SPH4U-C

Lesson 3

Forces and Motion

Revised August 31, 2016

Introduction

Our society is a society on the move; everything is becoming bigger, faster, and better. Since the first car that Henry Ford built in 1896 and the first flight that the Wright brothers undertook in 1903, transportation vehicles have undergone major transformations. An increased knowledge of force, aerodynamics, friction, and materials technology, much of which is gained through testing done in wind tunnels, has changed both transportation and society. Whereas, in the past, it could take hours for people just to get to the nearest supplier for groceries and necessities, today, people can fly around the world in a matter of hours.

While many of us cannot imagine living without the convenience, freedom, and adventure that modern transportation provides, others argue that this comes at a cost. The amount of air pollution that vehicles produce is one concern that environmentalists and government legislation are dealing with by supporting ideas like vehicle emissions testing and the development of hybrid vehicles and alternative fuels. The rapid rate at which disease can spread is another, newer issue that we must address. On the one hand, a rare disease that could have once been kept isolated and treated in one part of the world can now arrive and spread rapidly—within hours—in another remote country, challenging health officials with threats of pandemics. On the other hand, however, perhaps these risks are worth dealing with when we realize that it is because of modern transportation that, within mere hours, we can provide supplies and humanitarian relief to countries devastated by sudden disaster.

Planning Your Study

You may find this time grid helpful in planning when and how you will work through this lesson.

Suggested Timing for This Lesson (hours)	
Forces	½
Newton's Laws of Motion	½
Net Force	½
Problem Solving with Dynamics	1
A Closer Look at Friction	1
Key Questions	1

What You Will Learn

After completing this lesson, you will be able to

- understand and explain the effect of force on motion
- solve problems involving forces and motion
- identify advantages and disadvantages of friction

Forces

So far, you have been analyzing how objects move. In other words, you have been studying the kinematics of motion. In this lesson, however, the focus shifts to dynamics—the study of forces and why objects move the way they do.

Types of Forces

Objects move the way they do because of forces. A force ($\vec{F}$) is very simply either a push or a pull. It is measured in newtons (N) and is a vector quantity. Take a look now at the types of forces that you'll be working with in this unit.

Gravitational force ($\vec{F}_{\mathrm{g}}$) is the force of attraction that exists between objects. The gravitational force that you will be considering in this lesson is earth's gravitational force on the objects near its surface. For every 1 kg of mass near earth, there is an attractive force of 9.8 N between that mass and the earth, giving the earth a gravitational field strength ($\vec{g}$) of 9.8 N/kg [toward earth]. Therefore, earth's gravitational force is equal to an object's mass, multiplied by earth's gravitational field. In equation form, this is: $\vec{F}_{\mathrm{g}} = m\vec{g}$.

Normal force ($\vec{F}_{\mathrm{N}}$) is a force exerted by one surface onto another. The normal force always acts perpendicular to the surfaces in contact. For example, the surface you are sitting or standing on right now is exerting a normal force on you, keeping you from accelerating toward the earth.

Tension force ($\vec{F}_{\mathrm{T}}$) is the force applied to an object by a rope, cable, and so on, that can be stretched. An important point to remember is that the tension is constant in one continuous string (rope, cable, and so on), even if it goes through pulleys and changes direction.

Force of friction ($\vec{F}_{\mathrm{f}}$) refers to force that resists motion.

Air resistance ($\vec{F}_{\text{air resistance}}$) is a type of "friction" force experienced by objects travelling through air.

Applied force ($\vec{F}_{\mathrm{app}}$) is the force applied by one object onto another by pushing or pulling.

Showing Forces in Free-body Diagrams (FBDs)

To help you visualize and solve problems involving forces, it is necessary to be able to draw free-body diagrams (FBDs). These are diagrams in which the forces acting on an object in a given situation are drawn on the object, free of its surroundings.

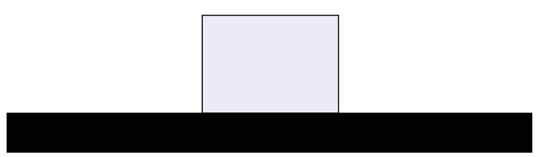
Take note of the following rules, when drawing FBDs:

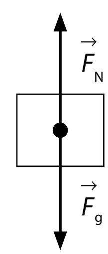
- Sketch the object, free of its surroundings. (Your object can be represented by a simple shape, such as a circle, square, or dot.)
- Draw the applicable force vectors so that their tails originate from a common point and the heads point away from this point in the direction in which the force is pushing or pulling.
- Draw force vectors to represent the magnitudes given. This helps you to visualize the situation and problem-solve. (There is no need to use scale diagrams, unless you are specifically requested to do so.)
- Label all of the forces.
- Establish a positive direction for both the horizontal and vertical planes. If the object is moving, choose the direction of motion to be one of your positive directions. This simplifies the problem solving.
- If there are vectors that do not fall along the designated horizontal and vertical planes, show their vector components.

Example

Here are some examples of FBDs:

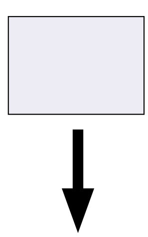
a) A crate sitting on the ground

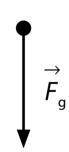




Notice that the force of gravity is acting downward in the direction that the crate would move, if it were not for the ground. The normal force pushes up on the crate, keeping it from falling. Whenever an object is not moving (or is moving at a constant velocity), the forces acting on the object are balanced. (This will be discussed later on, in more detail.)

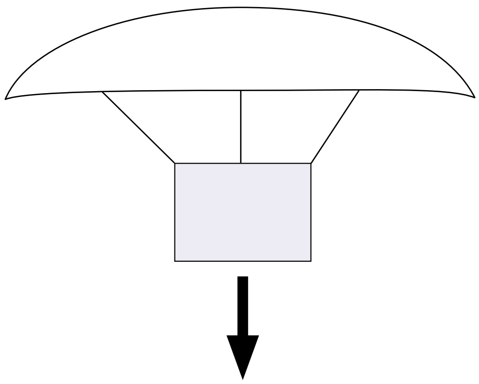
b) A crate just after it has been dropped (experiencing no air resistance)

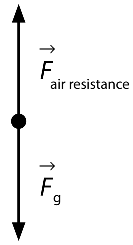




There is no normal force in this situation. The object will fall.

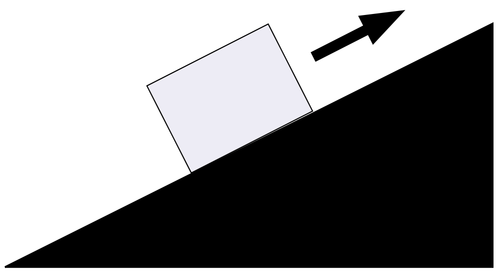
c) A crate with a parachute

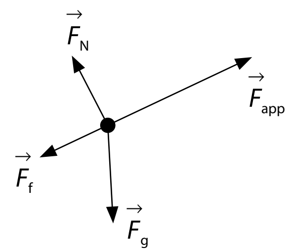




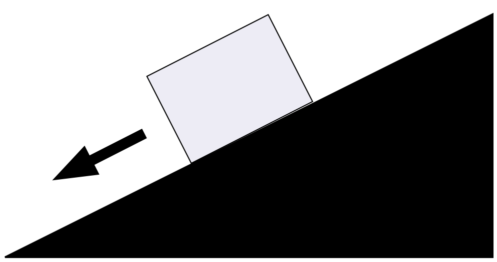
In this situation, there is air resistance. In order to know exactly how the two forces compare in magnitude, you would need a little more information.

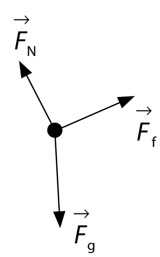
d) A crate being pushed up a ramp





e) A crate sliding down a ramp





Support Questions

Be sure to try the Support Questions on your own before looking at the suggested answers provided. Click on each "Suggested answer" button to check your work.

16. Draw FBDs to show the forces acting on each of the following:

a) A car parked on level ground

b) A car parked on a downward slope

c) A car skidding to a stop on a downward slope

d) A car in mid-air, after attempting a jump

Suggested answer

Newton's Laws of Motion

The real breakthrough in explaining forces was made by Sir Isaac Newton (1643–1727). He developed three elegant laws that can explain all motion on earth as well as explaining planetary motion around the sun!

You will begin this section by looking at the physics of seatbelts and how they can protect us from serious injury.

Newton's First Law of Motion

Have you ever been riding along in a vehicle when, for some reason, it comes to a sudden stop? If so, you probably felt yourself continuing to move forward, even though the car was stopping. Without a seat belt, you may even have been hurt, or at least a little startled. What is going on in a situation like this can be explained with Newton's first law of motion, which states:

> *An object at rest tends to stay at rest and an object in motion tends to stay in motion with the same speed and in the same direction, unless acted on by an unbalanced force.*

Example

Try this: put a piece of paper on a flat surface. Put something on top of the paper, for example, a book, pen, or calculator. Now, try to pull the piece of paper out from under the object, without moving the object. Can you do it? Try this again, using a heavier or lighter object. Which object is easier to keep stationary?

Solution

According to Newton's first law, the object sitting on the paper is at rest, and will tend to stay at rest unless it is forced to move. Usually, as long as the friction between the paper and the object is negligible, a heavier object is easier to use, when trying this. The tendency of mass to resist changes in motion is called inertia, and the more mass an object has, the more inertia it has, and the greater its tendency is to resist changes in motion. Newton's first law is also commonly known as the law of inertia.

Support Questions

17. A child is coasting on his bicycle, when the bicycle collides with a fence. Using Newton's first law, explain what will likely happen to the child. Suggested answer

Newton's Second Law of Motion

Imagine, again, that you are trying to pull a child on a sled. You are just starting to pull her along, picking up speed, when another child jumps onto the sled. If you don't change how hard you are pulling the sled, you're going to speed up at a much slower rate. To speed up more quickly, you will have to pull harder.

The physics of this situation can be explained with Newton's second law of motion, which states:

> *The acceleration of an object is directly proportional to the net force applied to the object and inversely proportional to the mass of the object.*

This relationship is often stated in equation form, as follows:

$$\vec{F}_{\text{net}} = m\vec{a}$$

Note: This is one of the most important equations in physics. Remembering and understanding it is essential.

Example

A 0.20 kg soccer ball experiences an acceleration of 25 m/s^2 [forward], when it is kicked. What is the net force of the soccer player's foot on the ball?

Solution

Given:

$m = 0.20$ kg

$\vec{a} = 25\ \text{m/s}^2$ [forward]

Required: $\vec{F}_{\text{net}}$

Analysis and solution:

Let forward be the positive direction.

$$F_{\text{net}} = ma$$
$$F_{\text{net}} = (0.20\ \text{kg})(25\ \text{m/s}^2)$$
$$F_{\text{net}} = 5.0\ \text{N}$$

Paraphrase: The net force of the soccer player's foot on the ball is 5.0 N [forward].

Support Questions

18. Use Newton's second law to explain why two objects that appear identical from the outside do not travel the same distance when the same amount of force is applied to them. Suggested answer

19. During a slapshot, 55 N of force is exerted on a 0.15 kg hockey puck. Neglecting (ignoring) friction, what will the puck's acceleration be? Suggested answer

Newton's Third Law of Motion

Go back to the sledding example once more. Imagine that you are pulling a child on a sled by pulling on a rope that the child is holding. You are exerting a force of 50 N [forward]. What force must the child be exerting on the rope, in order to hold on?

The answer, of course, must be 50 N [backward]. This can be explained with Newton's third law of motion, which states:

> *For every force exerted by one object onto a second object, there is a force exerted by the second object onto the first object that is equal in magnitude and opposite in direction. These forces are often referred to as action/reaction forces.*

For example:

- If you exert a force of 5 N [left] on a door handle, it exerts a reaction force of 5 N [right] on you.
- If the earth exerts a gravitational force of 630 N [down] on a man, there is a reaction force of 630 N [up] on the earth.
- If a mover pushes a box along the floor with a force of 25 N [east], the reaction force is the force of 25 N [west] exerted by the box on the mover.

Example

Henry is busy pulling things. Figure out the action-reaction pairs in the following examples, and determine the magnitude of tension in the rope.

a) Henry is pulling on a rope connected to a wall with a force of 100 N [left].

b) Henry is pulling on a rope connected to a dog with a force of 100 N [left] and the dog is pulling on the rope with a force of 100 N [right].

c) Henry is using a rope with a force of 100 N [forward] to get a wagon moving.

Solution

a) The action force: Henry exerts a force of 100 N [left] on the wall.

The reaction force: The wall exerts a force of 100 N [right] on Henry.

The tension throughout the rope will be 100 N.

b) The action force: Henry exerts a force of 100 N [left] on the dog.

The reaction force: The dog exerts a force of 100 N [right] on Henry.

The tension in the rope is 100 N. (This situation is no different to the situation in (a), except for the fact that the rope is connected to a dog instead of a wall.)

c) The action force: Henry exerts a force of 100 N [forward] on the wagon.

The reaction force: The wagon exerts a force of 100 N [back] on Henry.

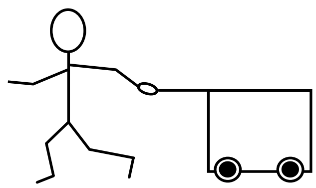
The tension in the rope is 100 N.

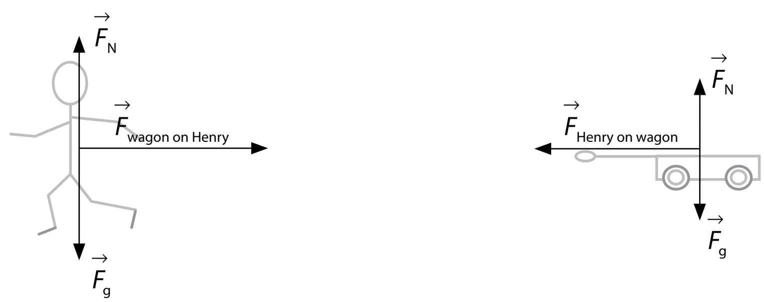
A Second Look at Newton's Third Law

Consider the last example with Henry and the wagon. According to Newton's third law, the magnitude of the force of Henry on the wagon is equal to the magnitude of the force of the wagon on Henry, but these forces are opposite in direction. How is it possible, then, that Henry is able to get the wagon moving? Don't equal and opposite forces mean that the net force is zero and the object will not accelerate?

Yes, *if* the forces were acting on the same object. Action-reaction pairs are equal and opposite, but they do not add together to get a net force of zero because they are *not* acting on the same object!

The action force, in the case of Henry and the wagon, is the force of Henry on the wagon. This force would be included if you were to draw an FBD of the wagon. It would not appear if you were to draw an FBD of Henry. It is the force of the wagon on Henry that would appear in this FBD. Very simply, Henry and the wagon are moving forward because they can move with a forward force that is great enough to overcome friction.





Support Questions

20. A book is lying on a table. State two sets of action-reaction forces associated with the book.

Suggested answer

21. Imagine that you are shown a heavy crate that you must pull to a finish line, using a rope. However, you are told that you must exert a force forwards on the crate and that the crate will exert an equal force backward on you. Before you get to pull the crate to the finish line, you must explain how you will deal with these equal, but opposite forces.

Suggested answer

Problem Solving with Dynamics

In this section, you will be presented with a set of examples that cover the main types of problems typically encountered. Situations and details will vary, but if you understand the techniques you use in this section, you will be equipped with the skills to deal with any problem.

Steps for Solving Dynamics Problems

Because problems involving dynamics can be complex, it is useful to have a systematic approach to solving them. Here are some suggested steps to follow:

1. **Read carefully to clearly understand the situation.** This is the most important step. Some of these problems require a lot of work and multiple calculations to solve. It is very frustrating to be nearing the end, only to realize that you misunderstood something at the very beginning.
2. **State the given and required information.** Stating the information given in a problem will often give you insight into what you need to do to solve the problem. A sketch of the situation helps, since being able to visualize the situation is often necessary. Some important things to watch out for are:
    - **Acceleration:** If acceleration is present, there is a net force, and you will most likely need to use Newton's second law.
    - **Constant velocity:** Constant velocity means that there is no acceleration. Therefore, the net force is zero and you have a balanced-force situation.
    - **A stationary object:** If the object is not moving, the velocity stays at zero, which means that there is no acceleration. Therefore, again the net force is zero and you have a balanced-force situation.
    - **Friction:** Is it present or is it negligible?
    - **Angles:** Be prepared to find the components.
3. **Construct FBDs.** This will be your analysis of the situation—the actual problem-solving part. To keep this analysis as straightforward as possible, choose a positive direction for the direction of acceleration (or motion, if there is no acceleration).
4. **Use $\vec{F}_{\text{net}} = m\vec{a}$.** If the problem is two-dimensional, use the second law, with components. If the acceleration is zero, this means that the sum of your forces will be zero. Regardless of the question, think about $\vec{F}_{\text{net}} = m\vec{a}$.

Net Force

Picture yourself trying to pull a child on a sled. Now, picture trying to pull the sled while someone else is pulling it in the opposite direction, and then imagine that this whole experiment is happening on a hill. The rides that the child will experience will likely vary, depending on the pushes and pulls involved.

It is not simply individual forces that determine the motion of an object, but rather the net (or total) effect of all of these forces acting together. Therefore, before you go on to solve problems involving forces and motion you must be able to add forces together to get the net force.

$\vec{F}_{\text{net}} = \vec{F}_1 + \vec{F}_2 + \vec{F}_3 \ ...$

This can also be written $\vec{F}_{\text{net}} = \sum_{i=1}^{n} (F_i)$

Calculating Net Force with Collinear Vectors

When forces are collinear, determining the net force comes down to simply adding or subtracting the individual forces based on their directions. Here are some examples.

Example 1

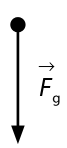
If the mass of a brick in free fall is 1.0 kg, determine the net force acting on the brick in the absence of air resistance.

Solution

Given: $m = 1.0$ kg

Required: $\vec{F}_{\text{net}}$

Analysis and solution: To be able to analyze a problem involving forces, an FBD is often necessary.



Let [down] be the positive direction.

$F_{net} = F_g$

$F_g = mg$ so

$F_{net} = mg$

$F_{net} = (1.0 \text{ kg})(9.8 \text{ N/kg})$

$F_{net} = 9.8 \text{ N}$

Paraphrase: The net force acting on the brick is 9.8 N.

Since the value is positive, the net force is downward.

Example 2

If the 1.0 kg brick is falling and experiencing a force of magnitude 2.0 N due to air resistance, what is the net force on the brick?

Solution

Given:

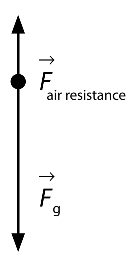
$m = 1.0 \text{ kg}$

$\vec{F}_{\text{air resistance}} = 2.0 \text{ N [up]}$

Note that you know the direction of the force due to air resistance because it opposes the downward motion.

Required: $\vec{F}_{net}$

Analysis and solution:



Let [down] be the positive direction.

$F_{net} = F_g - F_{\text{air resistance}}$

$F_{net} = 9.8 \text{ N} - 2.0 \text{ N}$

$F_{net} = 7.8 \text{ N}$

Paraphrase: The net force acting on the brick is 7.8 N.

Again, a positive answer indicates the net force is acting downward.

Calculating Net Force with Non-collinear Vectors

This is where things get more complicated because of angles. Important points to remember when dealing with angles are:

- When vectors are non-collinear, you must choose positive horizontal (x) and vertical (y) directions. In cases where inclined planes are involved, you must tilt the usual x-y orientation to match the physical geometry of the situation (as some of the following examples will show).
- The problem will be easier to solve if you choose the direction of motion or acceleration to be positive.
- Once you set your positive directions and establish the axes, any forces that do not fall along the axes must be resolved into components. These forces, broken into components, along with forces that lie along the axes, are put on your working FBD.
- Then create F_{net} statements for each direction. Remember that F_{net} can be replaced with ma when solving for acceleration.

Example 1: Working with Angles

A 15.0 kg suitcase, laid flat on the ground, is being pulled along a level floor with a force of 25 N applied to a rope that makes an angle of 40° with the horizontal. If the force of friction has a magnitude of 5.0 N, what is the acceleration of the suitcase? What is the normal force on the suitcase?

Solution

Given:

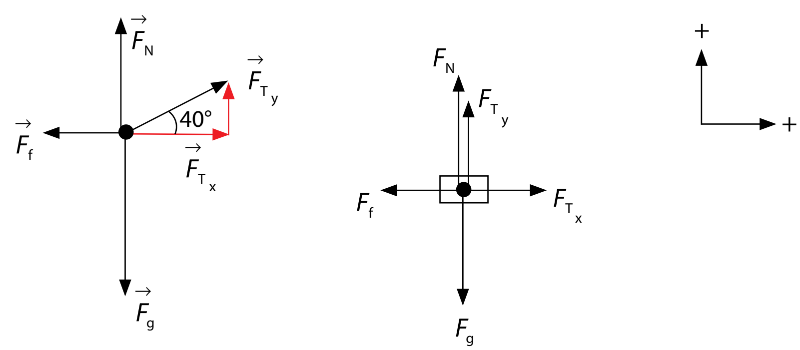
$m = 15.0$ kg

$\vec{F}_T = 25$ N [40° above horizontal]

$\vec{F}_f = 5$ N [back]

Required: $\vec{a}$ and $\vec{F}_N$

Analysis and solution:



To determine the acceleration of the suitcase, you need to know the net force on the suitcase. Analyzing the forces in the direction of motion, you get:

$$F_{net_x} = F_{T_x} - F_f$$
$$F_{net_x} = (25\text{ N})\cos 40 - 5\text{ N}$$
$$F_{net_x} = 14\text{ N}$$

Applying Newton's second law of motion:

$$F_{net_x} = ma_x$$
$$14.1\text{ N} = (15\text{ kg})a_x$$
$$a_x = \frac{14.1\text{ N}}{15\text{ kg}}$$
$$a_x = 0.94\text{ m/s}^2$$

To determine the normal force on the suitcase, you must consider the net force in the vertical direction. Because there is no motion in the vertical direction, you know that the net force is zero.

$$F_{net_y} = ma_y = 0\text{ N}$$
$$F_{net_y} = F_{N_y} + F_{T_y} - F_g$$
$$0\text{ N} = F_N + F_T(\sin 40) - mg$$
$$-F_N = (25\text{ N})(\sin 40) - (15\text{ kg})(9.8\text{ N/kg})$$
$$-F_N = -127.8\text{ N}$$

Because of significant digits, $F_N = 130$ N.

Paraphrase: Therefore, the acceleration of the suitcase is 0.94 m/s^2 [forward] and the normal force on the suitcase is 130 N [up].

Example 2: Inclined Planes

If the 1.0 kg brick now slides down an inclined plane that makes an angle of 30° with the horizontal ground, and the force of friction acting on the brick has a magnitude of 1.5 N, what is the net force on the brick?

Solution

Given:

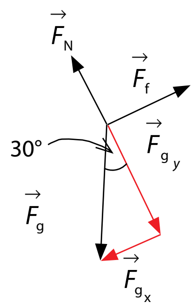
$m = 1.0$ kg

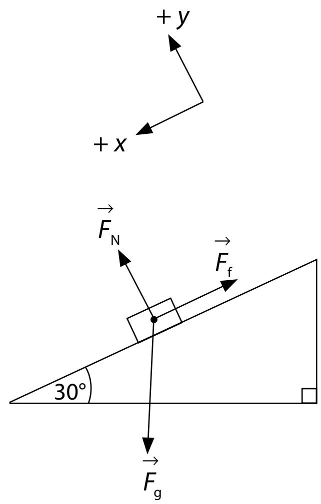
$\theta = 30°$

$\vec{F}_f = 1.5$ N [up the ramp]

Required: $\vec{F}_{net}$

Analysis and solution:





The motion in this situation is down the inclined plane, so this was chosen as the designated positive x-direction. Sometimes, this is called the parallel direction, and is designated by two vertical lines: | |.

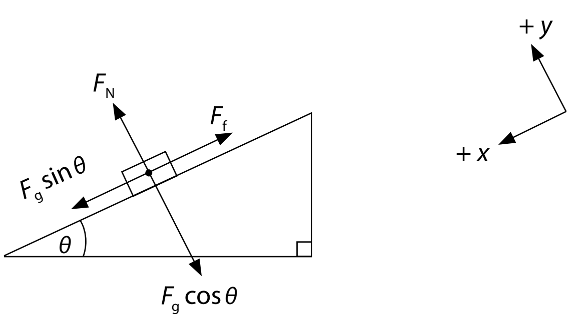
Considering only the forces affecting the motion along the ramp, that is, along the x-direction, and down the ramp is designated as positive:

$F_{net} = F_{g_x} - F_f$

All of the other forces cancel one another out.

You can use the sin function to determine the x-component because F_{g_x} is the component of $\vec{F}_g$, which is opposite the known angle. You can prove that this angle is equal to the angle that the ramp makes with the horizontal through some simple geometry.

When dealing with inclined planes (ramps), it is usual to specify the ramp angle relative to the horizontal. In this case, the component of gravity along the ramp is $F_g\sin\theta$, and it is $F_g\cos\theta$ perpendicular to the surface of the ramp. Remember that $F_g = mg$.



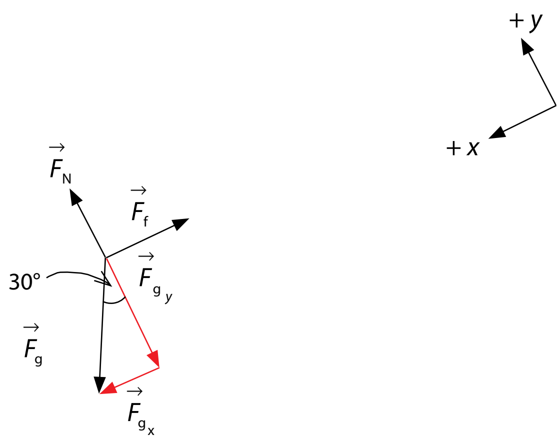
$$F_{net} = (mg\sin\theta) - 1.5\text{ N}$$
$$F_{net} = (1.0\text{ kg})(9.8\text{ N/kg})(\sin 30°) - 1.5\text{ N}$$
$$F_{net} = 3.4\text{ N}$$

Paraphrase: The net force acting on the brick is 3.4 N. Once again, because the answer is positive, the net force is acting down the ramp.

Example 3: Normal Force

Sometimes it will be necessary to know the normal force in a situation that involves an inclined plane, as in example 1 (the previous example). What is the value of the normal force in the previous example (1.0 kg brick, 30° angle of incline)?

Solution



All of the motion is occurring along the designated *x*-axis, in this situation. When there is no movement along the *y*-axis, this means that there must be no net push or pull in this direction, and that the net force along the *y*-axis is 0 N.

$$F_{net_y} = F_N - F_{g_y}$$

$$0 \text{ N} = F_N - (mg\cos\theta)$$

$$F_N = mg\cos\theta$$

$$F_N = (1.0 \text{ kg})(9.8 \text{ N/kg})(\cos 30°)$$

$$F_N = 8.5 \text{ N}$$

Therefore, the normal force has a magnitude of 8.5 N.

Support Questions

22. Determine the net force acting on the following objects:

a) A 0.50 kg physics book lying on a flat desk

b) A 0.50 kg physics book that is falling, just after being dropped (There is negligible air resistance.)

c) A 0.50 kg physics book that is being pushed across a desk with a force of 4.0 N and is experiencing a force of friction with a magnitude of 1.0 N

d) A 0.50 kg physics book that is being pulled up an inclined plane that makes an angle of 40° with the horizontal. A force of 6.0 N is being exerted on a string connected to the book to pull it, and the book is experiencing a frictional force of 1.0 N.

Suggested answer

23. A 136 kg piano is at the top of a ramp that makes an angle of 35° with level ground. As the piano slides down the ramp, it experiences a force of friction of 125 N. What is the acceleration of the piano down the ramp? Suggested answer

Example 4: Normal Force and Apparent Weight

Have you ever experienced the feeling of being in an elevator as it quickly accelerates from a rest position to move upwards? Do you remember feeling "heavier" for an instant? Or likewise, have you ever experienced a free-fall situation on an amusement-park ride when, momentarily, you felt "weightless"? You may even have felt this same sensation when riding quickly over the crest of a hill in a car or on a bicycle.

This sensation of "apparent weight" is the weight that you "feel" in a situation. It is actually based on the normal force exerted back on you by the surface on which you are standing. If you are standing on a stable, level floor or ground, the normal force exerted on you is equal to your force of gravity (that is, your weight). If you aren't standing on anything, there is no normal force, and you feel "weightless." If the surface you are on is accelerating you upward, the normal force on you is greater than your weight, so you will feel "heavier."

Assuming that your mass is 50.0 kg, determine the normal force (that is, the apparent weight) you would experience when you are standing in an elevator that is

a) at rest.

b) accelerating upward at a rate of 1.0 m/s^2.

c) moving upward at a constant speed.

d) accelerating downward at a rate of 1.0 m/s^2.

Solution

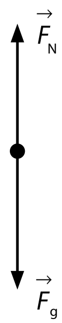
a) Given:

$m = 50\ \text{kg}$
$v = 0\ \text{m/s}$

Required: F_N

Analysis and solution: Let [up] be positive.

FBD:



Given that there is no acceleration, the net force on you is 0 N. Therefore, the forces are balanced and the normal force will be equal to the force of gravity.

$$
\begin{aligned}
F_{net} &= F_N - F_g \\
0 &= F_N - mg \\
F_N &= mg \\
F_N &= (50.0\ \text{kg})(9.8\ \text{N/kg}) \\
F_N &= 490\ \text{N}
\end{aligned}
$$

Paraphrase: Therefore, the magnitude of the normal force is equal to the magnitude of the force of gravity when the elevator is at rest.

b) Given:

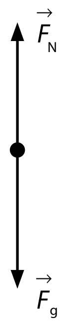
$m = 50\ \text{kg}$

$\vec{a} = 1.0\ \text{m/s}^2\ [\text{up}]$

Required: $\vec{F}_N$

Analysis and solution: Let [up] be positive.

FBD:



$$F_{net} = F_N - F_g$$
$$ma = F_N - mg$$
$$(50.0 \text{ kg})(1.0 \text{ m/s}^2) = F_N - 490 \text{ N}$$
$$F_N = 540 \text{ N}$$

Paraphrase: Therefore, the magnitude of the normal force is 540 N, when the elevator is accelerating upwards at 1.0 m/s^2.

Notice that the person apparently weighs more than their inertial or stationary weight. Next time you are accelerating up on a thrill ride, remember the feeling of being pressed down or feeling heavier!

c) Given:

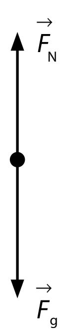
Let [up] be positive.

$m = 50$ kg
$a = 0$ m/s

Required: F_N

Analysis and solution:

FBD:



Given that there is no acceleration, the net force on you is 0 N. Therefore, the forces are balanced and the normal force will be equal to the force of gravity, just as it was in (a).

Paraphrase: Therefore, the normal force is equal to 490 N, when the elevator is moving at constant speed.

d) Given:

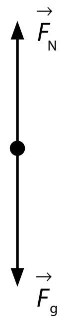
$m = 50$ kg

$\vec{a} = 1.0$ m/s^2 [down]

Required: $\vec{F}_N$

Analysis and solution: Let [down] be positive.

FBD:



$F_{net} = F_g - F_N$

$ma = mg - F_N$

$(50.0 \text{ kg})(1.0 \text{ m/s}^2) = (50.0 \text{ kg})(9.8 \text{ N/kg}) - F_N$

$F_N = 490 \text{ N} - 50.0 \text{ N}$

$= 440 \text{ N}$

Paraphrase: Therefore, the magnitude of the normal force is 440 N, when the elevator is accelerating downward at 1.0 m/s^2. Notice in this case that your apparent weight is less than your inertial weight. You actually feel lighter, like when you are dropping on a thrill ride.

Support Questions

24. A person weighing 45.0 kg is in an elevator, standing on a scale.

a) What will the reading on the scale be when the elevator is moving upward at constant velocity?

b) What will the reading on the scale be when the elevator is moving upward and, approaching the desired floor, slows down at a rate of 2.0 m/s^2?

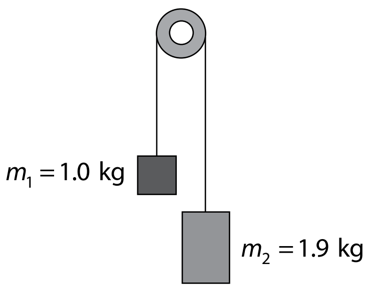
Suggested answer

Example 5: Tension and Connected Objects

The following diagram is of an Atwood machine, which is a machine consisting of two masses: a massless string, and a frictionless pulley. Due to the unequal masses on either end of the string, the system of masses will accelerate. Determine the acceleration of these masses, as well as the tension in the string.

Solution

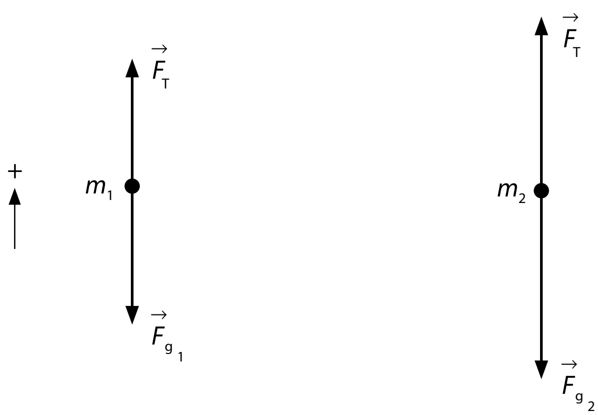
Given: m_1 = 1.0 kg and m_2 = 1.9 kg



Required: $\vec{a}$ and $\vec{F}_T$

Analysis and solution:

FBDs:



Let the direction of acceleration be the positive direction (that is, up on the left and down on the right).

For m_1: $F_{net} = F_T - F_g$ $m_1a = F_T - mg$ $(1.0 \text{ kg})a = F_T - (1.0 \text{ kg})(9.8 \text{ N/kg})$ We can ignore units temporarily for ease of calculation. $1.0a = F_T - 9.8$	For m_2: $F_{net} = F_{g_2} - F_T$ $m_2a = m_2g - F_T$ $1.9a = 18.6 - F_T$ Again, we leave units out for ease of calculation.

Notice that there are two unknowns in each of the equations. Acceleration will be the same for both objects, since they are connected. The magnitude of tension is also equal throughout the string. Therefore, to solve for acceleration, you can solve for F_T in each equation, then equate them.

$F_T = 1.0a + 9.8$ and $F_T = 18.6 - 1.9a$

Equate them and solve for a:

$18.6 - 1.9a = 1.0a + 9.8$

$2.9a = 8.8$

$a = 3.03$, which rounds to 3.0 m/s^2

Now, you can use either of the above equations to determine the force of tension in the string. Using equation 1:

$$(1.0 \text{ kg})a = F_T - 9.8 \text{ N}$$
$$(1.0 \text{ kg})(3.0 \text{ m/s}^2) = F_T - 9.8 \text{ N}$$
$$F_T = 3.0 \text{ N} + 9.8 \text{ N}$$
$$F_T = 12.8 \text{ N} = 13 \text{ N}$$

Paraphrase: Therefore, the acceleration of the system is 3.0 m/s^2 and the tension in the string is 13 N.

Extra note: In solving two equations with two unknowns, you also could have solved for one variable, then substituted the expression into the other equation. Thus,

$F_T = 1.0a + 9.8$

would get substituted into

$1.9a = 18.6 - F_T$

to become

$1.9a = 18.6 - (1.0a + 9.8)$

Then you would rearrange and solve for the acceleration.

Support Questions

25. A 3.0 kg cart on a table is connected to a string that hangs over a pulley suspending a 2.0 kg block over the side of the table. Determine the acceleration of the system, as well as the tension in the string.

Suggested answer

A Closer Look at Friction

Would it be more difficult to pull a sled across mud or snow? Are tires more effective on asphalt or ice? The answers to these questions are obvious, and the reasons behind them are due to the physics of friction. Although you have been considering friction to some extent as you have been working through this lesson, it is now time to take a closer look.

Static Friction

Static friction is the force of friction that acts on an object when it is stationary, preventing its motion. Consider the following example:

If you push on a box with an applied force of 5.0 N and the box does not move, what must the force of static friction be? Obviously, to maintain a net force of 0 N, the force of static friction must be 5.0 N in the opposite direction. If you then decide to push with an applied force of 10.0 N and the box still does not move, the force of static friction must now be 10.0 N [back]. Eventually, though, if you push hard enough, the box will move forward because you will surpass what is known as the *limiting static friction* (that is, the maximum force of static friction possible between the box and the floor).

The value of the limiting static friction is determined by the coefficient of static friction (μ_s)—a constant value unique to any surfaces, and the amount the two surfaces press against each other. This is actually the normal force. Thus $F_f = \mu_s F_N$.

Example

A wooden box with a mass of 40.0 kg sits on a wooden floor. Calculate the applied force necessary to get this box moving, if the coefficient of static friction is 0.35.

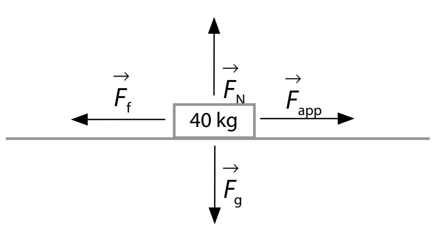
Solution

Given:

$m = 40$ kg

$\mu_s = 0.35$

Required: $\vec{F}_{app}$ necessary to get the box moving



First you find F_N.

Let up be the positive direction.

$F_{net_y} = F_N - F_g$

but $F_{net} = 0$ as it is not moving up or down.

$0 = F_N - F_g$

$F_N = mg$

$F_N = (40\ \text{kg})(9.8\ \text{N/kg})$

$= 392\ \text{N}$

Now find the force of friction.

$F_f = \mu F_N$

$= (0.35)(392\ \text{N})$

137.2 N

Now find F_{net} in the direction of the motion.

Let forward be the positive direction.

$F_{net} = F_{app} - F_f$

In order to get the box moving, we will assume $a = 0$ as it is just about to start.

$0 = F_{app} - F_f$

$F_{app} = F_f$

$=137.2\ \text{N}$

Rounded off to two significant digits, the answer becomes 140 N.

Paraphrase: Therefore, the applied force must be just greater than 140 N.

Activity: Forces and Motion

Open this simulation called Forces and Motion and familiarize yourself with the program. It has four tabs called *Introduction*, *Friction*, *Force Graphs* and *Robot Moving Company*.

Try various options and become comfortable with all the features.

Part A

Select the *Introduction* tab.

1. Set the surface to ice (no friction). Push the object and observe the motion. Is it accelerating? What happens if you push the object and then release it so no applied force is used? Suggested answer
2. Set the surface to wood. Push the object and observe the motion. Is it accelerating? What happens if you push the object and then release it so no applied force is used? Suggested answer
3. Increase the value of μ_s. How does it affect the force required to move the object? Suggested answer
4. Increase the value of μ_k. How does it affect the motion after you release the applied force? Does it affect the value of the applied force required to keep the object moving? Suggested answer

Try different situations. Change the Walls option to bouncy and repeat the steps. Observe the motion in terms of speed, acceleration, and distance travelled.

Part B

Select the *Friction* tab.

1. Calculate the amount of friction required to start the object (static friction) and to keep it moving (kinetic friction). Check the value using the program. Suggested answer
2. What effect does changing the mass have on the motion? Suggested answer
3. What effect does changing the celestial object you are on (Jupiter or the moon) have on the amount of force required to start the object? Suggested answer

Part C (Optional)

Select the *Robot Moving Company* tab. Try and accumulate the most energy points you can.

Support Questions

26. In trying to compare the coefficient of static friction of her running shoes, a physics-minded athlete carries out an investigation. She puts her shoe on a flat board and slowly raises the board until the shoe slides. When the shoe starts sliding, she records the angle of the incline. Upon repeating the procedure several times and taking the average value, she determines that the angle the board makes with the ground is 30°, when the shoe begins to slide. Calculate the shoe's coefficient of static friction.

Suggested answer

Kinetic Friction

Kinetic friction is the force of friction that resists the motion of an object already in motion. Just as with static friction, the magnitude of the force of kinetic friction is determined by the coefficient of kinetic friction (μ_k) and is a constant value unique to any two surfaces in contact. The coefficient of kinetic friction is equal to the ratio of the magnitudes of the force of kinetic friction and normal force.

Example

The coefficient of kinetic friction between a sled and snow is 0.10. What is the force you are exerting if you are pulling a child (with a combined mass of 45.0 kg) up a 9° slope on a sled, at a constant velocity?

Solution

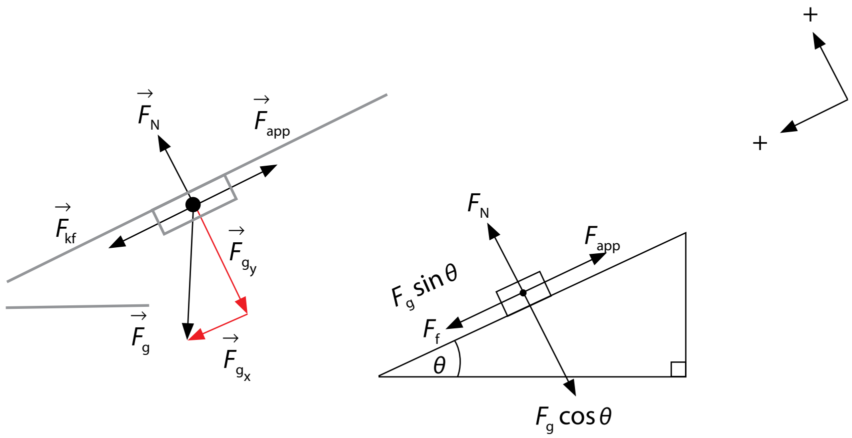
Given:

$\mu_k = 0.10$

$\theta = 9°$ constant velocity, therefore $\vec{a} = 0$ m/s.

Required: $\vec{F}_{app}$

Analysis and solution: Since $\vec{a} = 0\ \text{m/s}^2$, $\vec{F}_{net} = 0$ N. This means that the sum of the forces along the incline must be 0 N.



We need to find F_N first. Checking the component FBD,

$F_{net} = F_N - mg\cos\theta$

but it is not moving in or out of the surface, so

$F_{net} = 0$

Thus, $F_N = mg\cos\theta$

So $F_f = \mu mg\cos\theta$

In the other direction,

$F_{net} = F_{app} - mg\sin\theta - F_f$

Since the object is moving at a constant speed, the acceleration must be zero.

$0 = F_{app} - mg\sin\theta - \mu mg\cos\theta$

$F_{app} = (45\text{ kg})(9.8\text{ N/kg})\sin\theta + (0.10)(45\text{ kg})(9.8\text{ N/kg})\cos\theta$

$F_{app} = 68.99\text{ N} + 43.56\text{ N}$

$= 112.55\text{ N}$

Rounded to two significant digits, the answer becomes 110 N.

Paraphrase: The applied force must be 110 N in order to pull the sled at a constant velocity.

Support Questions

27. Now, to determine the coefficient of kinetic friction of her shoe, the athlete determines the angle of the board at which the shoe slides down the incline with a relatively constant velocity. After repeated trials, she determines that this happens at an angle of 26°. Calculate the shoe's coefficient of kinetic friction.

Suggested answer

Activity: Ramp Forces and Motion

Open this simulation called Ramp: Forces and Motion and familiarize yourself with the program. Like the previous simulation, it has four tabs called *Introduction*, *Friction*, *Force Graphs*, and *Robot Moving Company*. Try various options and become comfortable with all the features.

Part A

Select the *Introduction* tab.

1. Set the surface to ice (no friction). Check the Sum of Forces box. Set the angle of the ramp to about 10°. Give the object a push and release. Observe the motion. Describe what you see. Why is the sum of the forces zero on the flat section, and pointing down the ramp when the object is on the ramp? What force(s) are causing the object to slow down, stop, and then speed up on the ramp? Suggested answer
2. Apply a force and keep applying it, forcing the object to the wall. Observe the extra force going down the ramp. What force is this? Now balance the object on the ramp. Use only the applied force to hold it there. What force(s) are you counteracting? Suggested answer
3. Set the surface to wood. Choose the object to be a filing cabinet, set the ramp angle to about 10°, and push with a force of about 700 N. Make the push an instantaneous one (so the cabinet slides freely). Why doesn't the object come back? Suggested answer
4. Now increase the angle of the ramp. What happens to the motion of the cabinet? Suggested answer
5. Apply a constant force to the cabinet and pin it against the wall at the top of the ramp. What forces are acting down the ramp? Suggested answer
6. Apply a force up the ramp in such a way that the object does not move. What forces are in balance? Suggested answer

Try different situations. Experiment with different coefficients of friction, ramp angles and objects.

Part B

Select the *Friction* tab.

1. Calculate the amount of friction required to start the object (static friction) and to keep it moving (kinetic friction). Check the value using the program. Suggested answer
2. Calculate the amount of friction on the ramp. Account for the action of the object on the ramp. Suggested answer
3. What effect does changing the mass have on the motion? Suggested answer
4. What effect does changing the celestial object you are on (Jupiter or the moon) have on the amount of force required to start the object? Suggested answer

Part C (Optional)

Select the *Robot Moving Company* tab. Try and accumulate the most energy points you can.

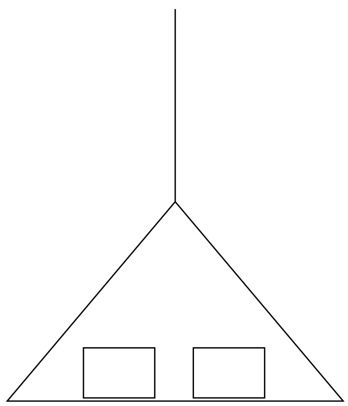
Key Questions

Now work on your Key Questions in the online submission tool. You may continue to work at this task over several sessions, but be sure to save your work each time. When you have answered all the unit's Key Questions, submit your work to the ILC.

(27 marks)

8. If an object is in motion, does that mean that the object has a net force in the direction of that motion? Explain. **(2 marks)**

9. At a construction site, a small crane is raising two boxes of nails on a plank to the roof. One box has already been opened and is half full, while the other box is new. The boxes, including the nails, weigh 10 kg and 20 kg, respectively, and are the same size.



a) As the plank tilts towards the heavier box, predict which box of nails will start to slide first. Explain your prediction. **(1 mark)**

b) If the coefficient of static friction is 0.4, draw an FBD for each box of nails and use it to calculate the angle at which each box begins to slide. **(6 marks)**

c) If the coefficient of kinetic friction is 0.3, how fast will the boxes accelerate along the plank, once they start to slide? **(5 marks)**

10. Design a simple experiment that you could carry out in your home to

i) determine the coefficient of static friction between an object and a surface.

ii) prove that the coefficient of static friction is dependent only on the surfaces in contact, and is not affected by any change in the mass of your object.

(**Hint:** You might want to look back at the last couple of Support Questions in this lesson, to help you.)

a) Describe your plan. It must include a list of materials, a diagram of the set-up, and an explanation of the steps you would take and the data you would collect. **(5 marks)**

b) Explain how you would analyze the collected data to determine the coefficient of static friction and prove that it is unaffected by any change in the mass of your object. **(2 marks)**

c) State one possible source of error that you might encounter in this experiment and state the steps you took to minimize or eliminate this source of error. **(1 mark)**

11. Efficient and safe transportation depends on friction being either minimized or maximized, as necessary.

Using research, find

a) one example in which friction is maximized to aid in transportation. **(2 marks)**

b) one example in which friction is minimized to aid in transportation. **(2 marks)**

For each situation, explain how the friction is maximized/minimized and why this is necessary or beneficial.

c) Give at least one source that you used for your research. **(1 mark)**

Save your answers to the Key Questions in the online submission tool. You'll be able to submit them when you've finished all of the Key Questions for this unit. Now go on to Lesson 4!