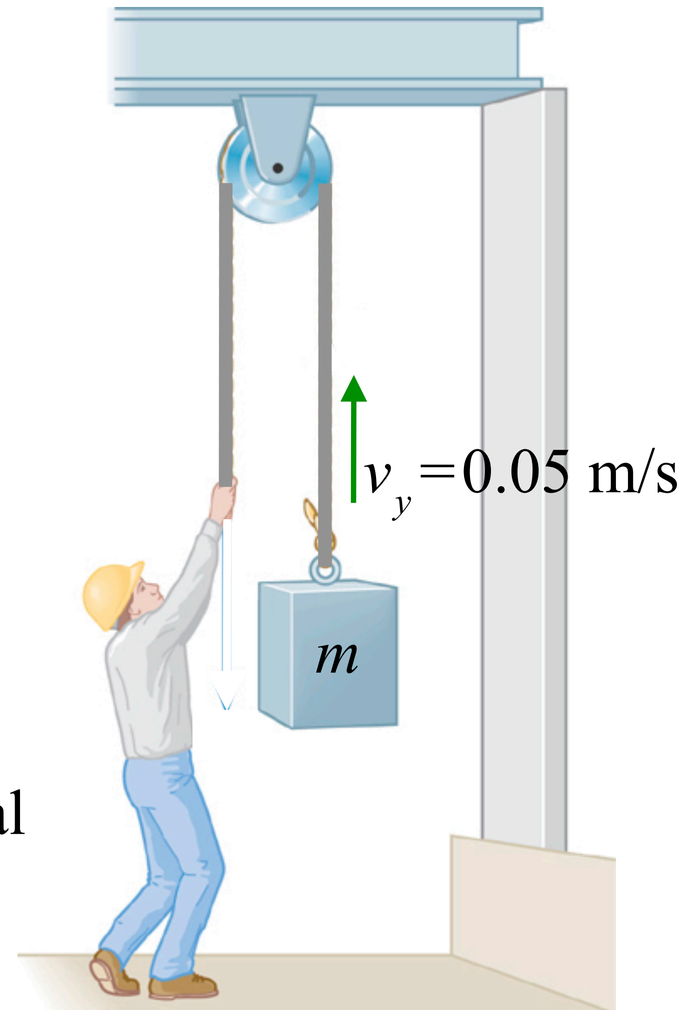


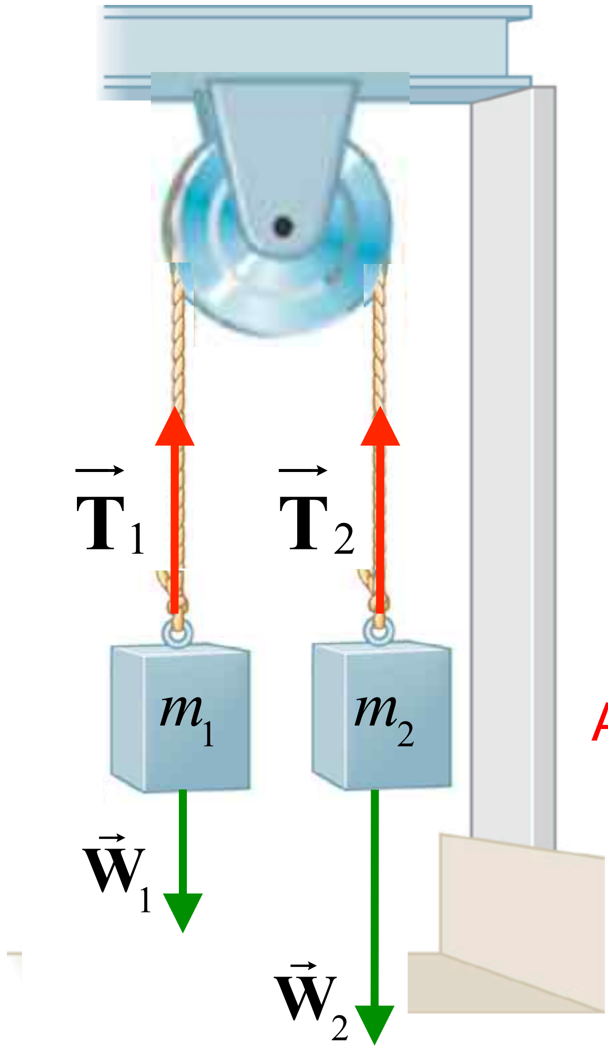
Constant speed and direction $\Leftrightarrow$ no net force.

The person must apply a force to the rope equal to the weight of the mass $= mg$.

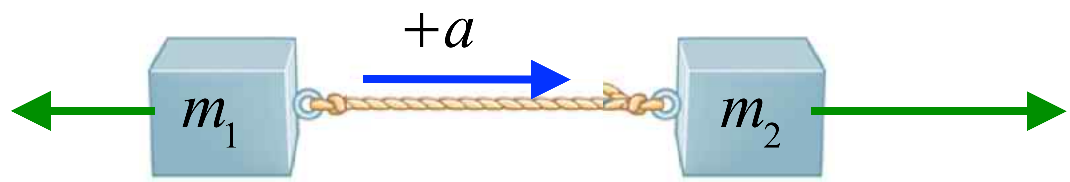
4.4 *The Tension Force (Atwood's machine)*

Atwood's machine: a choice of direction of + for $\vec{\mathbf{F}}$ & $\vec{\mathbf{a}}$.

Let $m_2 > m_1$

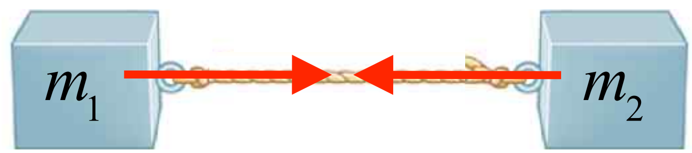


Acceleration is the same for both masses



$\vec{\mathbf{W}}_1 = -m_1 g$ $\qquad$ $\vec{\mathbf{W}}_2 = +m_2 g$

Tension magnitude is the same for both masses



$\vec{\mathbf{T}}_1 = +T$ $\qquad$ $\vec{\mathbf{T}}_2 = -T$

Apply Newton's 2nd Law ($F_{\text{Net}} = ma$) on each mass

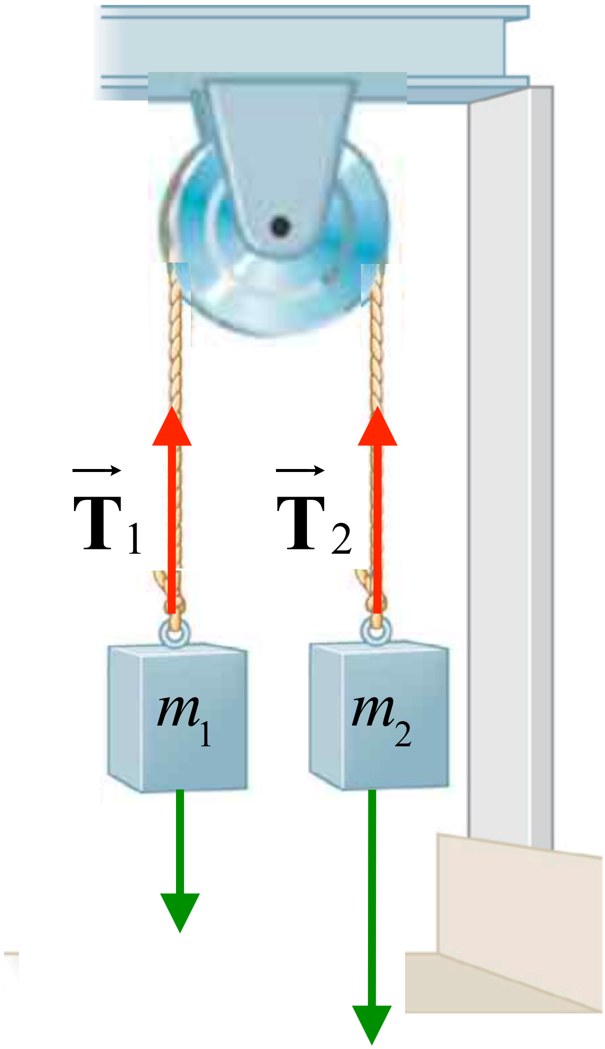
$$\text{on } m_1: \quad F_{\text{Net}} = +T - m_1 g = m_1 a$$

$$\text{on } m_2: \quad F_{\text{Net}} = -T + m_2 g = m_2 a$$

Simultaneous Equations for *T* and *a*

4.4 *The Tension Force (Atwood's machine)*

Solve for acceleration, *a*, and tension, *T*.



Simultaneous Equations for *T* and *a*

$$\text{on } m_1 : F_{\text{Net}} = +T - m_1 g = m_1 a$$

$$\text{on } m_2 : F_{\text{Net}} = -T + m_2 g = m_2 a$$

Adding Equations eliminates *T*, then solve for *a*

$$(m_2 - m_1)g = (m_1 + m_2)a$$

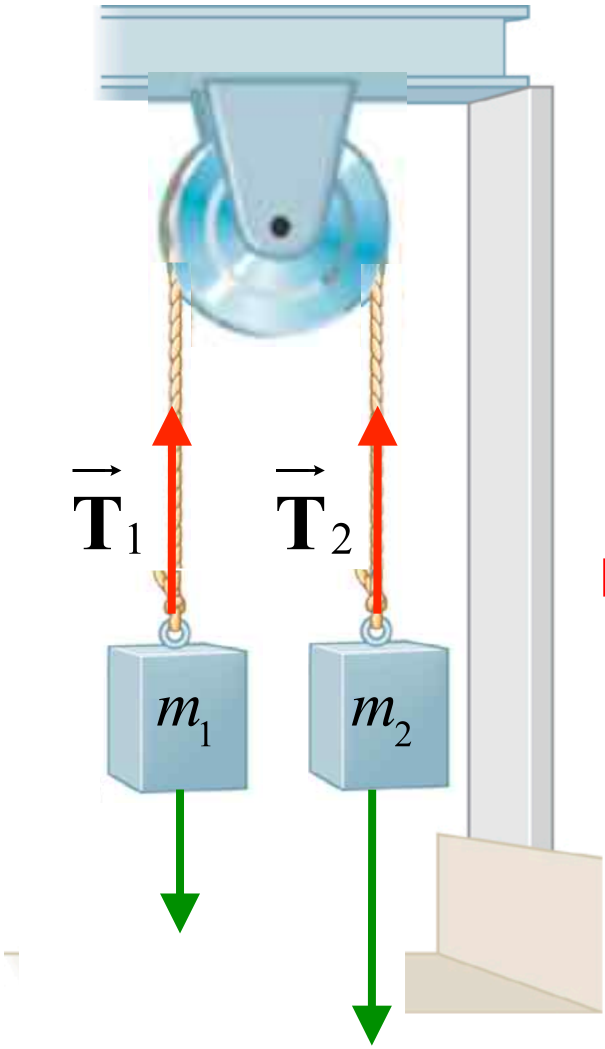
$$a = \frac{(m_2 - m_1)}{(m_1 + m_2)} g$$

Substitute for *a* in first equation to get *T*

$$T = m_1(a - g)$$

$$= m_1\left(\frac{(m_2 - m_1)}{(m_1 + m_2)} - 1\right) g = \frac{2m_1 m_2}{m_1 + m_2} g$$

4.4 The Tension Force (Atwood's machine)



Discussion of the solution

$$a = \frac{(m_2 - m_1)}{(m_1 + m_2)} g$$

$$T = \frac{2m_1 m_2}{m_1 + m_2} g$$

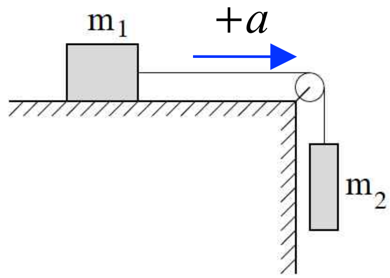
Note: If both masses are the same $= m$

$$\Rightarrow \quad a = 0 \quad \& \quad T = mg$$

However, moving upward or downward at a constant velocity is very possible.

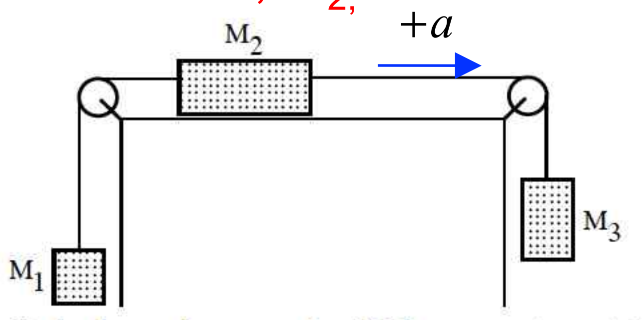
4.4 The Tension Force Lon-Capa HW variations

- on m_1 only T



$$\text{on } m_1 : F_{\text{Net}} = +T_1 = m_1 a$$

- add mid-mass, M_2, now two tensions



$$\text{on } M_1 : F_{\text{Net}} = +T_1 - M_1 g = M_1 a$$
$$\text{on } M_2 : F_{\text{Net}} = -T_1 + T_2 = M_2 a$$
$$\text{on } M_3 : F_{\text{Net}} = -T_2 + M_3 g = M_3 a$$

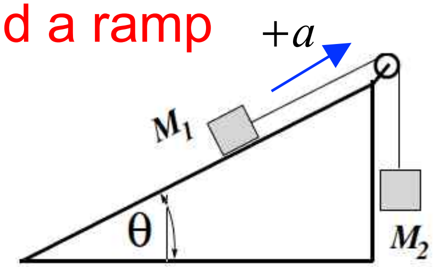
Eliminate T_1 and T_2 , tensions in two strings
Solve for *a*, then determine *v* at time *t*.

- Add kinetic friction, μ_k , between M_2 & table surfaces

$$f_k = \mu_k F_\perp = \mu_k M_2 g \text{ (left)}$$

$$\text{on } M_2 : F_{\text{Net}} = -T_1 - \mu_k M_2 g + T_2 = M_2 a$$

- Add a ramp



$$\text{on } M_1 : F_{\text{Net}} = +T_1 - M_1 g \sin\theta = M_1 a$$

Definition of Equilibrium

An object is in equilibrium when it has zero acceleration.

$$\sum F_x = 0$$

$$\sum F_y = 0$$

We have been using this concept for the entire Chapter 4

Reasoning Strategy

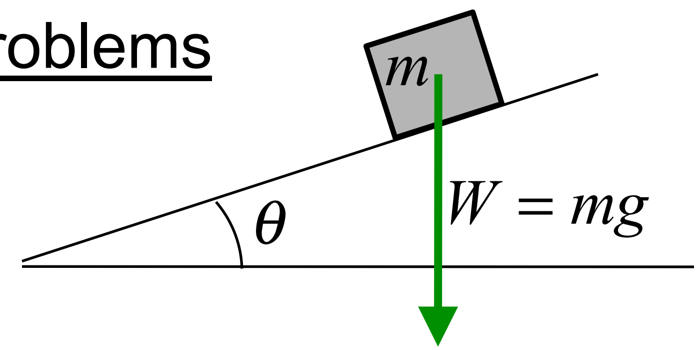
- Select an object(s) to which the equations of equilibrium are to be applied.

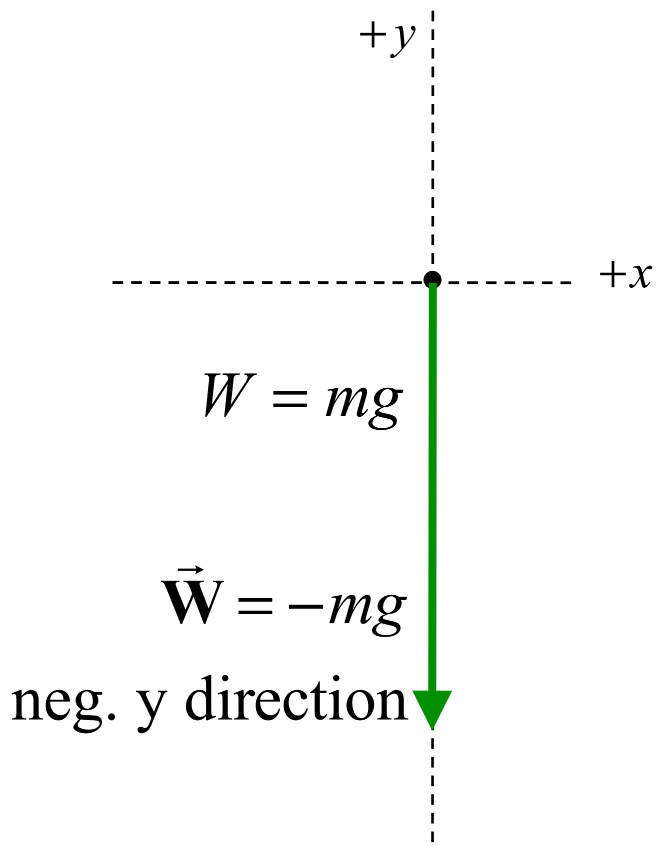
- Draw a free-body diagram for each object chosen above. Include only forces acting on the object, not forces the object exerts on its environment.

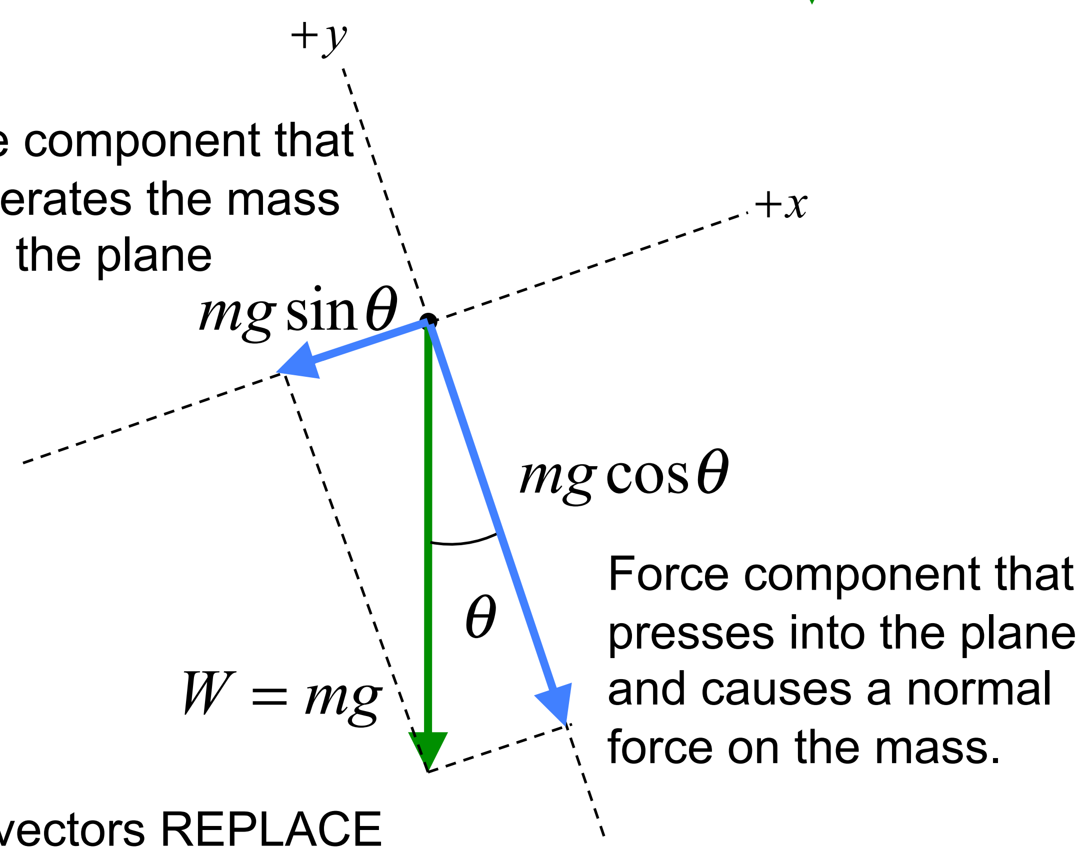
- Choose a set of *x*, *y* axes for each object and resolve all forces in the free-body diagram into components that point along these axes.

- Apply the equations and solve for the unknown quantities.

Inclined plane and similar problems







Blue component vectors REPLACE
the Green Weight vector (equivalent to)