Lecture 5.4 – Newton’s Third Law

DUSTIN ROTEN, PH.D.
WILKES COMMUNITY COLLEGE
FALL 2023

Newton's Third Law

- Newton's Second Law describes the dynamics of a single particle due to forces interacting with it. However, it does not describe interactions between two or more particles.

- An <u>interaction</u> is the mutual influence of two objects on each other.
    - When you sit in a chair, you apply a force downward (your weight) while the chair applies a force upward (normal force).

- If object A exerts a force on object B ($\vec{F}_{A\ on\ B}$) then object B will exert a force back on object A ($\vec{F}_{B\ on\ A}$).
    - This is an <u>action/reaction</u> pair
    - These *only exists as pairs*!

FIGURE 7.1 The hammer and nail are interacting with each other.

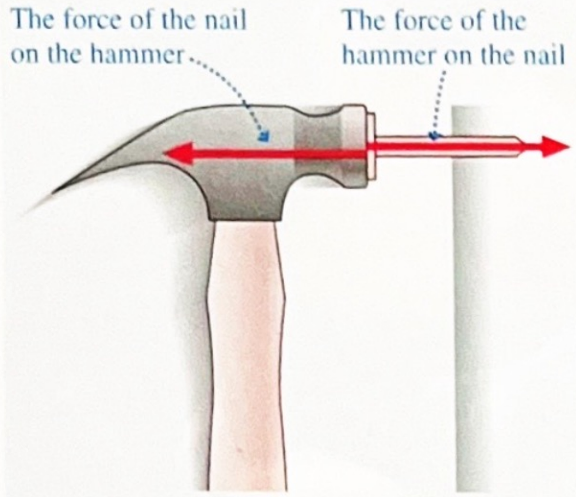
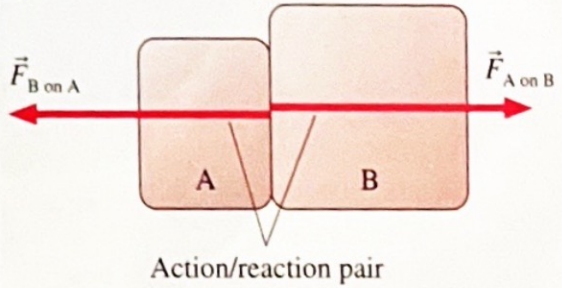


FIGURE 7.2 An action/reaction pair of forces.



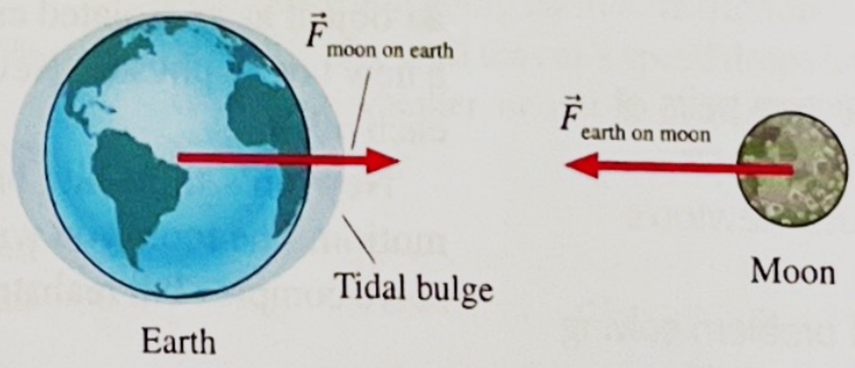
A Thought Experiment

- Given Newton's Third Law, does this mean that a ball in free-fall, under the influence of Earth's gravity, is also pulling up on the Earth? In other words, since there is a force $\vec{F}_{\text{Earth on Ball}}$ is there also a force $\vec{F}_{\text{Ball on Earth}}$?

- Yes!!

- Newton realized this from the Earth's tides. The Earth's gravity holds the Moon in place while the Moon's gravity causes tidal bulge.

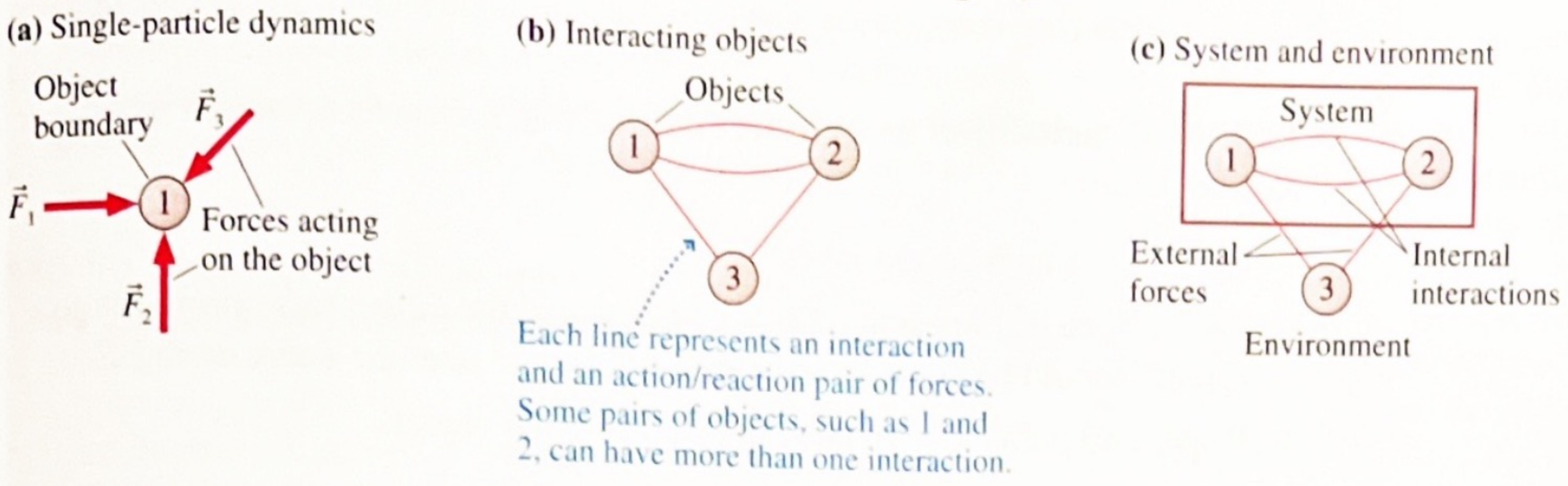
FIGURE 7.3 The ocean tides are an indication of the long-range gravitational interaction of the earth and the moon.



System & Environment

- System – objects whose motion will be analyzed
- Environment – objects external to the system
- Interaction Diagram – Encloses the objects in the system
- External Forces – Interactions with objects in the environment

FIGURE 7.4 Single-particle dynamics and a model of interacting objects.



Analyzing Interacting Objects

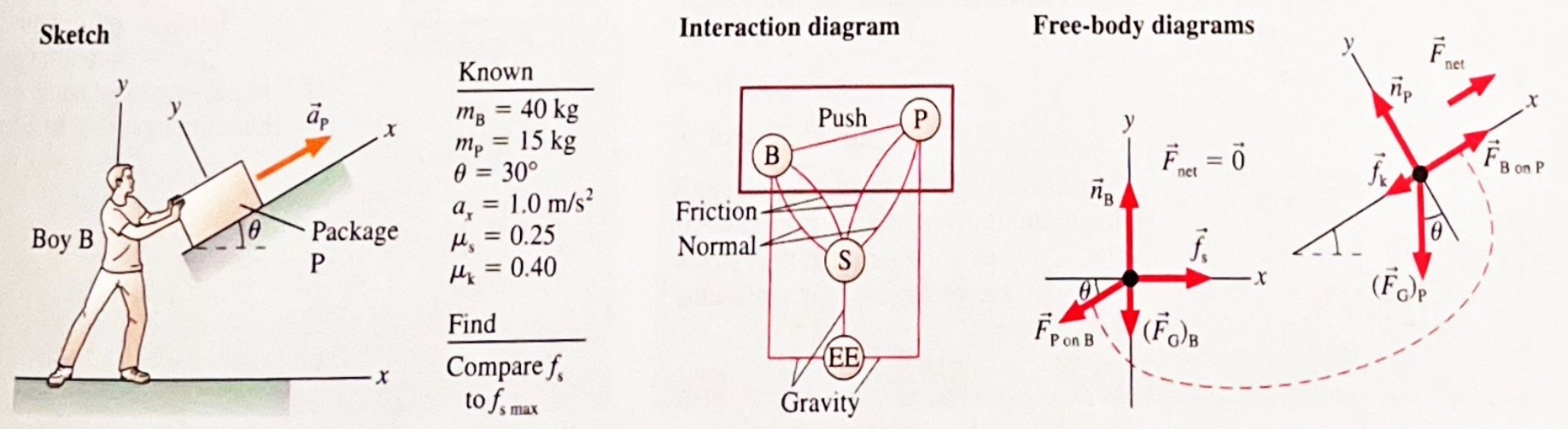
1. Represent each object as a circle with an appropriate label.
2. Identify interactions by drawing lines between the circles. Only include one line per interaction.
3. Identify the system by enclosing the objects of interest in a box.
4. Draw a free-body diagram for each object in the system, including only forces acting *on* each object (not *by* each object).

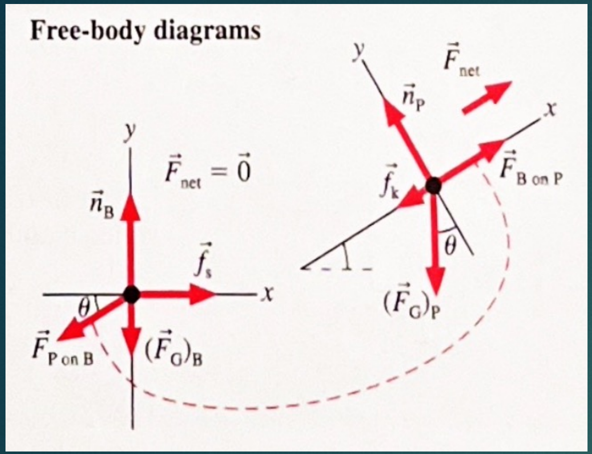
Example #1

EXAMPLE 7.10 Pushing a package

A 40 kg boy works at his dad's hardware store. One of the boy's jobs is to unload the delivery truck. He places each package on a 30° ramp and shoves it up the ramp into the storeroom. He needs to shove the package with an acceleration of at least 1.0 m/s^2 in order for the package to make it to the top of the ramp. One day the ground is wet with rain and he's wearing slick leather-soled shoes. The coefficient of static friction between his shoes and the ground is only 0.25. The largest package of the day is 15 kg, and its coefficient of kinetic friction on the ramp is 0.40. Can he give the package a big enough shove to reach the top of the ramp without his feet slipping?

- A lot of information is given in this set up.
- Sometimes it is easier to jump to the end of the description and identify the unknown.
- Simplifying the question: "can he push the package without his feet slipping?" What $\vec{f}_s$ is required?





Remember:
Using Newton's Third Law, we know that the the force of the boy's push is the same magnitude as the box's push on the boy. Therefore:

$$|\vec{F}_{\text{P on B}}| = |\vec{F}_{\text{B on P}}|$$

The Boy

$$\vec{F}_{net} = \sum_i \vec{F}_i = \vec{f}_s + \vec{F} + \vec{n}_B + (\vec{F}_G)_B = \vec{0}$$

$$(\sum F_x)_B = f_s - F\cos\theta = 0\text{N}$$

$$f_s = F\cos\theta$$

f_s is what we need to know but we don't know *F*!

$$(\sum F_y)_B = n_B - m_B g - F\sin\theta = 0\text{N}$$

$$n_B = m_B g + F\sin\theta$$

Notice that the boy's normal force is his weight PLUS some of the force from the package!

The Package

$$\vec{F}_{net} = \sum_i \vec{F}_i = \vec{f}_k + \vec{F} + \vec{n}_P + (\vec{F}_G)_P$$

$$(\sum F_x)_P = F - \mu_k n_P - m_P g\sin\theta = m_P a$$

$$F = m_P a + \mu_k n_P + m_P g\sin\theta$$

But what is n_P?

$$(\sum F_y)_P = n_P - m_P g\cos\theta = 0\text{N}$$

$$n_P = m_P g\cos\theta$$

There are lots of pieces floating around. Let's focus on putting them together.

Putting it all together…

From the Package's equations:

Put $n_P = m_P g \cos\theta$ into $F = m_P a + \mu_k n_P + m_P g \sin\theta$

$$F = m_p(a + \mu_k g\cos\theta + g\sin\theta) = (15\text{kg})\left(1.0\frac{\text{m}}{\text{s}^2} + \left(0.40\cdot 9.8\frac{\text{m}}{\text{s}^2}\cdot\cos 30°\right) + \left(9.8\frac{\text{m}}{\text{s}^2}\cdot\sin 30°\right)\right) = 139\text{N}$$

Going back to the Boy's equations, determine the required f_s:

$$f_s = F\cos\theta = (139\text{N})\cdot\cos 30° = 120\text{N}$$

What is the maximum static friction possible?

$$f_{s,\max} = \mu_s n_B = \mu_s(m_B g + F\sin\theta) = (0.25)\left(40\text{kg}\cdot 9.8\frac{\text{m}}{\text{s}^2} + 139\text{N}\cdot\sin 30°\right) = 115\text{N}$$

Since the required static friction is larger than $f_{s,\max}$ the Boy CANNOT push the package up the ramp without slipping!

Newton's Third Law

- Every force occurs as one member of an action/reaction pair of forces.
  - The two members of an action/reaction pair act on two different objects.
  - The two members of an action/reaction pair are equal in magnitude but opposite in direction: $\vec{F}_{A,B} = -\vec{F}_{B,A}$
- This completes our definition of <u>force</u>: an *interaction* between objects.
- In an interaction between two objects of different masses, the lighter mass will have a larger acceleration even though the forces are equal.

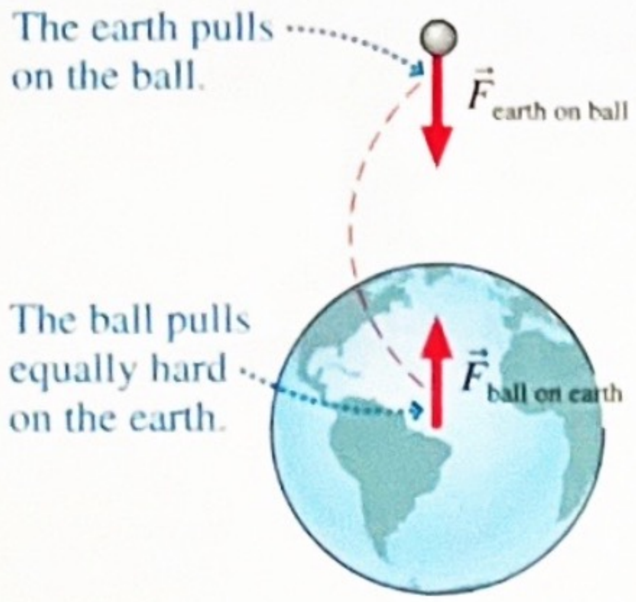
Revisiting the Ball in Free-fall

- In the case where a ball in free-fall is being pulled by Earth's gravity while simultaneously pulling "up" on the Earth reveals two very different accelerations for these objects.

- The falling ball is accelerating at $-g$.

- Although the force on the Earth is equal (and opposite), the Earth's acceleration is very SMALL due to its very LARGE mass.

FIGURE 7.12 The action/reaction forces of a ball and the earth are equal in magnitude.



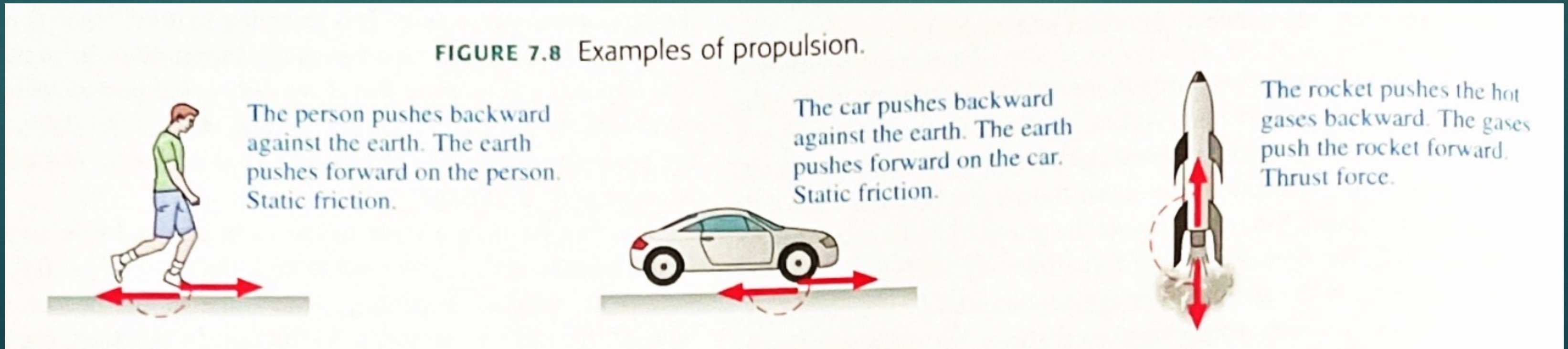
Propulsion

Friction between your shoes and the floor is an example of propulsion!

A system with an internal source of energy uses propulsion to drive itself forward.

For example: you walk by pushing the Earth away from you when you step forward. The Earth responds by pushing back.

Rockets get *thrust* by pushing off of the gas molecules making up their exhaust.



Ropes and Pulleys

- In single-particle dynamics, *tension* was defined as the force exerted on an object by a rope or string.
- In a rope or string, the tension force is supplied by its billions of stretched molecular bonds ("springs"). These "springs" pull in both directions.
- Tension is constant throughout a rope that is in equilibrium.

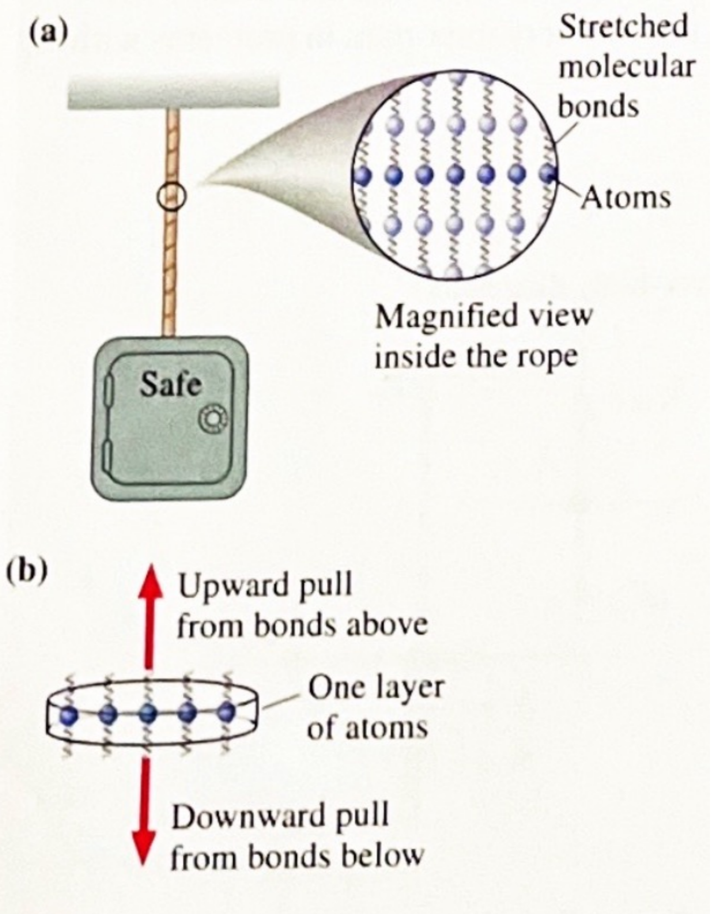


FIGURE 7.18 Tension forces within the rope are due to stretching the spring-like molecular bonds.

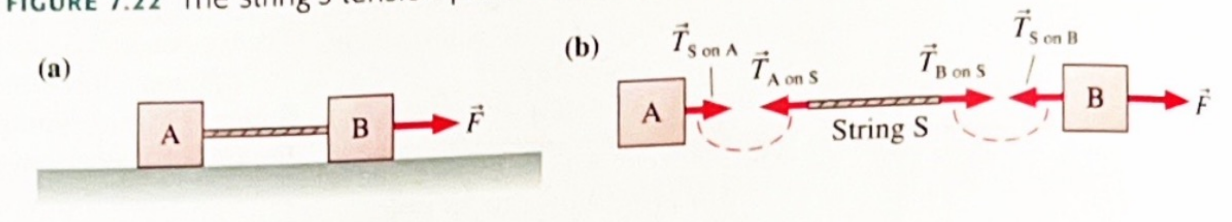
The "Massless" String Approximation

What if the string is accelerating?

If this is the case, then the string must have a net force ($\vec{F}_{\text{net}}$) applied to it.

Consider two blocks, *A* and *B*, connected by a string of mass m_s.

FIGURE 7.22 The string's tension pulls forward on block A, backward on block B.



Sum the net forces on the object (string):

$$F_{\text{net}} = +T_{\text{B on S}} - T_{\text{A on S}} = m_s a_s$$

Righthand side of the string:

$$T_{\text{B on S}} = T_{\text{A on S}} + m_s a_s$$

$$T_{\text{A on S}} = T_{\text{B on S}} - m_s a_s$$

The tension at the front of the accelerating string is higher than at the back.

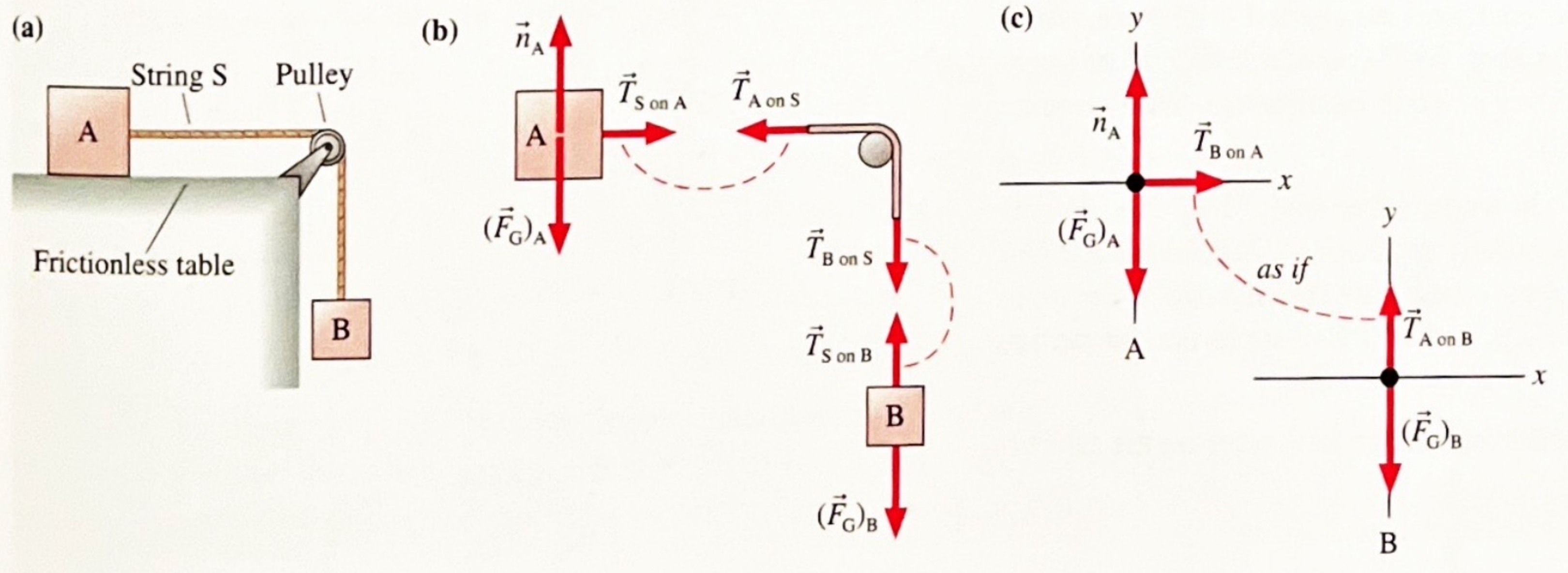
However, if we assume that m_s is really small ("massless"), then $T_{\text{B on S}} = T_{\text{A on S}}$. In this case, blocks A and B act as if they are a direct action/reaction pair.

Pulleys

- Strings and ropes are often passed over pulleys.

- Using simplifying assumptions:
  - The string *and* the pulley are both massless
  - There is no friction where the pulley turns on its axle

FIGURE 7.26 Blocks A and B are connected by a string that passes over a pulley.



The tension in the massless string remains constant as it passes over a massless, frictionless pulley.

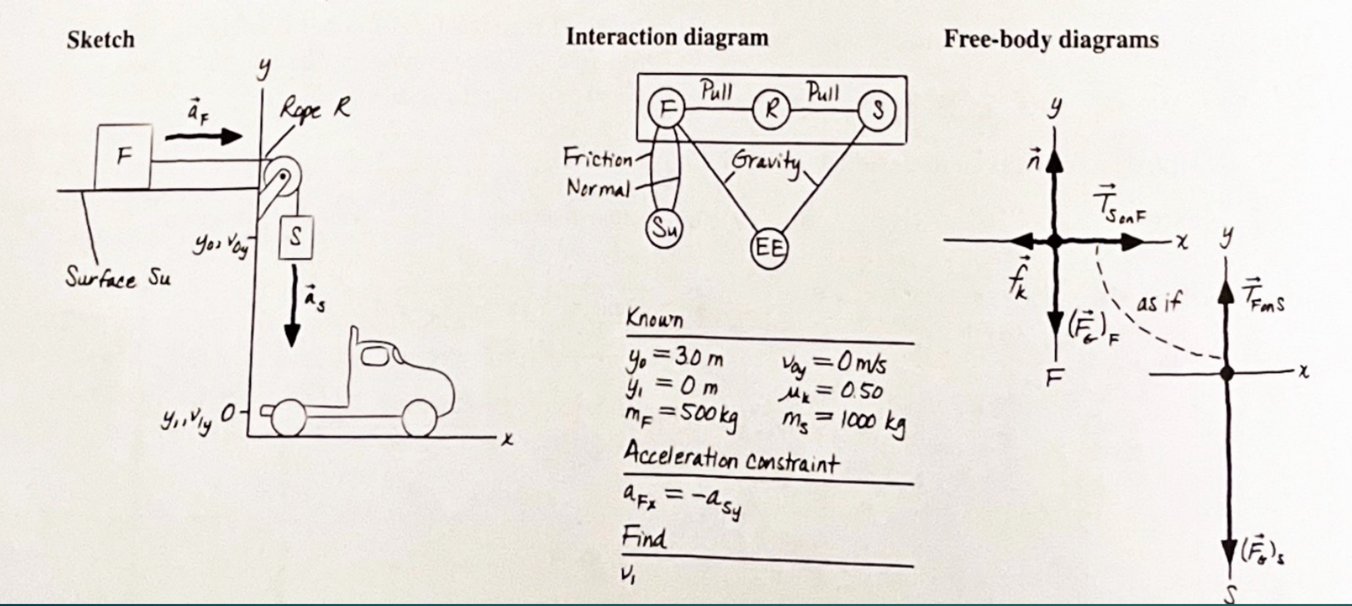
The tension force gets "turned" by the pulley.

The string "transfers" the interaction between blocks A and B.

Example #2

EXAMPLE 7.9 A not-so-clever bank robbery

Bank robbers have pushed a 1000 kg safe to a second-story floor-to-ceiling window. They plan to break the window, then lower the safe 3.0 m to their truck. Not being too clever, they stack up 500 kg of furniture, tie a rope between the safe and the furniture, and place the rope over a pulley. Then they push the safe out the window. What is the safe's speed when it hits the truck? The coefficient of kinetic friction between the furniture and the floor is 0.50.



The Furniture

$$\left(\vec{F}_{\text{net}}\right)_F = \left(\sum_i \vec{F}_i\right)_F = \vec{n}_F + \vec{T} + \vec{f}_k + \left(\vec{F}_G\right)_F$$

$$\left(\sum F_x\right)_F = T - f_k = T - \mu_k n_F = m_F a$$

$$\left(\sum F_y\right)_F = n_F - m_F g = 0\text{N} \quad \text{thus} \quad n_F = m_F g$$

The Safe

$$\left(\vec{F}_{net}\right)_S = \left(\sum_i \vec{F}_i\right)_S = \vec{T} + \left(\vec{F}_G\right)_S$$

$$\left(\sum F_y\right)_F = T - m_S g = m_S a$$

The tension and acceleration in the furniture's x-direction is the same as the tension and acceleration in the safe's y-direction. These can be set equal.

(Remember: the (+)*a* of the furniture becomes the (-)*a* of the safe!)

Furniture

$T - \mu_k n_F = m_F a_F = -m_F a_s$ becomes $T = -m_F a + \mu_k n_F = \mu_k m_F g - m_F a$

Safe

$T - m_S g = m_s a$ becomes $T = m_s a + m_s g$

$$m_s a + m_s g = \mu_k m_F g - m_F a$$
$$m_s a + m_F a = \mu_k m_F g - m_s g$$
$$a(m_s + m_F) = g(\mu_k m_F - m_s)$$

$$a = \left(\frac{\mu_k m_F - m_s}{m_s + m_F}\right) g = \left(\frac{0.5 \cdot 500\text{kg} - 1000\text{kg}}{1000\text{kg} + 500\text{kg}}\right)\left(9.8\,\frac{\text{m}}{\text{s}^2}\right) = -4.9\,\frac{\text{m}}{\text{s}^2}$$

Final speed:

$v_{f,y}^2 = v_{i,y}^2 + 2a\Delta y = 2a\Delta y$ therefore $v_{f,y} = \sqrt{2a\Delta y} = \sqrt{2 \cdot \left(-4.9\,\frac{\text{m}}{\text{s}^2}\right) \cdot (-3.0\text{m})} = 5.4\,\frac{\text{m}}{\text{s}}$