Phys101 Lecture 4,5

Dynamics: Newton's Laws of Motion

Key points:

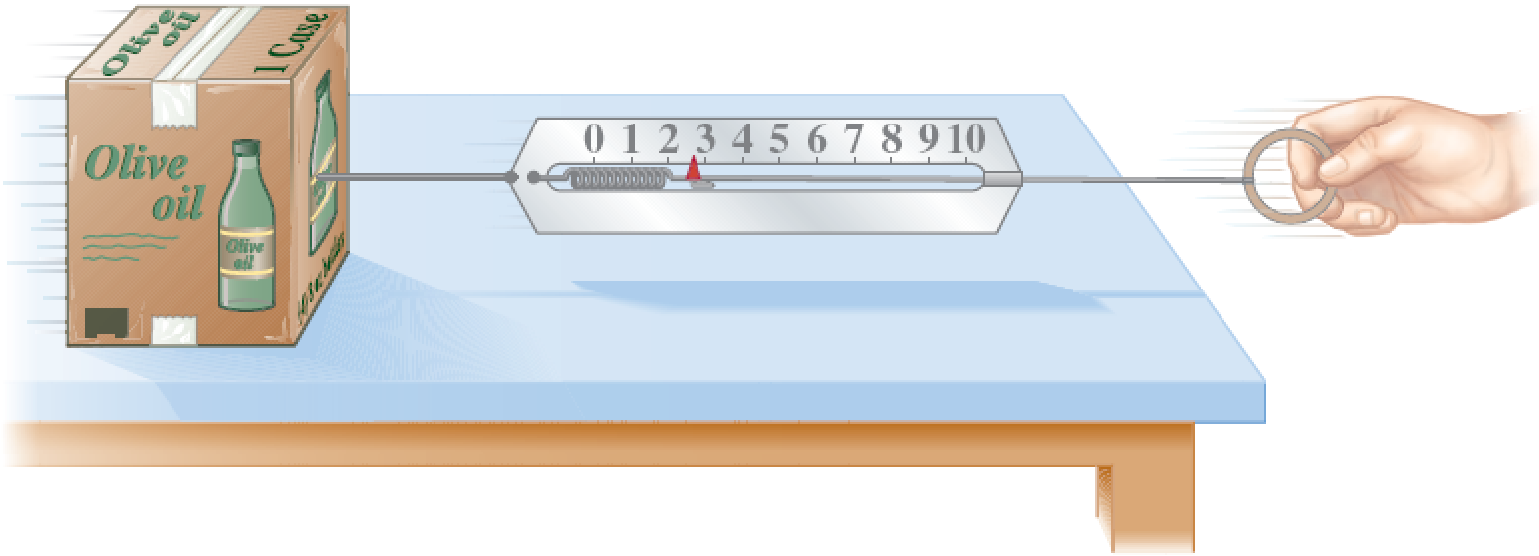
- **Newton's second law is a vector equation**
- **Action and reaction are acting on different objects**
- **Free-Body Diagrams**
- **Friction**
- **Inclines**

Ref: 4-1,2,3,4,5,6,7,8,9.

Force

A **force** is a **push** or **pull**. An object at rest needs a force to get it **moving**; a moving object needs a force to change its **velocity**.

Force is a vector



Force is a vector, having both **magnitude** and **direction**. The **magnitude** of a force can be measured using a spring scale.

Newton's First Law of Motion

This is Newton's first law, which is often called the law of inertia:

Every object continues in its state of rest, or of uniform velocity in a straight line, as long as no net force acts on it.

Demo: Driving without a seat belt.

Inertial Reference Frames:

Newton's first law does not hold in every reference frame, such as a reference frame that is accelerating or rotating.

An inertial reference frame is one in which Newton's first law is valid. This excludes rotating and accelerating frames.

How can we tell if we are in an inertial reference frame? By checking to see if Newton's first law holds!

The earth is approximately an inertial reference frame.

i-clicker question:
The greater the net force acting on an object, the faster the object is moving.

A) True
B) False

Newton’s Second Law of Motion

Newton’s **second law** is the relation between **acceleration** and **force**. Acceleration is **proportional** to force and **inversely** proportional to mass.

$$\sum \vec{F} = m\vec{a}$$

It takes a force to change either the direction or the velocity of an object. i.e., force is the cause of change of motion.

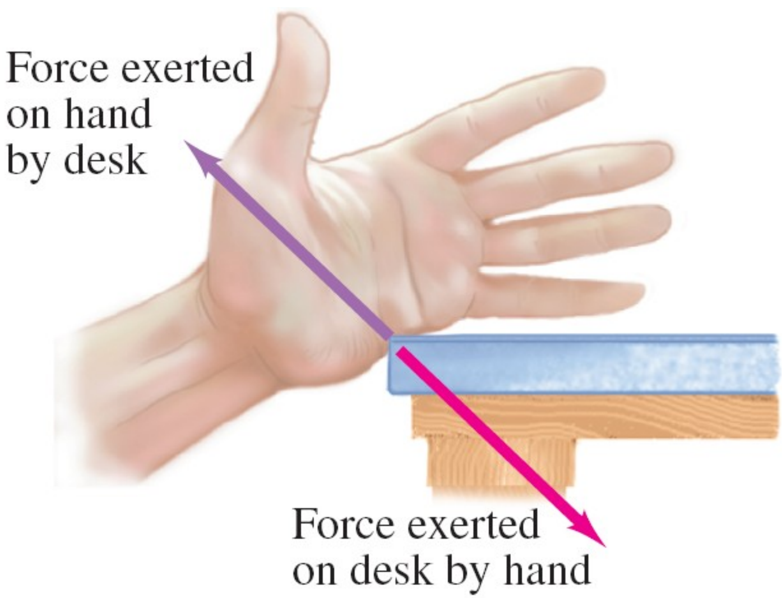
Note:

If we know the mass of an object and the net force acting on it, we will know its acceleration, but not the velocity (we don’t know how fast the object moves unless we have additional information).

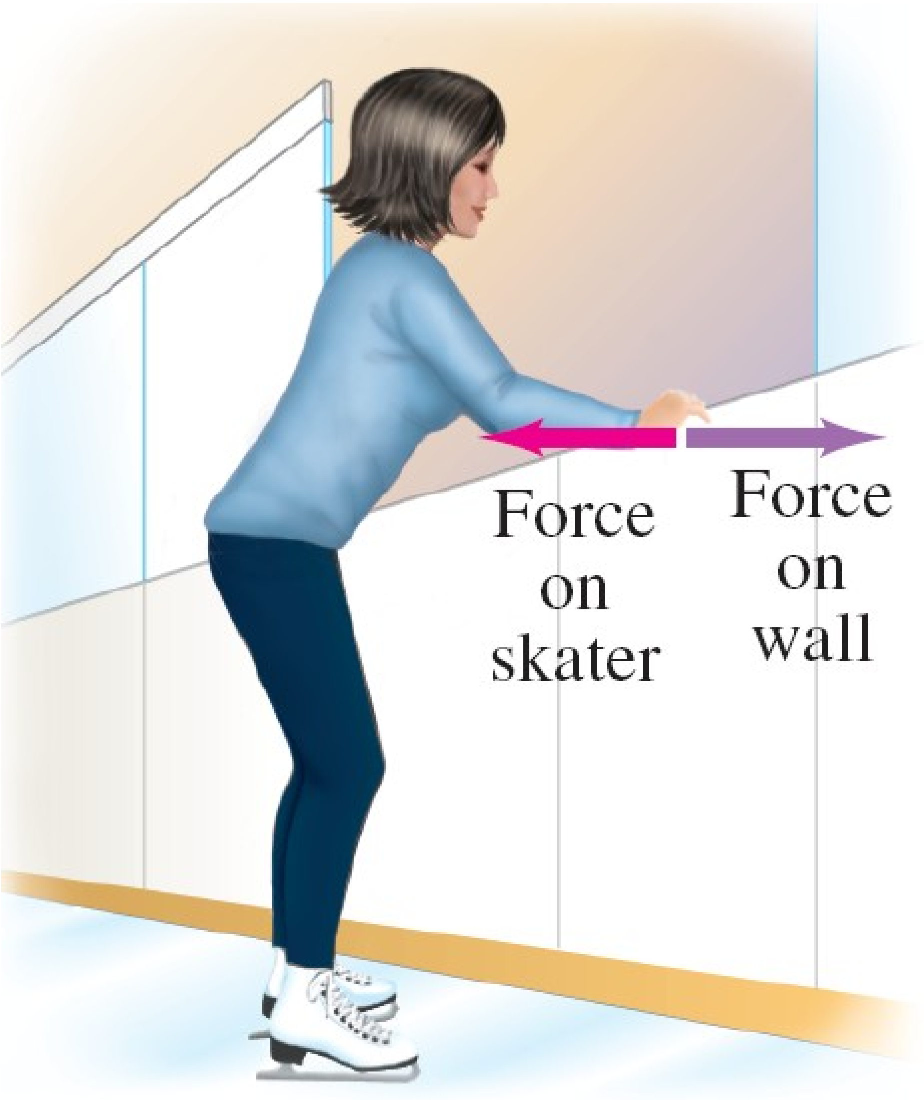
Newton's Third Law of Motion

Newton's third law:

Whenever one object exerts a force on a second object, the second exerts an equal force in the opposite direction on the first.



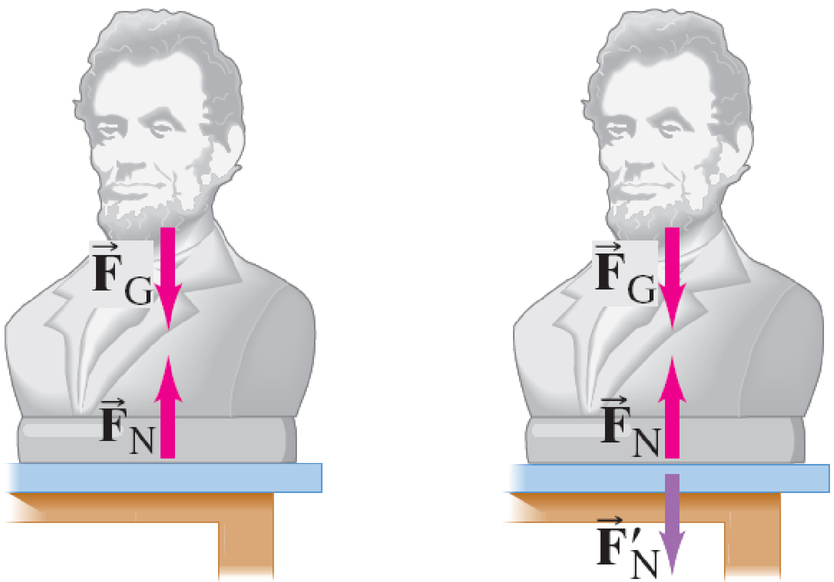
Newton’s Third Law of Motion



A key to the correct application of the third law is that *the forces are exerted on different objects*. Make sure you don’t use them as if they were acting on the *same* object.

The Normal Force

The force exerted perpendicular to a surface is called the normal force.



i-clicker question 4-1

A block of mass *m* rests on the floor of an elevator that is moving upward at constant speed. What is the relationship between the force due to gravity and the normal force on the block?

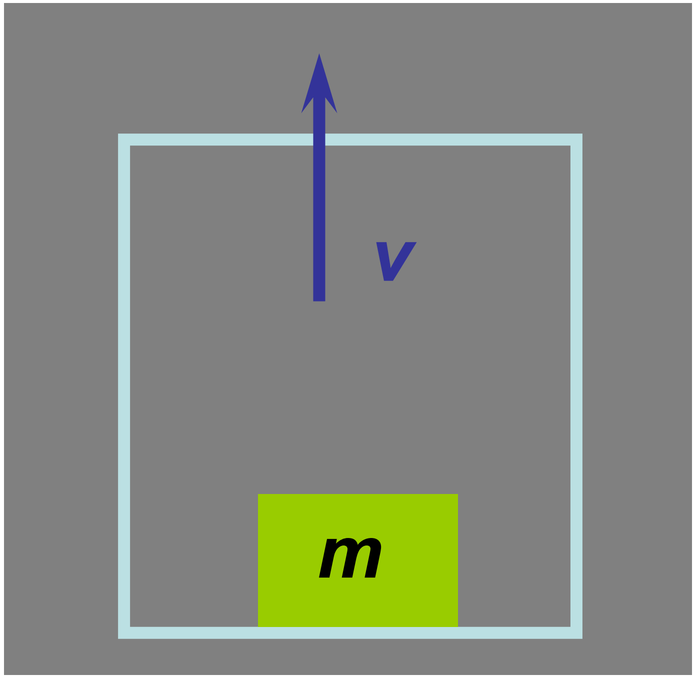
A. 1) $N > mg$

B. 2) $N = mg$

C. 3) $N < mg$ (but not zero)

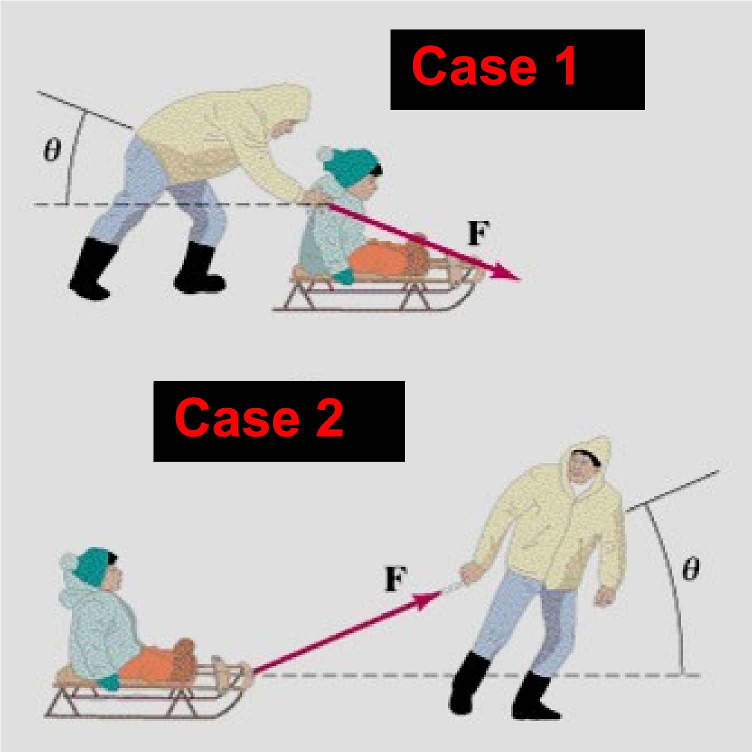
D. 4) $N = 0$

E. 5) depends on the size of the elevator



i-clicker question 4-2

Here you see two cases: a physics student pulling or pushing a sled with a force *F* that is applied at an angle θ. In which case is the normal force greater?



A) case 1

B) case 2

C) it's the same for both

D) depends on the magnitude of the force *F*

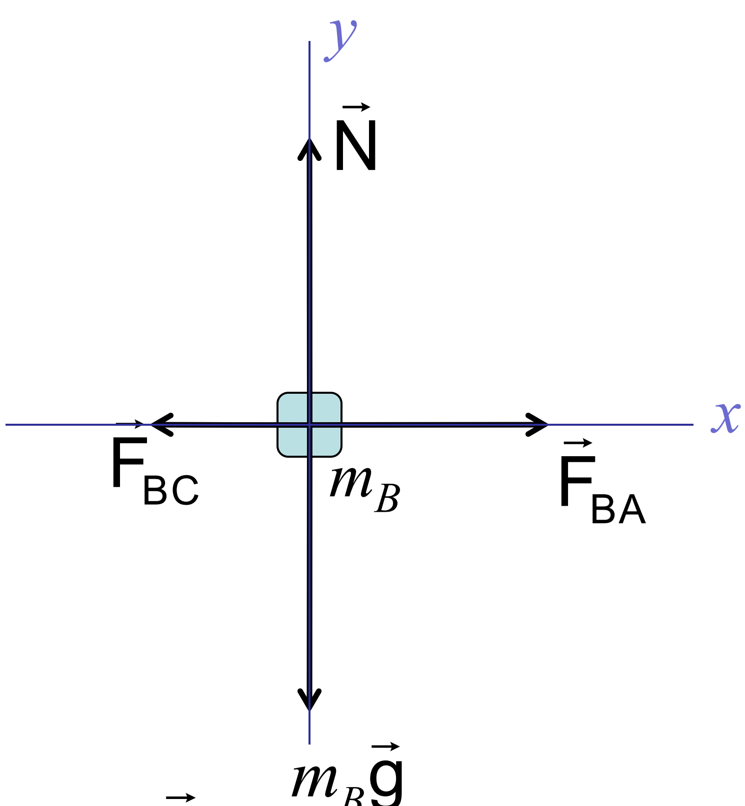
E) depends on the ice surface

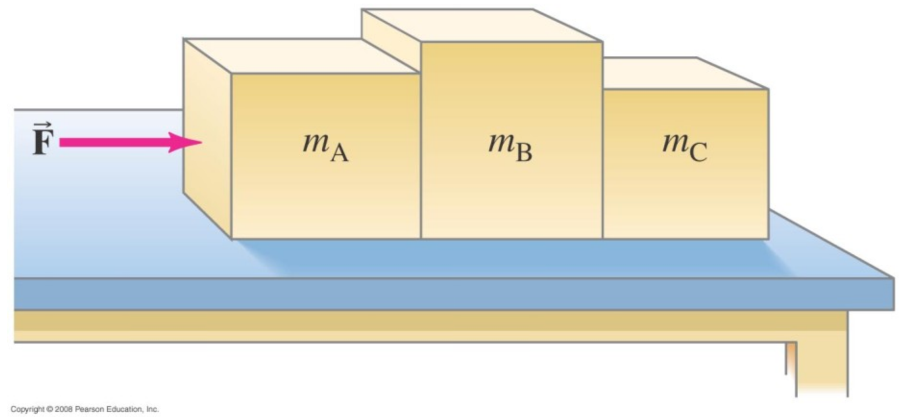
Free-Body Diagram

A diagram showing all forces acting ***on*** an object.

What does "free-body" mean? Isolate the object.

Example: Draw a FBD for object m_B (assume no friction)





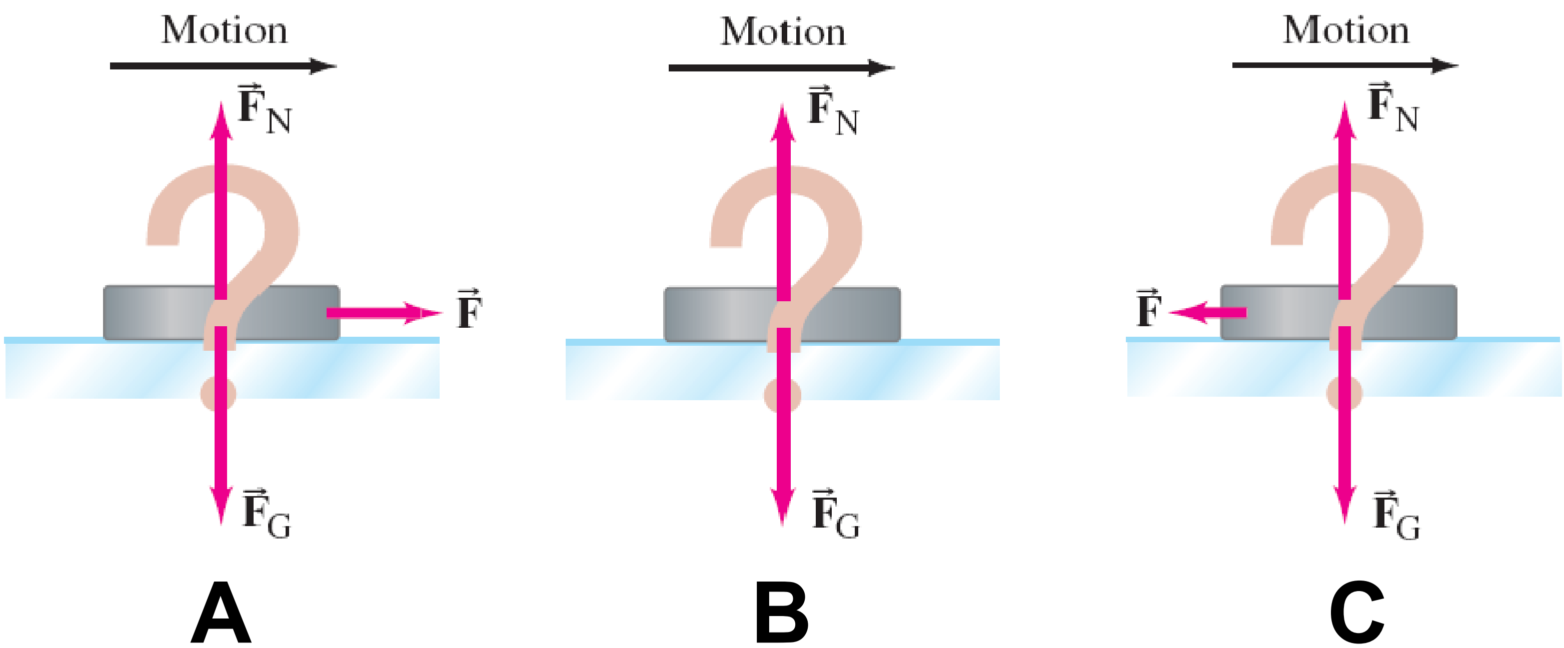
Set up your coordinate system for components.

Where is $\vec{F}$?

There are two kinds of forces:

1. **Contact forces**
2. **Field forces (gravity, electric, etc)**

i-clicker question 4-3 and 4-4

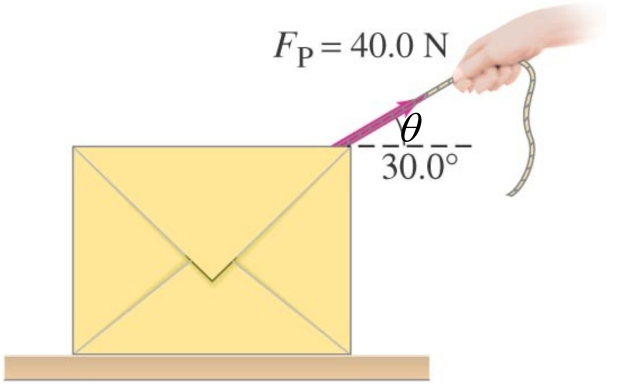


Conceptual Example: The hockey puck.

A hockey puck is sliding at constant velocity across a flat horizontal ice surface that is assumed to be frictionless. Which of these sketches is the correct free-body diagram for this puck? What would your answer be if the puck slowed down?

Example:

Tim pulls a 10-kg box by an attached cord on the smooth surface of a table. The magnitude of the force exerted by Tim is F_P = 40.0 N, and it is exerted at a 30.0° angle as shown. Calculate the acceleration of the box.

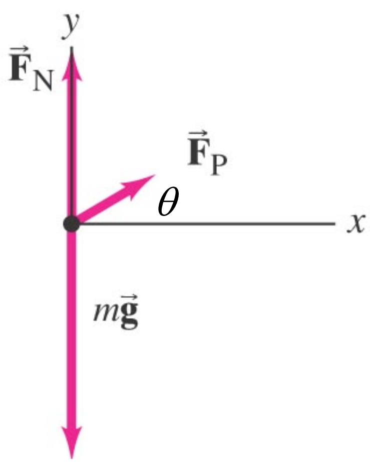


Free-body diagram:

contact forces: Pull by Tim;

Normal force.

Field forces: Gravity



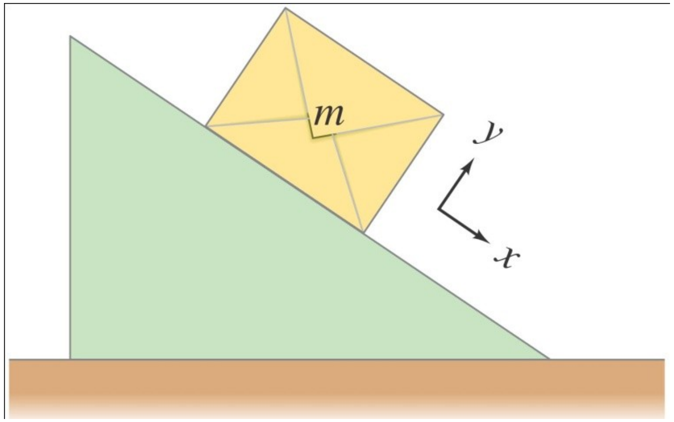
$$\text{Newton's Law}: \ \vec{F} = m\vec{a}$$

$$x\text{-component}: \ F_p \cos\theta = ma_x$$

$$y\text{-component}: \ F_N + F_P \sin\theta - mg = 0$$

$$\text{Solve for } a_x: \quad a_x = \frac{F_p \cos\theta}{m} = \frac{(40.0)(\cos 30°)}{10.0} = 3.46 m/s^2$$

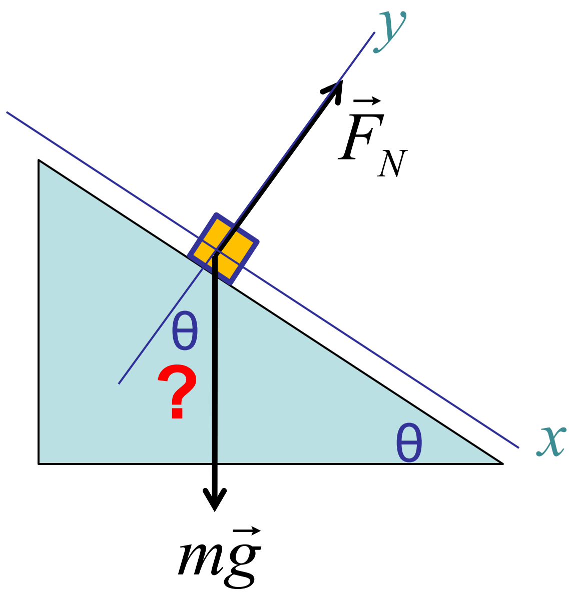
Example: Box slides down an incline.



A box of mass m is placed on a smooth incline that makes an angle θ with the horizontal. (a) Determine the normal force on the box. (b) Determine the box's acceleration. (c) Evaluate for a mass m = 10 kg and an incline of θ = 30°.

[Solution]

First, FBD and x-y coordinates.



Then, Newton's law in component form:

$$\vec{F} = m\vec{a}$$

x-comp: $mg\sin\theta = ma_x$

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

(a) $F_N = mg\cos\theta$

(b) $a = a_x = g\sin\theta$

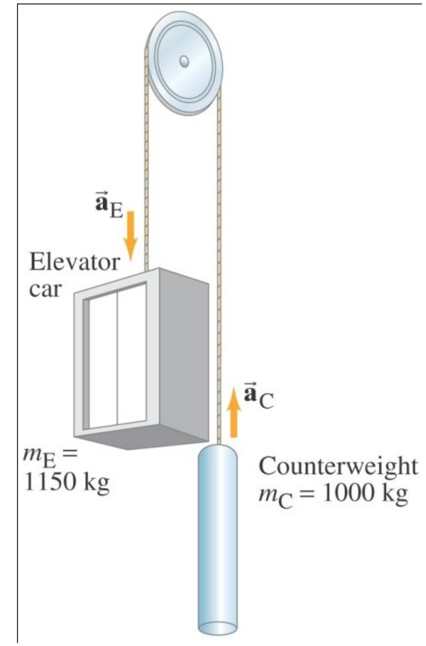
(c) $F_N = 85N, \quad a = 4.9m/s^2.$

Again, two kinds of forces:

1. **Contact forces**
2. **Gravity.**

Example: Elevator and counterweight (Atwood's machine).

The mass of the counterweight is 1000 kg. The total mass of the elevator with passengers is 1150 kg. Calculate (a) the acceleration of the elevator and (b) the tension in the cable. Ignore the mass of cable and friction.



[Solution] For each object, we need to draw a FBD and apply Newton's law.

Ignoring friction and cable mass means ?
the same tension in cables on both sides of pulley.

Kinematics relation: $a_{Cy} = -a_{Ey} = a$

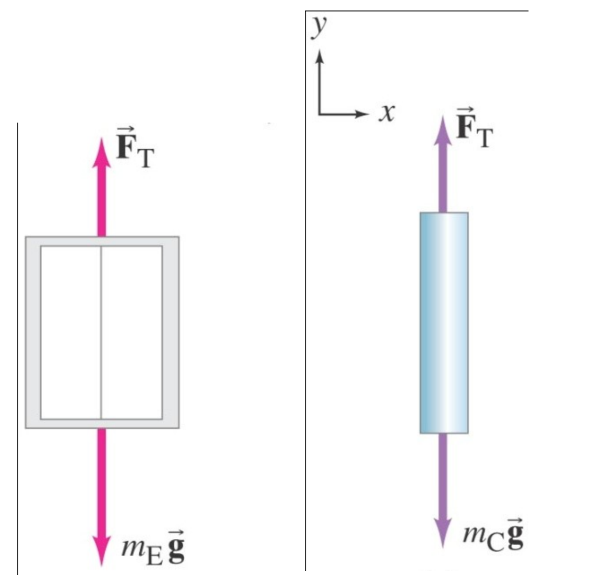
$$F_T - m_C g = m_C a_{Cy} = m_C a$$

$$F_T - m_E g = m_E a_{Ey} = -m_E a$$

Solve for a and F_T :

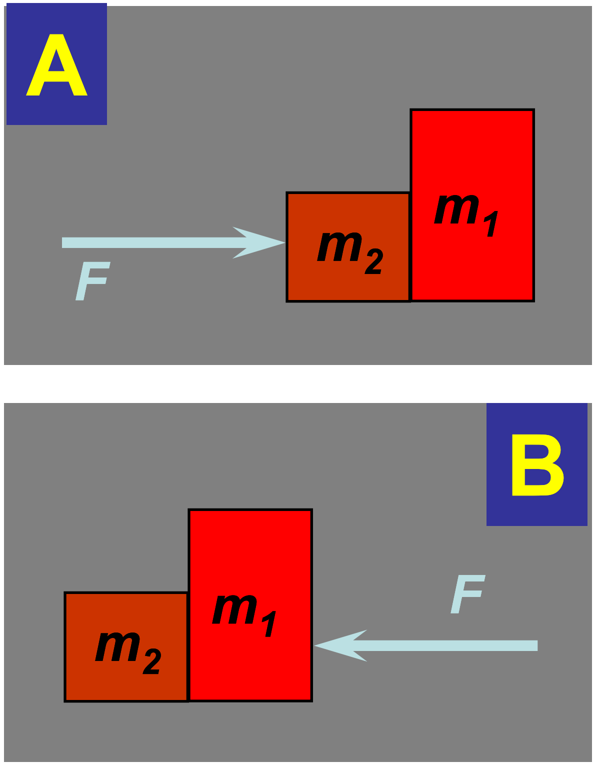
$$a = \frac{m_E - m_C}{m_E + m_C} g = 0.68 m/s^2$$

$$F_T = m_C (a + g) = 10500 N$$



i-clicker question 4-5

If you push with force *F* on either the heavy box (m_1) or the light box (m_2), in which of the two cases is the contact force between the two boxes larger? Ignore friction.



A) case A ?

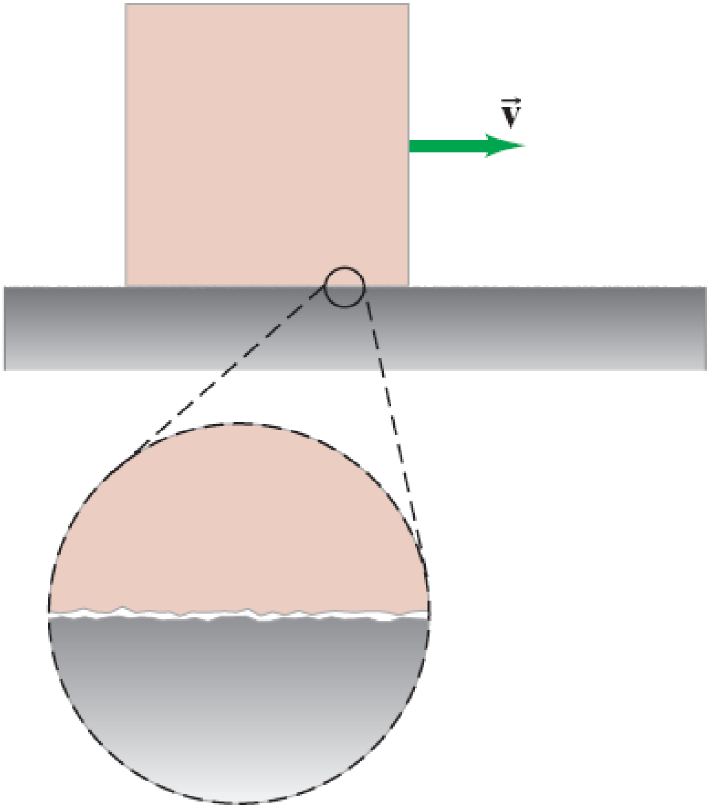
B) case B

C) same in both cases

Acceleration is the same for both cases $a = F/(m_1 + m_2)$.
Thus $m_1 a > m_2 a$

Friction

Friction is always present when two solid surfaces slide along each other.



The microscopic details are not yet fully understood.

Kinetic Friction

Sliding friction is called kinetic friction.

Approximation of the frictional force:

$$F_{\mathrm{fr}} = \mu_{\mathrm{k}} F_{\mathrm{N}} \,.$$

Here, F_{N} is the normal force, and μ_{k} is the coefficient of kinetic friction, which is different for each pair of surfaces.

Static Friction

Static friction applies when two surfaces are at rest with respect to each other (such as a book sitting on a table).

The static frictional force is as big as it needs to be to prevent slipping, up to a maximum value.

$$F_{\mathrm{fr}} \leq \mu_s F_{\mathrm{N}} .$$

Usually the coefficient of static friction is greater than the coefficient of kinetic friction.

Static and Kinetic Frictions

Note that, in general, $\mu_s > \mu_k$.

TABLE 5–1 Coefficients of Friction†

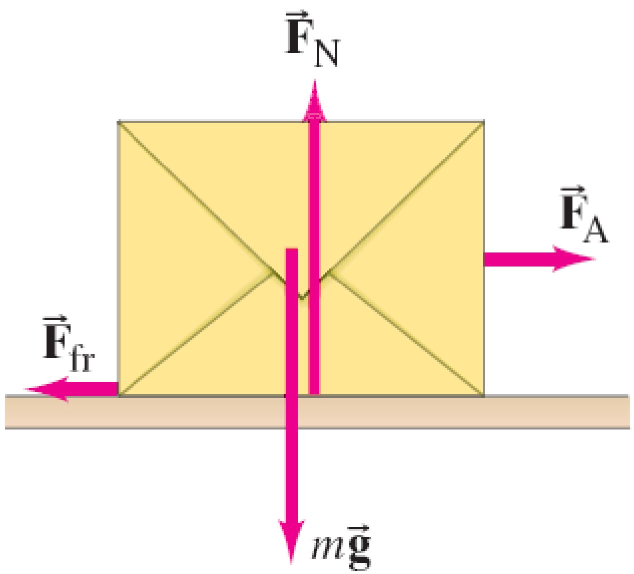
Surfaces	Coefficient of Static Friction, μ_s	Coefficient of Kinetic Friction, μ_k
Wood on wood	0.4	0.2
Ice on ice	0.1	0.03
Metal on metal (lubricated)	0.15	0.07
Steel on steel (unlubricated)	0.7	0.6
Rubber on dry concrete	1.0	0.8
Rubber on wet concrete	0.7	0.5
Rubber on other solid surfaces	1–4	1
Teflon® on Teflon in air	0.04	0.04
Teflon on steel in air	0.04	0.04
Lubricated ball bearings	<0.01	<0.01
Synovial joints (in human limbs)	0.01	0.01

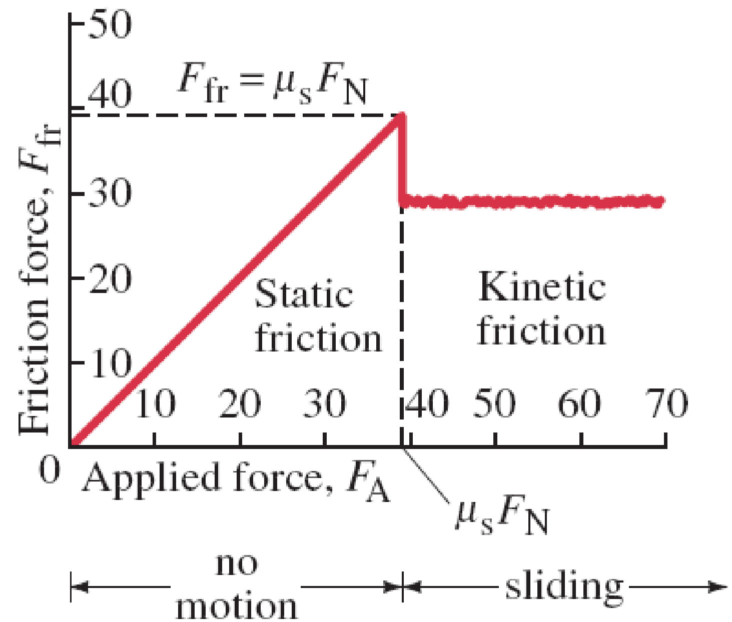
†Values are approximate and intended only as a guide.

Example: Friction: static and kinetic.

Our 10.0-kg mystery box rests on a horizontal floor. The coefficient of static friction is 0.40 and the coefficient of kinetic friction is 0.30. Determine the force of friction acting on the box if a horizontal external applied force is exerted on it of magnitude:

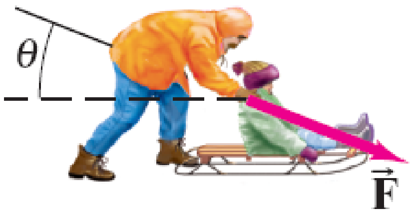
(a) 0, (b) 10 N, (c) 20 N, (d) 38 N, and (e) 40 N.



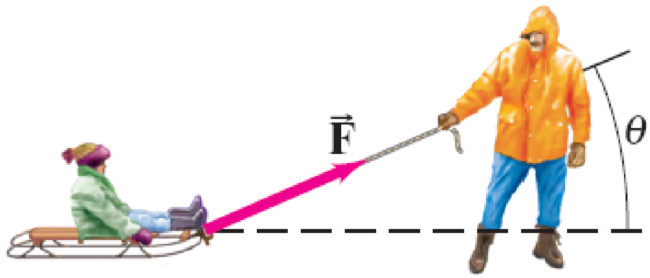


i-clicker question 4-6

To push or to pull a sled?



Your little sister wants a ride on her sled. If you are on flat ground, will you exert less force if you push her or pull her? Assume the same angle *θ* in each case.

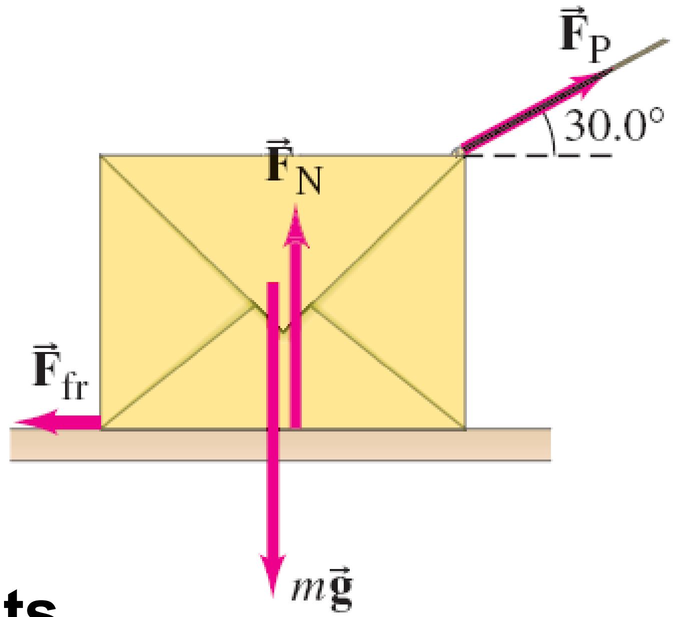


A) Push
B) Pull
C) No difference

$$F_{\mathrm{fr}} = \mu_k F_N .$$

Example: Pulling against friction.

A 10.0-kg box is pulled along a horizontal surface by a force of 40.0 N applied at a 30.0° angle above horizontal. The coefficient of kinetic friction is 0.30. Calculate the acceleration.



FBD and Coordinates

Newton's law in x- and y- components

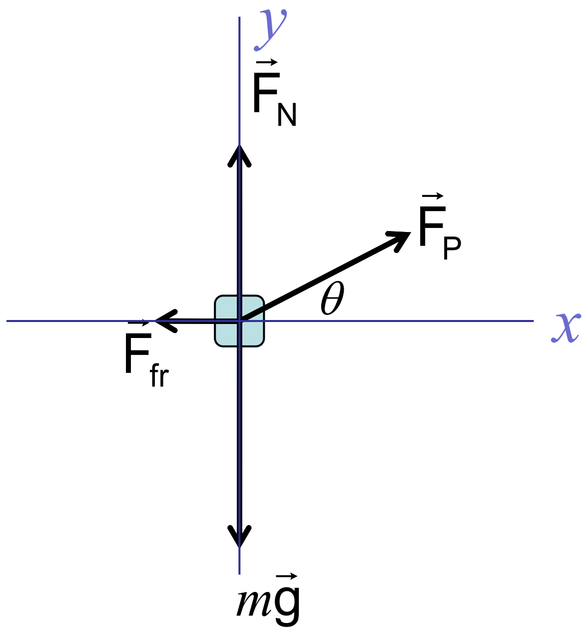
$$F_P \cos\theta - \mu_k F_N = ma_x \qquad (F_{fr} = \mu F_N)$$

$$F_N + F_P \sin\theta - mg = 0$$

Two unknowns, a_x and F_N. We can solve.

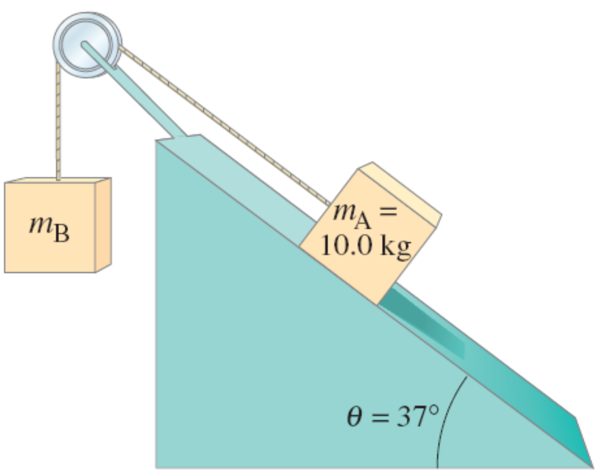
$$F_N = mg - F_P \sin\theta = 78N$$

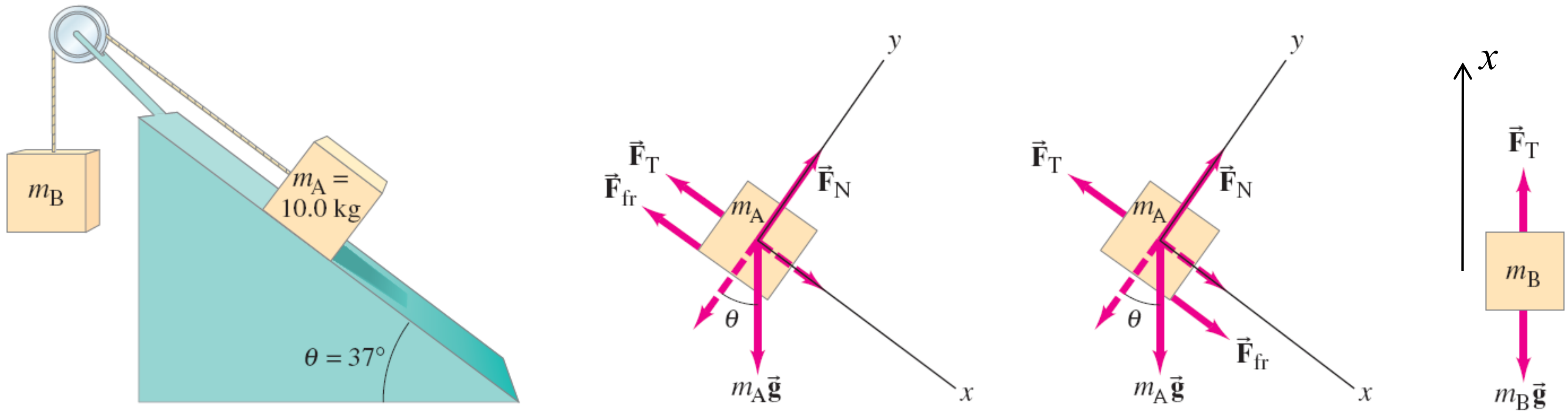
$$a_x = \frac{F_P \cos\theta - \mu_k F_N}{m} = 1.1 m/s^2$$



Example: A ramp, a pulley, and two boxes.

Box A, of mass 10.0 kg, rests on a surface inclined at 37° to the horizontal. It is connected by a lightweight cord, which passes over a massless and frictionless pulley, to a second box B, which hangs freely as shown. (a) If the coefficient of static friction is 0.40, determine what range of values for mass B will keep the system at rest. (b) If the coefficient of kinetic friction is 0.30, and m_B = 10.0 kg, determine the acceleration of the system.





(case i) Small m_B

(case ii) Large m_B

case i : small m_B

$$m_A g \sin\theta - F_T - F_{fr} = m_A a_x$$

$$F_N - m_A g \cos\theta = 0$$

$$F_T - m_B g = m_B a_x$$

we want $a_x = 0$,

maximum static friction : $F_{fr} = \mu_S F_N$

$$m_A g \sin\theta - F_T - \mu_S F_N = 0$$

$$F_N = m_A g \cos\theta$$

$$F_T = m_B g$$

$$m_A g \sin\theta - m_B g - \mu_S m_A g \cos\theta = 0$$

$$m_B = m_A \sin\theta - \mu_S m_A \cos\theta$$

$$m_B = 10 \sin 37° - (0.40)(10)\cos 37°$$

$$m_B = 2.8 kg$$

case ii : large m_B

$$m_A g \sin\theta - F_T + F_{fr} = 0$$

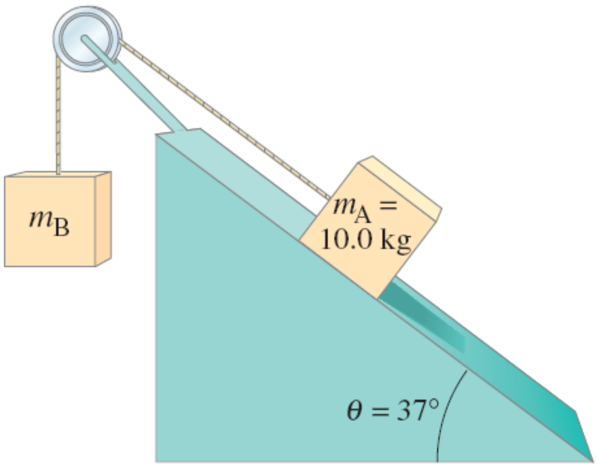
$$m_B = m_A \sin\theta + \mu_S m_A \cos\theta$$

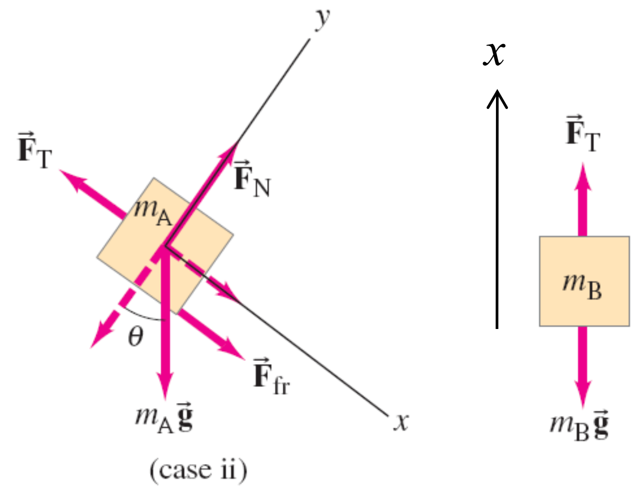
$$m_B = 10 \sin 37° + (0.40)(10)\cos 37°$$

$$m_B = 9.2 kg$$

$$2.8 kg < m_B < 9.2 kg$$

Part (b): Now $m_B = 10kg > 9.2kg$,





$$m_A g \sin\theta - F_T + F_{fr} = m_A a_x$$

$$F_N - m_A g \cos\theta = 0$$

$$F_T - m_B g = m_B a_x$$

Kinetic friction: $F_{fr} = \mu_k F_N$

$$F_N = m_A g \cos\theta$$

$$F_T = m_B g + m_B a_x$$

$$m_A g \sin\theta - m_B g - m_B a_x + \mu_k m_A g \cos\theta = m_A a_x$$

$$m_A g \sin\theta - m_B g + \mu_k m_A g \cos\theta = m_A a_x + m_B a_x$$

$$a_x = \frac{m_A g \sin\theta - m_B g + \mu_k m_A g \cos\theta}{m_A + m_B}$$

$$a_x = -0.78\, m/s^2$$