2.1 Forces and Free-Body Diagrams

Figure 1 A trebuchet converts the force of gravity downward on the counterweight into the motion of the projectile.

Understanding forces is essential for designing and developing technologies, both ancient and modern. For example, the machine in **Figure 1** is a model of an ancient weapon called a trebuchet. Trebuchets were used for hundreds of years, before gunpowder was available, to launch projectiles into cities under siege. In a trebuchet, the force of gravity pulls downward on a counterweight. That force causes the motion of the projectile, which can travel quite quickly. WEB LINK

A modern example of converting force into motion is the linear actuator, which can be used to reduce the strain of repetitive motion in the workplace. A motor drives a series of gears or screws, which convert the motor's power into the force of the actuator. You will learn more about linear actuators in Section 2.5.

Common Forces

force ($\vec{F}$) a push or a pull

newton the SI unit of force; symbol N

contact force a force that acts between two objects when they touch each other

non-contact force a force that acts between two objects without the objects touching; also called action-at-a-distance force

force of gravity ($\vec{F}_g$) the force of attraction between all objects due to mass

A **force** is a push or a pull. The measure of force in the SI system of units is called the **newton** (N). You encounter different kinds of forces every day. A force can even stabilize an object by counteracting another force on that object. Physicists classify forces as **contact forces**, where one object exerts a force on another object when they touch each other, and **non-contact forces**, such as gravity, where the two objects need not touch to exert a force on each other. Non-contact forces are also called action-at-a-distance forces.

Earth's **force of gravity** is responsible for everything from keeping your textbooks on your desk to keeping satellites in orbit around Earth. The force of gravity is an *attractive* force: all objects have mass and therefore attract each other. This attraction is quite weak when the objects are small or far apart. Earth exerts a relatively large attractive force on everything around you compared to other masses because Earth is so massive compared to other masses on Earth, such as buildings and bridges. For example, the gravitational attraction between a 30.0 kg desk and a 1.0 kg textbook 0.10 m apart is only 2.0×10^{-7} N, but Earth's force on the same textbook is 9.8 N.

normal force ($\vec{F}_N$) a force perpendicular to the surface between objects in contact

If Earth's force of gravity pulls downward on the textbook on your desk, why does the book remain stationary? There must be a force pushing up on the book perpendicular to the surface to balance the force of gravity. This balancing force is called the **normal force**, which is a force perpendicular to the surface between objects in contact. In **Figure 2**, the normal force points upward because the contact surface is parallel to the ground.

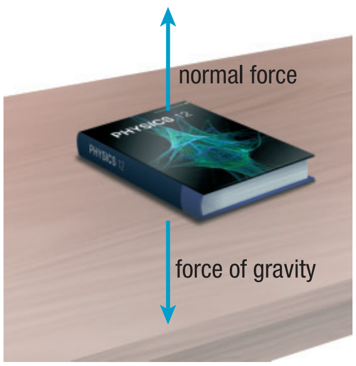


Figure 2 For a stationary object such as this textbook resting on a desk, Earth's gravity pulls downward while the normal force of the desk pushes upward, so the book does not move.

tension ($\vec{F}_T$) a force exerted by objects that can be stretched

Another common force is **tension**, which is a pulling force exerted by objects such as strings and ropes. **Figure 3(a)**, on the next page, shows how to measure tension using a spring scale. The more you stretch the spring in the spring scale, the more difficult it becomes to pull. The degree of difficulty indicates the amount of tension. Even when the direction of the force changes, such as when a string passes over a pulley (**Figure 3(b)**), the amount of tension stays uniform.

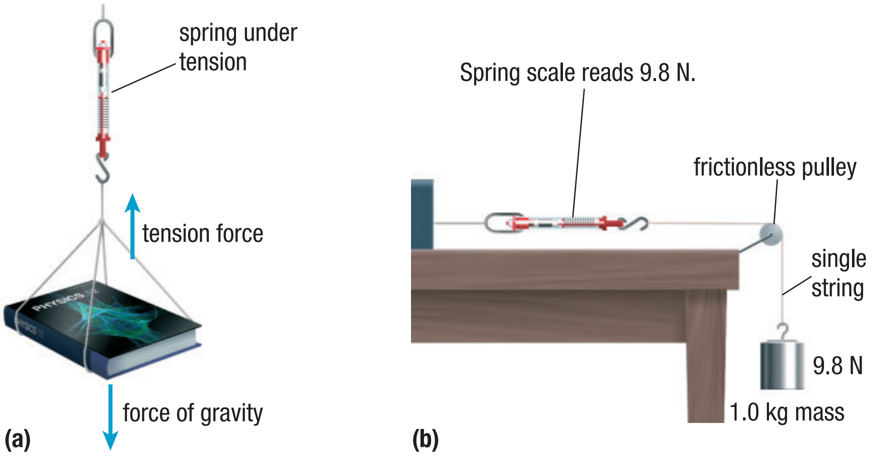


Figure 3 (a) The larger the stretch in the spring, the greater the tension. (b) The tension in the string is the same all along its length. The string pulls up on the 1.0 kg mass below the pulley with the same force as it pulls horizontally on the spring to the left of the pulley.

The force of **friction** exists between objects and always resists the sliding motion or attempted sliding motion between objects. Suppose a heavy box of books is on the floor. You try to push the box across the floor with a horizontal force, but the box does not move. You push harder, and the box starts to move. You have overcome the force of static friction. **Static friction** is a force that resists attempted motion between two surfaces—it keeps the stationary box of books from moving across the floor. **Kinetic friction** is a force exerted on a moving object by the surface in a direction opposite to the motion of the object. Pushing a box across the floor is made more difficult because kinetic friction acts in the direction opposite to motion. WEB LINK

Another important type of kinetic friction is air resistance. **Air resistance** is the friction between an object and the air around it. Air resistance is more noticeable for lightweight objects, such as a piece of paper falling through the air, and objects moving at high speeds, such as an airplane flying through the air. Air resistance can be neglected in most problem-solving situations unless it is logically required. CAREER LINK

Finally, an **applied force** is a force due to one object coming into contact with another object, such that a push or a pull results. When pushing on the box mentioned above with your hands, you are applying a force.

friction ($\vec{F}_f$) a force that opposes the sliding of two surfaces across one another; acts opposite to motion or attempted motion

static friction ($\vec{F}_S$) a force that resists attempted motion between two surfaces in contact

kinetic friction ($\vec{F}_K$) a force exerted on a moving object by a surface in the direction of motion opposite to the motion of the object

air resistance ($\vec{F}_{air}$) the friction between objects and the air around them

applied force ($\vec{F}_a$) a force due to one object pushing or pulling on another

Free-Body Diagrams

When solving physics problems, it is sometimes difficult to visualize all the forces acting on an object. One way to visualize all the different forces acting on an object is with a diagram. A **free-body diagram** (FBD) is a simple line drawing of an object that shows all the forces acting on the object at one moment in time. Arrows represent the approximate direction and magnitude of each force. A dot in the centre represents the object. The underlying assumption is that we are modelling the object as a point particle, so the dot makes this assumption visually apparent. Some people draw FBDs with a dot and a rectangle, but in this textbook the FBDs just have the dot. All forces point outward from the dot. Sometimes, you may need to sketch a system diagram showing all objects involved in a situation first before drawing an FBD (**Figure 4**).

free-body diagram a simple line drawing that shows all the forces acting on an object

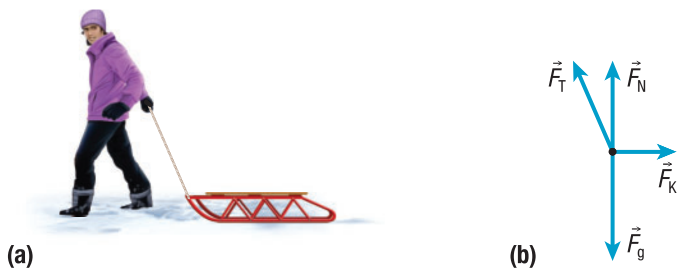


Figure 4 (a) A system diagram of a person pulling a sled. (b) An FBD shows the forces acting on the sled.

In Tutorial 1, you will practise drawing both an FBD and a system diagram for different forces.

Tutorial 1 Drawing Free-Body and System Diagrams

This Tutorial demonstrates how to draw free-body and system diagrams used to study forces.

Sample Problem 1: Applying a Horizontal Force

You are pushing with a horizontal force to the right against a large printer on a table. The printer remains stationary. Draw a system diagram and an FBD of the forces acting on the printer.

Solution

Step 1. Identify the objects in the scenario.

The objects in the scenario are two hands, a printer, a table, and Earth.

Step 2. Draw a simple system diagram.

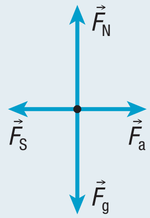
Step 3. Identify the forces acting on the printer.

The forces acting on the printer are the force of gravity, the normal force, and an applied force. The printer is not moving, so the force of static friction is also acting on the printer.

Step 4. Determine the direction of each force.

The normal force exerted by the desk pushes upward on the printer, and the force of gravity is pulling downward on the printer. The applied force is acting to the right. The force of static friction is acting on the printer to the left.

Step 5. Draw an FBD by drawing a dot to represent the printer. Draw individual arrows to represent each force and its direction. The lengths of the arrows should reflect the magnitudes of the forces. If two forces have the same magnitude, then the lengths of the arrows will be the same. Label each arrow with the appropriate force symbol.



Sample Problem 2: Applying a Non-horizontal Force

A rope pulls a skier up a hill to the right at a constant velocity. Draw a system diagram and an FBD of the forces acting on the skier.

Solution

Step 1. Identify the objects in the scenario.

The objects in the scenario are a skier, a rope, and an incline.

Step 2. Draw a simple system diagram.

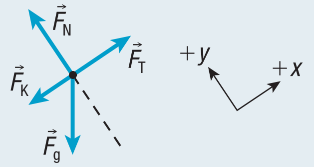
Step 3. Identify the forces acting on the skier.

The forces acting on the skier are gravity, the normal force, the force of tension in the rope, and the force of kinetic friction.

Step 4. Determine the direction of each force.

Gravity acts in the downward vertical direction. The normal force acts perpendicular to the slope of the hill. The tension of the rope acts on the skier to the upper right, and the kinetic friction between the skis and the snow acts on the skis in the opposite direction of the force of tension.

Step 5. Draw an FBD by drawing a dot to represent the skier. Draw individual arrows to represent each force and its direction. Indicate the magnitudes of the forces by the lengths of the arrows. Label each arrow with the appropriate force symbol.



Practice

1. Draw a simple system diagram and an FBD for each of the following objects. K/U C A
   (a) a pen sitting on a table
   (b) a rope connected to a crane raising a piano vertically upward at a constant speed
   (c) a lamp that has just begun falling from a table to the floor; air resistance is negligible
   (d) a dresser that is being pulled to the right up a ramp into a delivery truck by a cable parallel to the ramp; the ramp is at an angle of 14° above the horizontal
2. You throw a ball vertically upward. Air resistance is negligible. Draw an FBD of the ball
   (a) just after it leaves your hand
   (b) at the top of its motion
   (c) as it is falling back down K/U C A
3. A skydiver whose parachute is open can see his instantaneous height above ground level on an electronic screen. The skydiver has reached terminal speed. (Recall from earlier studies that when an object falls at terminal speed it is falling at a constant velocity.) For this question, assume the skydiver and the parachute together act as one body. Draw a system diagram and an FBD for the situation. K/U C A

Determining Net Force in Two Dimensions

Once you identify all of the forces acting on an object, you can calculate the **net force** on the object, or the sum of all the forces acting on an object. The term *net force* and the symbol $\Sigma\vec{F}$ are used to represent this sum, but the terms *total force* and *resultant force* are also used. The symbol for net force uses the Greek letter Σ (sigma) in front of the $\vec{F}$. In mathematics, sigma indicates a sum of several different terms or numbers. Sigma is used here to remind you to add up (or sum) all forces acting on a single object at one moment in time to calculate the net force.

net force ($\Sigma\vec{F}$) the sum of all the forces acting on an object

When several forces are acting on an object, those forces are not always parallel or perpendicular to each other. This can make determining the sum of the forces more difficult. In these cases, it is often convenient to think about the components of the forces in the *x*- and *y*-directions. We will use the symbols ΣF_x and ΣF_y for these components. In addition, FBDs are helpful to visualize the forces. In Tutorial 2, you will calculate the net force on an object in different contexts.

Tutorial 2 Determining Net Force

This Tutorial models how to determine the net force acting on objects when the individual forces are not all parallel or perpendicular to each other.

Sample Problem 1: Net Force above the Horizontal

A baseball player lightly bunts a baseball with an average force of 14 N at 29° above the horizontal (**Figure 5**). The force of gravity on the baseball is 1.4 N. Calculate the net force on the ball at the moment of contact, assuming that air resistance is negligible.

Figure 5

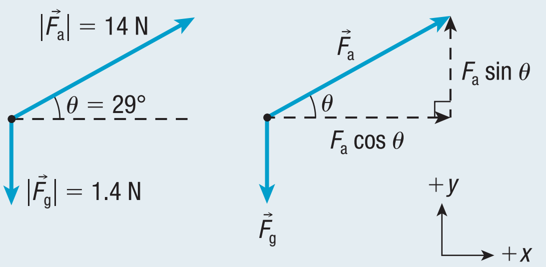
Given: $\vec{F}_a = 14$ N; $\theta = 29°$ above the horizontal; $F_{gx} = 0.0$ N; $F_{gy} = 1.4$ N

Required: ΣF_x (net force); θ (direction)

Analysis: Draw FBDs to show the force on the baseball and the components of the force. Use $F_{ax} = F\cos\theta$ and $F_{ay} = F\sin\theta$ to determine the components of the force on the baseball. Add the components to the components of the force of gravity, and use $|\Sigma\vec{F}| = \sqrt{(\Sigma F_x)^2 + (\Sigma F_y)^2}$ to calculate the net force.

Use $\phi = \tan^{-1}\left(\frac{\Sigma F_y}{\Sigma F_x}\right)$ to determine the direction.

Solution: The FBDs are shown in **Figure 6** and **Figure 7**.



(a) **(b)**

Figure 6 (a) The FBD shows forces acting on the baseball. (b) Components of the forces in the vertical and horizontal directions.

$$\begin{aligned} F_{ax} &= F\cos\theta \\ &= (14\text{ N})\cos 29° \\ F_{ax} &= 12.2\text{ N} \end{aligned}$$

$$\begin{aligned} \Sigma F_x &= F_{ax} + F_{gx} \\ &= 12.2\text{ N} + 0.0\text{ N} \\ \Sigma F_x &= 12.2\text{ N} \end{aligned}$$

$$\begin{aligned} F_{ay} &= F\sin\theta \\ &= (14\text{ N})\sin 29° \\ F_{ay} &= 6.79\text{ N (one extra digit carried)} \end{aligned}$$

$$\begin{aligned} \Sigma F_y &= F_{ay} + (-F_{gy}) \\ &= 6.79\text{ N} - 1.4\text{ N} \\ \Sigma F_y &= 5.39\text{ N (one extra digit carried)} \end{aligned}$$

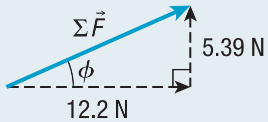


Figure 7 Net force on the baseball

$$\begin{aligned} |\Sigma\vec{F}| &= \sqrt{(\Sigma F_x)^2 + (\Sigma F_y)^2} \\ &= \sqrt{(12.2\text{ N})^2 + (5.39\text{ N})^2} \\ |\Sigma\vec{F}| &= 13\text{ N} \end{aligned}$$

$$\begin{aligned} \phi &= \tan^{-1}\left(\frac{\Sigma F_y}{\Sigma F_x}\right) \\ &= \tan^{-1}\left(\frac{5.39\text{ N}}{12.2\text{ N}}\right) \\ \phi &= 24° \end{aligned}$$

Statement: The net force on the baseball is 13 N at 24° above the horizontal.

Sample Problem 2: Total Force of Friction on a Towed Object

A go-cart is being towed north by a car along a road with a net force of zero. The go-cart is attached to the car by two ropes. The tension in the ropes is the same, 31 N. The ropes make 22° angles to the direction of motion, one on the west side and the other on the east. Determine the force of friction on the go-cart. **Figure 8** shows a top view of the go-cart. The figure does not show the normal force and gravity because they are perpendicular to the page and cancel each other.

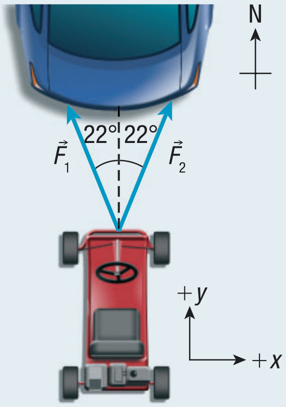


Figure 8

Given: $\Sigma\vec{F} = 0$; $\vec{F}_1 = 31$ N [N 22° W]; $\vec{F}_2 = 31$ N [N 22° E]

Required: force of friction on go-cart, $\vec{F}_K$

Analysis: Draw an FBD. There is no net force on the go-cart, so ΣF_x equals zero and ΣF_y equals zero. The normal force and the force of gravity cancel each other. Use $F_x = F\cos\theta$ and $F_y = F\sin\theta$ to determine the components of the tension forces on the go-cart. To calculate the force of friction on the go-cart, use $\Sigma F_x = F_{1x} + F_{2x} + F_{fx}$ and $\Sigma F_y = F_{1y} + F_{2y} + F_{fy}$. Use north and east as the positive directions when determining components.

Solution: The FBD is shown in **Figure 9**.

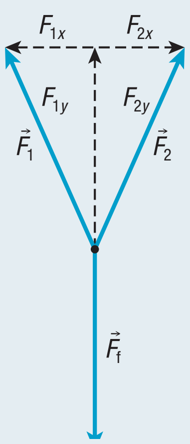


Figure 9

For the x-component of the tension force,

$$\begin{aligned} F_{1x} &= -F_1\cos\theta \\ &= -(31\text{ N})\cos 22^\circ \\ F_{1x} &= -28.7\text{ N (one extra digit carried)} \end{aligned}$$

$$\begin{aligned} F_{2x} &= F_2\cos\theta \\ &= (31\text{ N})\cos 22^\circ \\ F_{2x} &= 28.7\text{ N (one extra digit carried)} \end{aligned}$$

$$\begin{aligned} \Sigma F_x &= F_{1x} + F_{2x} + F_{fx} \\ F_{fx} &= \Sigma F_x - (F_{1x} + F_{2x}) \\ &= 0 - (-28.7\text{ N} + 28.7\text{ N}) \\ F_{fx} &= 0\text{ N} \end{aligned}$$

For the y-component of the tension force,

$$\begin{aligned} F_{1y} &= F_1\sin\theta \\ &= (31\text{ N})\sin 22^\circ \\ F_{1y} &= 11.6\text{ N} \end{aligned}$$

$$\begin{aligned} F_{2y} &= F_2\sin\theta \\ &= (31\text{ N})\sin 22^\circ \\ F_{2y} &= 11.6\text{ N} \end{aligned}$$

$$\begin{aligned} F_{fy} &= \Sigma F_y - (F_{1y} + F_{2y}) \\ &= 0 - 11.6\text{ N} - 11.6\text{ N} \\ F_{fy} &= -23\text{ N} \end{aligned}$$

Statement: The forces of the ropes in the x-direction cancel, so there is no force of friction in that direction. The force of friction is 23 N [S].

Practice

1. Determine the net force acting on each of the following objects. In each case assume that all forces acting on the object are given. K/U T/I
   (a) At an instant when a soccer ball is slightly off the ground, a player kicks it, exerting a force of 25 N at 40.0° above the horizontal. The force of gravity acting on the ball is 4.2 N [down]. [ans: 23 N [32° above the horizontal]]
   (b) Two children pull a sled across the ice. One child pulls with a force of 15 N [N 35° E], and the other pulls with a force of 25 N [N 54° W]. There is negligible friction acting on the sled. [ans: 29 N [N 23° W]]
   (c) In a circus act, a performer with a force of gravity of 4.4×10^2 N on her is lifted by two different ropes at the same time. One rope exerts a tension of 4.3×10^2 N [up and 35° left], and the other rope exerts a force of 2.8×10^2 N [up]. [ans: 3.1×10^2 N [up 38° left]]
2. Two tractors pull a large rock east through a construction site with a net force of zero on the rock. Tractor 1 exerts a force of 1.2×10^4 N [E 12° N] on the rock, and tractor 2 exerts a force of 1.2×10^4 N [E 12° S]. K/U T/I
   (a) Calculate the force of friction acting on the rock. [ans: 2.3×10^4 N [W]]
   (b) Discuss two ways someone could spot that the force of friction on the rock must be to the west before solving the problem.
3. **Figure 10** shows three masses connected by wires and hung vertically. Draw an FBD for each mass, and determine the tensions in the three wires. K/U T/I A [ans: top wire: 3.4×10^2 N; middle wire: 2.0×10^2 N; bottom wire: 1.3×10^2 N]

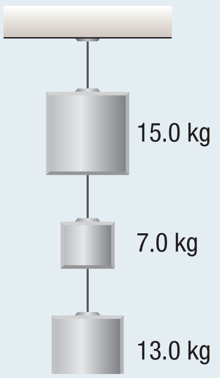


Figure 10

4. At one moment during its flight, a thrown baseball experiences a gravitational force of 1.5 N [down] and a force from air resistance of 0.40 N [32° above the horizontal]. Calculate the magnitude and direction of the net force on the ball. K/U T/I A [ans: 1.3 N [75° below the horizontal]]
5. The force of gravity on a basketball is 16 N [down]. K/U T/I A
   (a) What is the net force on the ball while held stationary in your hand? [ans: 0 N]
   (b) Neglecting air resistance, calculate the net force acting on the ball if you suddenly remove your hand. [ans: 16 N [down]]
   (c) You push the ball with a force of 12 N [right]. Calculate the net force on the ball. [ans: 20 N [right 53° down]]
   (d) You push the ball with a force of 26 N [up 45° right]. Calculate the net force on the ball. [ans: 19 N [right 7.4° up]]

2.1 Review

Summary

- Examples of common forces that you encounter every day are Earth's gravity, the normal force, tension, friction, applied forces, and air resistance.
- Static friction prevents a stationary object from moving, and kinetic friction opposes the motion of an object. Air resistance opposes the motion of an object through air.
- A free-body diagram (FBD) is a simple drawing of an object that shows all forces acting on the object. FBDs can help you visualize the forces, determine the components, and calculate the net force.
- The net force, $\Sigma\vec{F}$, is the sum of all of the forces acting on an object.

Questions

1. Summarize the common forces in a table with the following headings: Name, Symbol, Contact/Non-contact, Direction, Example in daily life. K/U C
2. Study the traction system shown in **Figure 11**. The tension in the vertical cord above the mass is 22 N. A student claims that the tension in the vertical cord above the leg must be more than 22 N. Discuss the validity of this statement. K/U T/I C

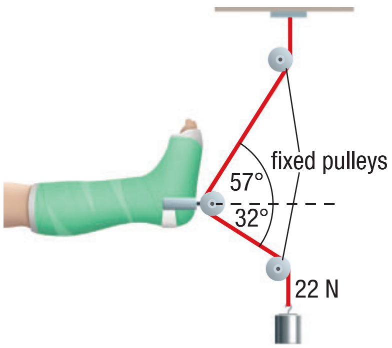


Figure 11

3. Explain why ropes can only pull and never push. K/U
4. You push your textbook at a constant velocity to the right across the table by applying a force at an angle of 23° below the horizontal. K/U T/I C A
   (a) List the forces acting on the textbook.
   (b) Draw an FBD of the textbook.
5. Given the forces $\vec{F}_A$ = 2.3 N [S 35° W], $\vec{F}_B$ = 3.6 N [N 14° W], and $\vec{F}_C$ = 4.2 N [S 24° E], calculate the following:
   (a) $\vec{F}_A + \vec{F}_B + \vec{F}_C$
   (b) $\vec{F}_B - \vec{F}_C$ T/I
6. Given $\vec{F}_A$ = 33 N [E 22° N] and $\vec{F}_B$ = 42 N [S 15° E], calculate the force $\vec{F}_C$ needed so that $\vec{F}_A + \vec{F}_B + \vec{F}_C$ is zero. T/I
7. At the beach, three children pull on a floating toy. Child 1 pulls with a force of 15 N [N 24° E], child 2 pulls south, and child 3 pulls west. The net force on the toy is zero. Assume that there are no other significant forces acting on the toy. T/I
   (a) Calculate the magnitude of the forces exerted by child 2 and child 3 on the toy.
   (b) Child 2 lets go, and the other children maintain the same force. Calculate the net force on the toy.
   (c) What force must child 3 exert on the toy to cancel the force of child 1 on her own?
8. During a competition for charity, two students push horizontally on a heavy cart during a race. The net force on the cart is 180 N [E]. One student pushes with a force of 120 N [E 14° S]. Calculate the force that the second student exerts on the cart. T/I
9. You exert a force of 55 N on a heavy sled as shown in **Figure 12**. The force of gravity acting on the sled is 120 N [down]. The sled does not move across the rough horizontal surface, and the net force is zero. T/I

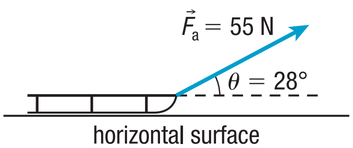


Figure 12

   (a) Draw an FBD of the sled.
   (b) Determine the normal force acting on the sled. Why is the magnitude of the normal force less than the magnitude of the force of gravity? Explain your answer.
   (c) Calculate the force of static friction acting on the sled.