5.0 - Introduction

Objects can speed up, slow down, and change direction while they move. In short, they accelerate.

A famous scientist, Sir Isaac Newton, wondered how and why this occurs. Theories about acceleration existed, but Newton did not find them very convincing. His skepticism led him to some of the most important discoveries in physics.

Before Newton, people who studied motion noted that the objects they observed on Earth always slowed down. According to their theories, objects possessed an internal property that caused this acceleration. This belief led them to theorize that a force was required to keep things moving.

This idea seems like common sense. Moving objects do seem to slow down on their own: a car coasts to a stop, a yo-yo stops spinning, a soccer ball rolls to a halt. Newton, however, rejected this belief, instead suggesting the opposite: The nature of objects is to continue moving unless some force acts on them. For instance, Newton would say that a soccer ball stops rolling because of forces like friction and air resistance, not because of some property of the soccer ball. He would say that if these forces were not present, the ball would roll and roll and roll. A force (a kick) is required to start the ball’s motion, and a force such as the frictional force of the grass is required to stop its motion.

Newton proposed several fundamental principles that govern forces and motion. Nearly 300 years later, his insights remain the foundation for the study of forces and much of motion. This chapter stands as a testament to a brilliant scientist.

At the right, you can use a simulation to experience one of Newton’s fundamental principles: his law relating a net force, mass and acceleration. In the simulation, you can attempt some of the basic tasks required of a helicopter pilot. To do so, you control the net force upward on the helicopter. When the helicopter is in the air, the net force equals the lift force minus its weight. (The lift force is caused by the interaction of the spinning blades with the air, and is used to propel the helicopter upward.) The net force, like all forces, is measured in newtons (N).

When the helicopter is in the air, you can set the net force to positive, negative, or zero values. The net force is negative when the helicopter’s lift force is less than its weight. When the helicopter is on the ground, there cannot be a negative net force because the ground opposes the downward force of the helicopter’s weight and does not allow the helicopter to sink below the Earth’s surface.

The simulation starts with the helicopter on the ground and a net force of 0 N. To increase the net force on the helicopter, press the up arrow key (↑) on your keyboard; to decrease it, press the down arrow key (↓). This net force will continue to be applied until you change it.

To start, apply a positive net force to cause the helicopter to rise off the ground. Next, attempt to have the helicopter reach a constant vertical velocity. For an optional challenge, have it hover at a constant height of 15 meters, and finally, attempt to land (not crash) the helicopter.

Once in the air, you may find that controlling the craft is a little trickier than you anticipated – it may act a little skittish. Welcome to (a) the challenge of flying a helicopter and (b) Newton’s world.

Here are a few hints: Start slowly! Initially, just use small net forces. You can look at the acceleration gauge to see in which direction you are accelerating. Try to keep your acceleration initially between plus or minus 0.25 m/s².

This simulation is designed to help you experiment with the relationship between force and acceleration. If you find that achieving a constant velocity or otherwise controlling the helicopter is challenging – read on! You will gain insights as you do.

5.1 - Force

Force: Loosely defined as “pushing” or “pulling.”

Your everyday conception of force as pushing or pulling provides a good starting point for explaining what a force is.

There are many types of forces. Your initial thoughts may be of forces that require direct contact: pushing a box, hitting a ball, pulling a wagon, and so on.

Some forces, however, can act without direct contact. For example, the gravitational force of the Earth pulls on the Moon even though hundreds of thousands of kilometers separate the two bodies. The gravitational force of the Moon, in turn, pulls on the Earth.
Electromagnetic forces also do not require direct contact. For instance, two magnets will attract or repel each other even when they are not touching each other.

We have discussed a few forces above, and could continue to discuss more of them: static friction, kinetic friction, weight, air resistance, electrostatic force, tension, buoyant force, and so forth. This extensive list gives you a sense of why a general definition of force is helpful.

These varied types of forces do share some essential attributes. Newton observed that a force, or to be precise, a net force, causes acceleration.

All forces are vectors: their direction matters. The weightlifter shown in Concept 1 must exert an upward force on the barbell in order to accelerate it off the ground. For the barbell to accelerate upward, the force he exerts must be greater than the downward force of the Earth's gravity on the barbell. The net force (the vector sum of all forces on an object) and the object's mass determine the direction and amount of acceleration.

The SI unit for force is the newton (N). One newton is defined as one kg·m/s². We will discuss why this combination of units equals a newton shortly.

We have given examples where a net force causes an object to accelerate. Forces can also be in equilibrium (balance), which means there is no net force and no acceleration. When a weightlifter holds a barbell steady over his head after lifting it, his upward force on the barbell exactly balances the gravitational force on it, and the barbell's acceleration is zero. The net force would also be zero if he were lifting the barbell at constant velocity.

5.2 - Newton's first law

**Newton's first law**: “Every body perseveres in its state of being at rest or of moving uniformly straight forward except insofar as it is compelled to change by forces impressed.”

This translation of Newton's original definition (Newton wrote it in Latin) may seem antiquated, but it does state an admirable amount of physics in a single sentence.

Today, we are more likely to summarize Newton's first law as saying that an object remains at rest, or maintains a constant velocity, unless a net external force acts upon it. (Newton's formulation even includes an "insofar" to foreshadow his second law, which we will discuss shortly.)

To state his law another way: An object's velocity changes – it accelerates – when a net force acts upon it. In Concept 1, a puck is shown gliding across the ice with nearly constant velocity because there is little net force acting upon it. The puck that is stationary in Concept 2 will not move until it is struck by the hockey stick.

The hockey stick can cause a great change in the puck's velocity: a professional's slap shot can travel 150 km/hr. Forces also cause things to slow down. As a society, we spend a fair amount of effort trying to minimize these forces. For example, the grass of a soccer field is specially cut to reduce the force of friction to ensure that the ball travels a good distance when passed or shot.

Top athletes also know how to reduce air resistance. Tour de France cyclists often bike single file. The riders who follow the leader encounter less air resistance. Similarly, downhill ski racers "tuck" their bodies into low, rounded shapes to reduce air resistance, and they coat the bottoms of their skis with wax compounds to reduce the slowing effect of the snow's friction.

Newton's first law states that an object will continue to move "uniformly straight" unless acted upon by a force. Today we state this as "constant velocity," since a change in direction is acceleration as much as a change in speed. In either formulation, the point is this: Direction matters. An object not only continues at the same speed, it also moves in the same direction unless a net force acts upon it.

You use this principle every day. Even in as basic a task as writing a note, your fingers apply changing forces to alter the direction of the pen's motion even as its speed is approximately constant.

There is an important fact to note here: Newton's laws hold true in an inertial reference frame. An object that experiences no net force in an inertial reference frame moves at a constant velocity. Since we assume that observations are made in such a reference frame, we will be terse here about what is meant. The surface of the Earth (including your physics lab) approximates an inertial reference frame, certainly closely enough for the typical classroom lab experiment. (The motion of the Earth makes it less than perfect.)

A car rounding a curve provides an example of a non-inertial reference frame. If you decided to conduct your experiments inside such a car, Newton's laws would not apply. Objects might seem to accelerate (a coffee cup sliding along the dashboard, for example) yet you would
observe no net force acting on the cup. However, the nature of observations made in an accelerating reference frame is a topic far removed from this chapter’s focus, and this marks the end of our discussion of reference frames in this chapter.

5.3 - Mass

**Mass:** A property of an object that determines how much it will resist a change in velocity.

Newton’s second law summarizes the relationship of force, mass and acceleration. Mass is crucial to understanding the second law because an object’s mass determines how much it resists a change in velocity.

More massive objects require more net force to accelerate than less massive objects. An object’s resistance to a change in velocity is called its **inertial mass**. It requires more force to accelerate the bus on the right at, say, five m/s² than the much less massive bicycle.

A common error is to confuse mass and weight. Weight is a force caused by gravity and is measured in newtons. Mass is an object’s resistance to change in velocity and is measured in kilograms. An object’s weight can vary: Its weight is greater on Jupiter’s surface than on Earth’s, since Jupiter’s surface gravity is stronger than Earth’s. In contrast, the object’s mass does not change as it moves from planet to planet. The kilogram (kg) is the SI unit of mass.

5.4 - Gravitational force: weight

**Weight:** The force of gravity on an object.

We all experience weight, the force of gravity. On Earth, by far the largest component of the gravitational force we experience comes from our own planet. To give you a sense of proportion, the Earth exerts 1600 times more gravitational force on you than does the Sun. As a practical matter, an object’s weight on Earth is defined as the gravitational force the Earth exerts on it.

Weight is a force; it has both magnitude and direction. At the Earth’s surface, the direction of the force is toward the center of the Earth.

The magnitude of weight equals the product of an object’s mass and the rate of freefall acceleration due to gravity. On Earth, the rate of acceleration due to gravity is 9.80 m/s². The rate of freefall acceleration depends on a planet’s mass and radius, so it varies from planet to planet. On Jupiter, for instance, gravity exerts more force than on Earth, which makes for a greater value for freefall acceleration. This means you would weigh more on Jupiter’s surface than on Earth’s.

Scales, such as the one shown in Concept 1, are used to measure the magnitude of weight. The force of Earth’s gravity pulls Kevin down and compresses a spring. This scale is calibrated to display the amount of weight in both newtons and pounds, as shown in Equation 1. Forces like weight are measured in pounds in the British system. One newton equals about 0.225 pounds.

A quick word of caution: In everyday conversation, people speak of someone who “weighs 100 kilograms,” but kilograms are units for mass, not weight. Weight, like any force, is measured in newtons. A person with a mass of 100 kg weighs 980 newtons.
Newton's second law: “A change in motion is proportional to the motive force impressed and takes place along the straight line in which that force is impressed.”

Newton stated that a change in motion (acceleration) is proportional to force. Today, physicists call this Newton’s second law, and it is stated to explicitly include mass. Physicists state that acceleration is proportional to the net force on an object and inversely proportional to its mass.

To describe this in the form of an equation: net force equals mass times acceleration, or $\Sigma F = ma$. It is the law. The $\Sigma$ notation means the vector sum of all the forces acting on an object: in other words, the net force. Both the net force and acceleration are vectors that point in the same direction, and Newton’s formulation stressed this point: “The change in motion...takes place along the straight line in which that force is impressed.” The second law explains the units that make up a newton (kg·m/s$^2$); they are the result of multiplying mass by acceleration.

In the illustrations, you see an example of forces and the acceleration caused by the net force. The woman who stars in these illustrations lifts a suitcase. The weight of the suitcase opposes this motion. This force points down. Since the force supplied by the woman is greater than the weight, there is a net force up, which causes the suitcase to accelerate upward.

In Example 1, the woman lifts the suitcase with a force of 158 N upward. The weight of the suitcase opposes the motion with a downward force of 147 newtons. The two forces act along a line, so we use the convention that up is positive and down is negative, and subtract to find the net force. (If both forces were not acting along a line, you would have to use trigonometry to calculate their components.)

The net force is 11 N, upward. The mass of the suitcase is 15 kg. Newton’s second law can be used to determine the acceleration: It equals the net force divided by the mass. The suitcase accelerates at 0.73 m/s$^2$ in the direction of the net force, upward.

$\Sigma F = ma$

$\Sigma F =$ net force
$m =$ mass
$a =$ acceleration

Units of force: newtons (N, kg·m/s$^2$)
What is the suitcase’s acceleration?

\[ \Sigma F = ma \]
\[ F + (-mg) = ma \]
\[ a = (F - mg)/m \]
\[ a = (158 N - 147 N)/(15 kg) \]
\[ a = 0.73 \text{ m/s}^2 \text{ (upward)} \]

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### 5.6 - Sample problem: Rocket Guy

Rocket Guy weighs 905 N and his jet pack provides 1250 N of thrust, straight up. What is his acceleration?

Above you see “Rocket Guy,” a superhero who wears a jet pack. The jet pack provides an upward force on him, while Rocket Guy’s weight points downward.

**Variables**

All the forces on Rocket Guy are directed along the \( \hat{y} \) axis.

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>thrust</td>
<td>( F_T = 1250 \text{ N} )</td>
</tr>
<tr>
<td>weight</td>
<td>( -mg = -905 \text{ N} )</td>
</tr>
<tr>
<td>mass</td>
<td>( m )</td>
</tr>
<tr>
<td>acceleration</td>
<td>( a )</td>
</tr>
</tbody>
</table>

**What is the strategy?**

1. Determine the net force on Rocket Guy.
2. Determine Rocket Guy’s mass.
3. Use Newton’s second law to find his acceleration.

**Physics principles and equations**

Newton’s second law

\[ \Sigma F = ma \]
Step-by-step solution

We start by determining the net force on Rocket Guy.

<table>
<thead>
<tr>
<th>Step</th>
<th>Reason</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. $\Sigma F = F_T + mg$</td>
<td>calculate net vertical force</td>
</tr>
<tr>
<td>2. $\Sigma F = F_T + (-mg)$</td>
<td>apply sign conventions</td>
</tr>
</tbody>
</table>
| 3. $\Sigma F = 1250 \text{ N} + (-905 \text{ N})$  
$\Sigma F = 345 \text{ N}$ | enter values and add |

Now we find Rocket Guy’s mass.

<table>
<thead>
<tr>
<th>Step</th>
<th>Reason</th>
</tr>
</thead>
<tbody>
<tr>
<td>4. $m = \frac{\text{weight}}{g}$</td>
<td>definition of weight</td>
</tr>
</tbody>
</table>
| 5. $m = \frac{905 \text{ N}}{(9.80 \text{ m/s}^2)}$  
$m = 92.3 \text{ kg}$ | calculate m |

Finally we use Newton’s second law to calculate Rocket Guy’s acceleration.

<table>
<thead>
<tr>
<th>Step</th>
<th>Reason</th>
</tr>
</thead>
<tbody>
<tr>
<td>6. $\Sigma F = ma$</td>
<td>Newton’s second law</td>
</tr>
<tr>
<td>7. $a = \frac{\Sigma F}{m}$</td>
<td>solve for $a$</td>
</tr>
</tbody>
</table>
| 8. $a = \frac{345 \text{ N}}{92.3 \text{ kg}}$  
$a = 3.74 \text{ m/s}^2$ (upward) | enter values from steps 3 and 5, and divide |

5.7 - Interactive checkpoint: heavy cargo

A helicopter of mass 3770 kg can create an upward lift force $F$. When empty, it can accelerate straight upward at a maximum of 1.37 m/s$^2$. A careless crewman overloads the helicopter so that it is just unable to lift off. What is the mass of the cargo?

Answer:

$m_c = \boxed{\text{kg}}$
5.8 - Interactive checkpoint: pushing a box

Len pushes toward the right on a 12.0 kg box with a force of magnitude 31.0 N. Martina applies a 11.0 N force on the box in the opposite direction. The magnitude of the kinetic friction force between the box and the very smooth floor is 4.50 N as the box slides toward the right. What is the box’s acceleration?

Answer:

\[ a = \text{m/s}^2 \]

5.9 - Interactive problem: flying in formation

The simulation on the right will give you some practice with Newton’s second law. Initially, all the space ships have the same velocity. Their pilots want all the ships to accelerate at 5.15 m/s\(^2\). The red ships have a mass of 1.27\times10^4 kg, and the blue ships, a mass of 1.47\times10^4 kg. You need to set the amount of force supplied by the ships’ engines so that they accelerate equally. The masses of the ships do not change significantly as they burn fuel.

Apply Newton’s second law to calculate the engine forces needed. The simulation uses scientific notation; you need to enter three-digit leading values. Enter your values and press GO to start the simulation. If all the ships accelerate at 5.15 m/s\(^2\), you have succeeded. Press RESET to try again.

If you have difficulty solving this problem, review Newton's second law.

5.10 - Newton’s third law

**Newton's third law:** “To any action there is always an opposite and equal reaction; in other words, the actions of two bodies upon each other are always equal and always opposite in direction.”

Newton’s third law states that forces come in pairs and that those forces are equal in magnitude and opposite in direction. When one object exerts a force on another, the second object exerts a force equal in magnitude but opposite in direction on the first.

For instance, if you push a button, it pushes back on you with the same amount of force. When someone leans on a wall, it pushes back, as shown in the illustration above.
To illustrate this concept, we use an example often associated with Newton, the falling apple shown in Example 1. The Earth’s gravitational force pulls an apple toward the ground and the apple pulls upward on the Earth with an equally strong gravitational force. These pairs of forces are called action-reaction pairs, and Newton’s third law is often called the action-reaction law.

If the forces on the apple and the Earth are equal in strength, do they cause them to accelerate at the same rate? Newton’s second law enables you to answer this question. First, objects accelerate due to a net force, and the force of the apple on the Earth is minor compared to other forces, such as those of the Moon or Sun. But, even if the apple were exerting the sole force on the Earth, its acceleration would be very, very small because of the Earth’s great mass. The forces are equal, but the acceleration for each body is inversely proportional to its mass.

Normal force: When two objects are in direct contact, the force one object exerts in response to the force exerted by the other. This force is perpendicular to the objects’ contact surface.

The normal force is a force exerted by one object in direct contact with another. The normal force is a response force, one that appears in response to another force. The direction of the force is perpendicular to the surfaces in contact. (One meaning of “normal” is perpendicular.)

A normal force is often a response to a gravitational force, as is the case with the block shown in Concept 1 to the right. The table supports the block by exerting a normal force upward on it. The normal force is equal in magnitude to the block’s weight but opposite in direction. The normal force is perpendicular to the surface between the block and the table.

You experience the normal force as well. The force of gravity pulls you down, and the normal force of the Earth pushes in the opposite direction. The normal force prevents you from being pulled to the center of the Earth.

Let’s consider the direction and the amount of the normal force when you are standing in your classroom. It is equal in magnitude to the force of gravity on you (your weight) and points in the opposite direction. If the normal force were greater than your weight, the net force would accelerate you upward (a surprising result), and if it were less, you would accelerate toward the center of the Earth (equally surprising and likely more distressing). The two forces are equal in strength and oppositely directed, so the amount of the normal force is the same as the magnitude of your weight.

What is the source of the normal force? The weight of the block causes a slight deformation in the table, akin to you lying on a mattress and causing the springs to compress and push back. With a normal force, the deformation occurs at the atomic level as atoms and molecules attempt to “spring back.”

Normal forces do not just oppose gravity, and they do not have to be directed upward. A normal force is always perpendicular to the surface where the objects are in contact. When you lean against a wall, the wall applies a normal force on you. In this case, the normal force opposes your push and is acting horizontally.

We have discussed normal forces that are acting solely vertically or horizontally. The normal force can also act at an angle, as shown with the block on a ramp in Example 1. The normal force opposes a component of the block’s weight, not the full weight. Why? Because the normal force is always perpendicular to the contact surface. The normal force opposes the component of the weight perpendicular to the surface of the ramp.

Example 2 makes a similar point. Here again the normal force and weight are not equal in magnitude. The string pulls up on the block, but not enough to lift it off the surface. Since this reduces the force the block exerts on the table, the amount of the normal force is correspondingly reduced. The force of the string reduces the net downward force on the table to 75 N, so the amount of the normal force is 75 N, as well. The
direction of the normal force is upward.

The string supplies an upward force on the block which is resting on the table. What is the normal force of the table on the block?

\[ \Sigma F = ma = 0 \]
\[ F_N + T + (-mg) = 0 \]
\[ F_N + 35 \text{ N} - 110 \text{ N} = 0 \]
\[ F_N = 75 \text{ N} \text{ (upward)} \]

5.12 - Tension

_Tension_: Force exerted by a string, cord, twine, rope, chain, cable, etc.

In physics textbooks, tension means the pulling force conveyed by a string, rope, chain, tow-bar, or other form of connection. In this section, we will use a rope to illustrate the concept of tension.

The rope in Concept 1 is shown exerting a force on the block; that force is called tension. This definition differs slightly from the everyday use of the word tension, which often refers to forces within a material or object – or a human brain before exams.

In physics problems, two assumptions are usually made about the nature of tension. First, the force is transmitted unchanged by the rope. The rope does not stretch or otherwise diminish the force. Second, the rope is treated as having no mass (it is massless). This means that when calculating the acceleration of a system, the mass of the rope can be ignored.

Example 1 shows how tension forces can be calculated using Newton’s second law. There are two forces acting on the block: its weight and the tension. The vector sum of those forces, the net force, equals the product of its mass and acceleration. Since the mass and acceleration are stated, the problem solution shows how the tension can be determined.

\[ T = 19 \text{ N} \text{ (upward)} \]

5.13 - Newton's second and third laws

It might seem that Newton’s third law could lead to the conclusion that forces do not cause acceleration, because for every force there is an equal but opposite force. If for every force there is an equal but opposite force, how can there be a net non-zero force? The answer lies in the fact that the forces do not act on the same object. The pair of forces in an action-reaction pair acts on different objects. In this section, we illustrate this often confusing concept with an example.
Consider the box attached to the rope in Concept 1. We show two pairs of action-reaction forces. Normally, we draw all forces in the same color, but in this illustration, we draw each pair in a different color. One pair is caused by the force of gravity. The force of the Earth pulls the box down. In turn, the box exerts an upward gravitational force of equal strength on the Earth.

There is also a pair of forces associated with the rope. The tension of the rope pulls up on the box. In response, the box pulls down on the rope. These forces are equal but opposite and form a second action-reaction pair. (Here we only focus on pairs that include forces acting on the box or caused by the box. We ignore other action-reaction pairs present in this example, such as the hand pulling on the rope, and the rope pulling on the hand.)

Now consider only the forces acting on the box. This means we no longer consider the forces the box exerts on the Earth and on the rope. The two forces on the box are gravity pulling it down and tension pulling it up. In this example, we have chosen to make the force of tension greater than the weight of the box.

The Concept 2 illustration reflects this scenario: The tension vector is longer than the weight vector, and the resulting net force is a vector upward. Because there is a net upward force on the box, it accelerates in that direction.

Now we will clear up another possible misconception: that the weight of an object resting on a surface and the resulting normal force are an action-reaction pair. They are not. Since they are often equal but opposite, they are easily confused with an action-reaction pair. Consider a block resting on a table. The action-reaction pair is the Earth pulling the block down and the block pulling the Earth up. It is not the weight of the block and the normal force.

Here is one way to confirm this: Imagine the block is attached to a rope pulling it up so that it just touches the table. The normal force is now near zero, yet the block’s weight is unchanged. If the weight and the normal force are supposed to be equal but opposite, how could the normal force all but disappear? The answer is that the action-reaction pair in question is what is stated above: the equal and opposite forces of gravity between the Earth and the block.

**Free-body diagrams**

A drawing of the external forces exerted on an object.

Free-body diagrams are used to display multiple forces acting on an object. In the drawing above, the free body is a monkey, and the free-body diagram in Concept 1 shows the forces acting upon the monkey: the tension forces of the two ropes and the force of gravity.

The diagram only shows the external forces acting on the monkey. There are other forces present in this configuration, such as forces within the monkey, and forces that the monkey exerts. Those forces are not shown; a free-body diagram shows just the forces that act on a single object like the monkey.

Although we often draw force vectors where they are applied to an object, in free-body diagrams it is useful to draw the vectors starting from a single point, typically the origin. This allows the components of the vectors to be more easily analyzed. You see this in Concept 1.

Free-body diagrams are useful in a variety of ways. They can be used to determine the magnitudes of forces. For instance, if the mass of the monkey and the orientations of the ropes are known, the tension in each rope can be determined.

When forces act along multiple dimensions, the forces and the resulting acceleration need to be considered independently in each dimension. In the illustration, the monkey is stationary, hanging from two ropes. Since there is no vertical acceleration, there is no net force in the vertical dimension. This means the downward force of gravity on the monkey must equal the upward pull of the ropes.

The two ropes also pull horizontally (along the x axis). Because the monkey is not accelerating horizontally, these horizontal forces must
balance as well. By considering the forces acting in both the horizontal and vertical directions, the tensions of the ropes can be determined.

In Example 1, one of the forces shown is friction, \( f \). Friction acts to oppose motion when two objects are in contact.

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**Example 1**

Draw a free-body diagram of the forces on the box.

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In this section, you practice drawing a free-body diagram. Above, you see the situation: A block is being pulled horizontally by a rope. It accelerates to the right at 11 m/s\(^2\). In the simulation on the right, the force vectors on the block are drawn, but each one points in the wrong direction, has the wrong magnitude, or both. We ignore the force of air resistance in this simulation.

Your job is to fix the force vectors. You do this by clicking on the heads of the vectors and dragging them to point in the correct direction. (To simplify your work, they “snap” to vertical and horizontal orientations, but you do need to drag them close before they will snap.) You change both their lengths (which determine their magnitudes) and their directions with the mouse.

The mass of the block is 5.0 kg. The tension force \( T \) is 78 N and the force of friction \( f \) is 23 N. The friction force acts opposite to the direction of the motion. Calculate the magnitudes of the weight \( mg \) and the normal force \( F_N \), to the nearest newton, and then drag the heads of the vectors to the correct positions, or click on the up and down arrow buttons, and press GO. If you are correct, the block will accelerate to the right at 11 m/s\(^2\). If not, the block will move based on the net force as determined by your vectors as well as its mass. Press RESET to try again.

There is more than one way to arrange the vectors to create the same acceleration, but there is only one arrangement that agrees with all the information given.

If you have difficulty solving this problem, review the sections on weight and normal force, and the section on free-body diagrams.
5.16 - Sample problem: pushing a box horizontally

The girl shown above is pushing the box horizontally, causing it to accelerate. The force of friction opposes this movement. You are asked to find the acceleration of the box.

With problems like this, we start with a free-body diagram.

**Draw a free-body diagram**

The free-body diagram shows all the forces acting on the box. In solving the problem, we use only the horizontal forces from the push and friction in our calculations. There is no net vertical force because the downward force of weight is balanced by the upward normal force. The fact that there is no vertical acceleration confirms that there is no net vertical force.

**Variables**

Since the motion is in one dimension, we use signs to indicate direction. As usual, we take the positive direction to be to the right.

<table>
<thead>
<tr>
<th>Force</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>force of push</td>
<td>$-F_{\text{push}} = -34.0 \text{ N}$</td>
</tr>
<tr>
<td>force of friction</td>
<td>$F_{\text{friction}} = 18.0 \text{ N}$</td>
</tr>
<tr>
<td>mass</td>
<td>$m = 15.0 \text{ kg}$</td>
</tr>
<tr>
<td>acceleration</td>
<td>$a$</td>
</tr>
</tbody>
</table>

**What is the strategy?**

1. Draw a free-body diagram.
2. Calculate the net force on the box.
3. Use Newton’s second law to calculate the acceleration of the box.

**Physics principles and equations**

Newton’s second law

$$\Sigma F = ma$$
Step-by-step solution

As noted, we use the convention that forces to the right are positive and those to the left are negative. A more rigorous approach would be to calculate the vector components of these forces using the cosine of 0° for the frictional force and the cosine of 180° for the pushing force. The result would be x components of 18.0 N and ~34.0 N (the same conclusion we reached via inspection and convention). Many instructors prefer this approach. It does not change the answer to the problem, but the component method is more rigorous, and is required to solve more difficult problems.

<table>
<thead>
<tr>
<th>Step</th>
<th>Reason</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. ( \Sigma F = F_{\text{push}} + F_{\text{friction}} )</td>
<td>net horizontal force</td>
</tr>
<tr>
<td>2. ( \Sigma F = -34.0 , \text{N} + 18.0 , \text{N} )</td>
<td>enter values and add</td>
</tr>
<tr>
<td>( \Sigma F = -16.0 , \text{N} )</td>
<td></td>
</tr>
<tr>
<td>3. ( \Sigma F = ma )</td>
<td>Newton's second law</td>
</tr>
<tr>
<td>4. ( a = \Sigma F / m )</td>
<td>solve for ( a )</td>
</tr>
<tr>
<td>5. ( a = (-16.0 , \text{N}) / (15.0 , \text{kg}) )</td>
<td>enter values</td>
</tr>
<tr>
<td>6. ( a = -1.07 , \text{m/s}^2 )</td>
<td>division</td>
</tr>
</tbody>
</table>

5.17 - Interactive problem: lifting crates

The helicopter on the right is being used as a scale, making it one of the more expensive scales in the world, we suspect. This simulation includes three crates; each has a slightly different mass. Your assignment is to find the crate with a mass of 661 kg. Do this by lifting each crate with the helicopter and noting the acceleration. The helicopter lifts each crate with a force of 10,748 N via the tension in the cable. The resulting acceleration of each crate will let you calculate its mass.

Click on the graphic to start the simulation. To determine the answer, drag the helicopter to each of the three crates and press GO to make the helicopter lift the crate. Record the acceleration of each crate and use the acceleration to calculate the mass. When you have found the crate with a mass of 661 kg, select it by clicking on it. The simulation will tell you whether you clicked on the correct one.

If you cannot solve the problem, review Newton's second law and the section on weight.

5.18 - Friction

Friction: A force that resists the motion of one object sliding past another.

If you push a cardboard box along a wooden floor, you have to push to overcome the force of friction. This force makes it harder for you to slide the box. The force of friction opposes any force that can cause one object to slide past another. There are two types of friction: static and kinetic. These forces are discussed in more depth in other sections. In this section, we discuss some general properties of friction.

The amount of friction depends on the materials in contact. For example, the box would slide more easily over ice than wood. Friction is also proportional to the normal force. For a box on the floor, the greater its weight, the greater the normal force, which increases the force of friction.

Humans expend many resources to combat friction. Motor oil, Teflon™, WD-40™, Tri-Flo™ and many other products are designed to reduce this force. However, friction can be very useful. Without it, a nail would slip out of a board, the tires of a car would not be able to “grip” the road, and you would not be able to walk.

Friction exists even between seemingly smooth surfaces. Although a surface may appear smooth, when magnified sufficiently, any surface will look bumpy or rough, as the illustration in Concept 2 on the right shows. The magnified picture of the “smooth” crystal reveals its microscopic “rough” texture. Friction is a force caused by the interaction of molecules in two surfaces.
You might think you can defeat friction by creating surfaces that are highly polished. Instead, you may get an effect called cold welding, in which the two highly polished materials fuse together. Cold welding can be desirable, as when an aluminum connector is crimped onto a copper wire to create a strong electrical connection.

Objects can also move in a fashion that is called slip and slide. They slide for a while, stick, and then slide some more. This phenomenon accounts for both the horrid noise generated by fingernails on a chalkboard and the joyous noise of a violin. (Well, joyous when played by some, chalkboard-like when played by others.)

**Friction**

*Force that opposes "sliding" motion*

*Varies by materials in contact*

*Proportional to normal force*

---

**5.19 - Static friction**

**Static friction:** A force that resists the sliding motion of two objects that are stationary relative to one another.

Imagine you are pushing a box horizontally but cannot move it due to friction. You are experiencing a response force called static friction. If you push harder and harder, the amount of static friction will increase to exactly equal – but not exceed – the amount of horizontal force you are supplying. For the two surfaces in contact, the friction will increase up to some maximum amount. If you push hard enough to exceed the maximum amount of static friction, the box will slide.

For instance, let’s say the maximum amount of static friction for a box is 30 newtons. If you push with a force of 10 newtons, the box does not move. The force of static friction points in the opposite direction of your force and is 10 newtons as well. If it were less, the box would slide in the direction you are pushing. If it were greater, the box would accelerate toward you. The box does not move in either direction, so the friction force is 10 newtons. If you push with 20 newtons of force, the force of static friction is 20 newtons, for the same reasons.

You keep pushing until your force is 31 newtons. You have now exceeded the maximum force of static friction and the box accelerates in the direction of the net force. The box will continue to experience friction once it is sliding, but this type of friction is called kinetic friction.

Static friction occurs when two objects are motionless relative to one another. Often, we want to calculate the maximum amount of static friction so that we know how much force we will have to apply to get the object to move. The equation in Equation 1 enables you to do so. It depends on two values. One is the normal force, the perpendicular force between the two surfaces. The second is called the coefficient of static friction.

Engineers calculate this coefficient empirically. They place an object (say, a car tire) on top of another surface (perhaps ice) and measure how hard they need to push before the object starts to move. Coefficients of friction are specific to the two surfaces. Some examples of coefficients of static friction are shown in the table in Equation 2.

You might have noticed a fairly surprising fact: The amount of surface area between the two objects does not enter into the calculation of maximum static friction. In principle, whether a box of a given mass has a surface area of one square centimeter or one square kilometer, the
maximum amount of static friction is constant. Why? With the greater contact area, the normal and frictional forces per unit area diminish proportionally.

\[ f_{s,\text{max}} = \mu_s F_N \]

- \( f_{s,\text{max}} \) = maximum static friction
- \( \mu_s \) = coefficient of static friction
- \( F_N \) = normal force

### Anna is pushing but the box does not move. What is the force of static friction?

\( f_s = 7 \text{ N to the right} \)

### What is the maximum static

\( F_N = 27 \text{ N} \)
**Kinetic friction**: Friction when an object slides along another.

Kinetic friction occurs when two objects slide past each other. The magnitude of kinetic friction is less than the maximum amount of static friction for the same objects. Some values for coefficients of kinetic friction are shown in Equation 2 to the right. These are calculated empirically and do not vary greatly over a reasonable range of velocities.

Like static friction, kinetic friction always opposes the direction of motion. It has a constant value, the product of the normal force and the coefficient of kinetic friction.

In Example 1, we state the normal force. Note that the normal force in this case does not equal the weight; instead, it equals a component of the weight. The other component of the weight is pulling the block down the plane.

\[
f_{k,\text{max}} = \mu_s F_N = (0.31)(27 \text{ N}) = 8.4 \text{ N}
\]

*Coefficients of kinetic friction*
What is the force of friction?

\[ f_k = \mu_k F_N \]

\[ f_k = (0.67)(10 \text{ N}) \]

\[ f_k = 6.7 \text{ N} \text{ (pointing up the ramp)} \]

5.21 - Interactive checkpoint: moving the couch

While rearranging your living room, you push your couch across the floor at a constant speed with a horizontal force of 69.0 N. You are using special pads on the couch legs that help it slide easier. If the couch has a mass of 59.5 kg, what is the coefficient of kinetic friction between the pads and the floor?

Answer:

\[ \mu_k = \boxed{?} \]

5.22 - Sample problem: friction and tension

The coefficient of kinetic friction is 0.200. What is the magnitude of the tension force in the rope?

Above, you see a block accelerating to the right due to the tension force applied by a rope. What is the magnitude of tension the rope applies to the block?

Starting this type of problem with a free-body diagram usually proves helpful.

Draw a free-body diagram
Variables

<table>
<thead>
<tr>
<th></th>
<th>x component</th>
<th>y component</th>
</tr>
</thead>
<tbody>
<tr>
<td>normal force</td>
<td>0</td>
<td>$F_N = mg$</td>
</tr>
<tr>
<td>acceleration</td>
<td>$a = 2.20 \text{ m/s}^2$</td>
<td>0</td>
</tr>
<tr>
<td>tension</td>
<td>$T$</td>
<td>0</td>
</tr>
<tr>
<td>friction force</td>
<td>$-f_k$</td>
<td>0</td>
</tr>
<tr>
<td>mass</td>
<td>$m = 1.60 \text{ kg}$</td>
<td></td>
</tr>
<tr>
<td>coefficient of kinetic friction</td>
<td>$\mu_k = 0.200$</td>
<td></td>
</tr>
</tbody>
</table>

What is the strategy?
1. Draw a free-body diagram.
2. Find an expression for the net force on the block.
3. Substitute the net force into Newton’s second law to find the tension.

Are there any useful relationships?
Since the surface is horizontal, the amount of normal force equals the weight of the block.

Physics principles and equations

Newton’s second law
$$\sum F = ma$$

The magnitude of the force of kinetic friction is found by
$$f_k = \mu_k F_N$$

Step-by-step solution

We begin by determining the net horizontal force on the block.

<table>
<thead>
<tr>
<th>Step</th>
<th>Reason</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>$\sum F = T + (-f_k)$</td>
</tr>
<tr>
<td>2.</td>
<td>$f_k = \mu_k F_N$</td>
</tr>
<tr>
<td>3.</td>
<td>$\sum F = T - \mu_k F_N$</td>
</tr>
<tr>
<td>4.</td>
<td>$\sum F = T - \mu_k mg$</td>
</tr>
</tbody>
</table>

Now we substitute the net force just found into Newton’s second law. This allows us to solve for the tension force.

<table>
<thead>
<tr>
<th>Step</th>
<th>Reason</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.</td>
<td>$\sum F = ma$</td>
</tr>
<tr>
<td>6.</td>
<td>$T - \mu_k mg = ma$</td>
</tr>
<tr>
<td>7.</td>
<td>$T = \mu_k mg + ma$</td>
</tr>
<tr>
<td>8.</td>
<td>$T = (0.200)(1.60 \text{ kg})(9.80 \text{ m/s}^2) + (1.60 \text{ kg})(2.20 \text{ m/s}^2)$</td>
</tr>
<tr>
<td>9.</td>
<td>$T = 6.66 \text{ N}$</td>
</tr>
</tbody>
</table>
5.23 - Sample problem: a force at an angle

Above, you see a bat hitting a ball at an angle. You are asked to find the net force and the acceleration of the ball along the $x$ and $y$ axes.

Draw a free-body diagram

The forces on the ball are its weight down and the force of the bat at the angle $\theta$ to the $x$ axis.

Variables

<table>
<thead>
<tr>
<th></th>
<th>$x$ component</th>
<th>$y$ component</th>
</tr>
</thead>
<tbody>
<tr>
<td>weight</td>
<td>0</td>
<td>$mg \sin 270^\circ = -1.40$ N</td>
</tr>
<tr>
<td>force</td>
<td>$F \cos \theta$</td>
<td>$F \sin \theta$</td>
</tr>
<tr>
<td>acceleration</td>
<td>$a_x$</td>
<td>$a_y$</td>
</tr>
<tr>
<td>force</td>
<td>$F = 262$ N</td>
<td></td>
</tr>
<tr>
<td>angle</td>
<td>$\theta = 60.0^\circ$</td>
<td></td>
</tr>
<tr>
<td>mass</td>
<td>$m = mg/g = (1.40 \text{ N}) / (9.80 \text{ m/s}^2) = 0.143 \text{ kg}$</td>
<td></td>
</tr>
</tbody>
</table>

What is the strategy?

1. Draw a free-body diagram.
2. Use trigonometry to calculate the net force on the ball along each axis.
3. Use Newton’s second law to find the acceleration of the ball along each axis. The mass of the ball is not given, but you can determine it because you are told its weight. We do this in the variables table.

Physics principles and equations

Newton’s second law

$\Sigma F = ma$

Step-by-step solution

We begin by calculating the net force along the $x$ axis.

<table>
<thead>
<tr>
<th>Step</th>
<th>Reason</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. $\Sigma F_x = F \cos \theta$</td>
<td>net force along $x$ axis</td>
</tr>
<tr>
<td>2. $\Sigma F_x = (262 \text{ N})(\cos 60.0^\circ)$</td>
<td>$x$ component of force</td>
</tr>
<tr>
<td>3. $\Sigma F_x = 131 \text{ N}$</td>
<td>evaluate</td>
</tr>
</tbody>
</table>
We next calculate the force along the $y$ axis. In this case, there are two forces to consider.

<table>
<thead>
<tr>
<th>Step</th>
<th>Reason</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.</td>
<td>$\Sigma F_y = F \sin \theta + (-1.40 \text{ N})$ net force along $y$ axis</td>
</tr>
<tr>
<td>5.</td>
<td>$\Sigma F_y = (262 \text{ N})(\sin 60.0^\circ) + (-1.40 \text{ N})$ enter values</td>
</tr>
<tr>
<td>6.</td>
<td>$\Sigma F_y = 225 \text{ N}$ evaluate</td>
</tr>
</tbody>
</table>

Now we calculate the acceleration along the $x$ axis, using Newton's second law.

<table>
<thead>
<tr>
<th>Step</th>
<th>Reason</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.</td>
<td>$\Sigma F_x = ma_x$ Newton's second law</td>
</tr>
<tr>
<td>8.</td>
<td>$a_x = \Sigma F_x/m$ solve for $a_x$</td>
</tr>
<tr>
<td>9.</td>
<td>$a_x = (131 \text{ N}) / (0.143 \text{ kg})$ enter values from step 3 and table</td>
</tr>
<tr>
<td>10.</td>
<td>$a_x = 916 \text{ m/s}^2$ division</td>
</tr>
</tbody>
</table>

We calculate the acceleration along the $y$ axis.

<table>
<thead>
<tr>
<th>Step</th>
<th>Reason</th>
</tr>
</thead>
<tbody>
<tr>
<td>11.</td>
<td>$\Sigma F_y = ma_y$ Newton's second law</td>
</tr>
<tr>
<td>12.</td>
<td>$a_y = \Sigma F_y/m$ solve for $a_y$</td>
</tr>
<tr>
<td>13.</td>
<td>$a_y = (225 \text{ N})/(0.143 \text{ kg})$ enter values from step 6, table</td>
</tr>
<tr>
<td>14.</td>
<td>$a_y = 1570 \text{ m/s}^2$ division</td>
</tr>
</tbody>
</table>

The acceleration values may seem very large, but this is the acceleration during the brief moment the bat is in contact with the ball.

### 5.24 - Interactive problem: forces on a sliding block

Above, you see an illustration of a block that is being pulled up a ramp by a rope. In the simulation on the right, the force vectors on the block are drawn, but they are in the wrong directions, have the wrong magnitudes, or both. Your job is to fix the force vectors. If you do this correctly, the block will accelerate up the ramp at a rate of 4.3 m/s$^2$. If not, the block will move due to the net force as determined by your vectors as well as its mass.

The mass of the block is 6.0 kg. The amount of tension from the rope is 78 N and the coefficient of kinetic friction is 0.45. The angle the ramp makes with the horizontal is $30^\circ$. Calculate (to the nearest newton) the directions and magnitudes of the weight, normal force and friction force. Drag the head of a vector to set its magnitude and direction. You can also set the magnitudes in the control panel. The vectors will "snap" to angles.

When you have arranged all the vectors, press the GO button. If your free-body diagram is correct, the block will accelerate up the ramp at 4.3 m/s$^2$. Press RESET to try again.

There is more than one way to set the vectors to produce the same acceleration, but only one arrangement agrees with all the information given. If you have difficulty solving this problem, review the sections on kinetic friction and the normal force, and the sample problem involving a force at an angle.
5.25 - Sample problem: moving down a frictionless plane

Above, you see a toy car going down an inclined plane. The diagram shows the mass of the car and the angle the plane makes with the horizontal. You are asked to calculate the car’s acceleration. In this problem, ignore any friction or air resistance, as well as any energy consumed by the rotation of the wheels.

**Draw a free-body diagram**

By rotating the axes so that the $x$ axis is parallel to the car’s motion down the ramp, we make the forces along the $y$ axis sum to zero. (These two forces are the $y$ component of the car’s weight and the normal force from the ramp.) Rotating the axes means there is a net force only along the $x$ axis, and this reduces the steps required to solve the problem.

It may be a little difficult to see why $\theta$, the angle that the plane makes with the horizontal, is the same as the angle $\theta$ in the free-body diagram. The drawing to the right of the free-body diagram uses two similar right triangles to show why this is true. The triangle ABC has one leg (AC) that is the weight vector, and its hypotenuse (AB) lies along the $x$ axis. The hypotenuse of the smaller triangle ACD is the weight vector. These are both right triangles and share a common angle at A, so they are similar.

It is often useful to check this angle with the situation shown. At a 30° angle, the $y$ component of the weight is larger than the $x$ component (the cosine of 30° is greater than the sine of 30°). Looking at the picture above, this is what you would expect. The component of the weight down the plane is less than the component on the plane. It may help to push it to the extreme: What would you expect at a 0° angle? At 90°?

**Variables**

With the axes rotated and $\theta$ as shown, the $x$ component of the weight is computed using the sine, and the $y$ component with the cosine. (Without the rotation, the $x$ component would be calculated with the cosine, and the $y$ component with the sine.)

<table>
<thead>
<tr>
<th>x component</th>
<th>y component</th>
</tr>
</thead>
<tbody>
<tr>
<td>weight</td>
<td>$m g \sin \theta$</td>
</tr>
<tr>
<td>normal force</td>
<td>$F_N$</td>
</tr>
<tr>
<td>acceleration</td>
<td>$a$</td>
</tr>
<tr>
<td>mass</td>
<td>$m = 0.100$ kg</td>
</tr>
<tr>
<td>angle</td>
<td>$\theta = 30.0^\circ$</td>
</tr>
</tbody>
</table>

**What is the strategy?**

1. Draw a free-body diagram, rotating the axes so the $x$ axis is parallel to the motion of the car.
2. Use trigonometry to calculate the net force on the car.
3. Use Newton’s second law to determine the acceleration of the car.

**Physics principles and equations**

Newton’s second law

$$\Sigma F = ma$$
Step-by-step solution

<table>
<thead>
<tr>
<th>Step</th>
<th>Reason</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>( \Sigma F_x = mg \sin \theta ) net force along x axis</td>
</tr>
<tr>
<td>2.</td>
<td>( \Sigma F_x = (0.100 \text{ kg}) (9.80 \text{ m/s}^2) (\sin 30.0^\circ) ) enter values</td>
</tr>
<tr>
<td>3.</td>
<td>( \Sigma F_x = 0.490 \text{ N} ) evaluate</td>
</tr>
<tr>
<td>4.</td>
<td>( \Sigma F_x = ma ) Newton's second law</td>
</tr>
<tr>
<td>5.</td>
<td>( a = \frac{\Sigma F_x}{m} ) solve for ( a )</td>
</tr>
<tr>
<td>6.</td>
<td>( a = \frac{(0.490 \text{ N})}{(0.100 \text{ kg})} ) enter values</td>
</tr>
<tr>
<td>7.</td>
<td>( a = 4.90 \text{ m/s}^2 ) (down the plane) division</td>
</tr>
</tbody>
</table>

5.26 - Sample problem: two forces at different angles

Two players kick the soccer ball lying on the ground with the forces shown. What are the x and y components of the resulting acceleration of the ball?

You see a top–down view of the ball and the forces exerted on it by the players. You are asked to find the x and y components of the resulting acceleration. When solving the problem, ignore the force of friction.

Draw a free-body diagram

Variables

We use trigonometry to calculate the components of each force. The angles \( \theta_1 \) and \( \theta_2 \) are measured from the positive x axis.

<table>
<thead>
<tr>
<th>force 1</th>
<th>x component</th>
<th>y component</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( F_1 \cos \theta_1 )</td>
<td>( F_1 \sin \theta_1 )</td>
</tr>
<tr>
<td>force 2</td>
<td>( F_2 \cos \theta_2 )</td>
<td>( F_2 \sin \theta_2 )</td>
</tr>
<tr>
<td>acceleration</td>
<td>( a_x )</td>
<td>( a_y )</td>
</tr>
<tr>
<td>mass</td>
<td>0.420 kg</td>
<td></td>
</tr>
<tr>
<td>force 1 angle</td>
<td>( \theta_1 = 171^\circ )</td>
<td></td>
</tr>
<tr>
<td>force 2 angle</td>
<td>( \theta_2 = 285^\circ )</td>
<td></td>
</tr>
<tr>
<td>force 1</td>
<td>( F_1 = 162 \text{ N} )</td>
<td></td>
</tr>
<tr>
<td>force 2</td>
<td>( F_2 = 215 \text{ N} )</td>
<td></td>
</tr>
</tbody>
</table>
What is the strategy?

1. Draw a free-body diagram.
2. Calculate the net force on the ball along each axis by finding the components of the two forces using trigonometry.
3. Use Newton’s second law to find the acceleration of the ball along each axis.

Physics principles and equations

Newton’s second law

\[ \Sigma F = ma \]

Step-by-step solution

We begin by calculating the net force along the \( x \) axis.

<table>
<thead>
<tr>
<th>Step</th>
<th>Reason</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. ( \Sigma F_x = F_1 \cos \theta_1 + F_2 \cos \theta_2 )</td>
<td>net force along ( x ) axis</td>
</tr>
<tr>
<td>2. ( \Sigma F_x = 162 \cos(171^\circ) \text{N} + 215 \cos(285^\circ) \text{N} )</td>
<td>enter values</td>
</tr>
<tr>
<td>3. ( \Sigma F_x = -104 \text{ N} )</td>
<td>evaluate</td>
</tr>
</tbody>
</table>

Next we calculate the net force along the \( y \) axis.

<table>
<thead>
<tr>
<th>Step</th>
<th>Reason</th>
</tr>
</thead>
<tbody>
<tr>
<td>4. ( \Sigma F_y = F_1 \sin \theta_1 + F_2 \sin \theta_2 )</td>
<td>net force along ( y ) axis</td>
</tr>
<tr>
<td>5. ( \Sigma F_y = 162 \sin(171^\circ) \text{N} + 215 \sin(285^\circ) \text{N} )</td>
<td>enter values</td>
</tr>
<tr>
<td>6. ( \Sigma F_y = -182 \text{ N} )</td>
<td>evaluate</td>
</tr>
</tbody>
</table>

Using Newton’s second law and the net force in the \( x \) dimension, calculated above, we find the acceleration in the \( x \) dimension.

<table>
<thead>
<tr>
<th>Step</th>
<th>Reason</th>
</tr>
</thead>
<tbody>
<tr>
<td>7. ( \Sigma F_x = ma_x )</td>
<td>Newton's second law</td>
</tr>
<tr>
<td>8. ( a_x = \Sigma F_x / m )</td>
<td>solve for ( a_x )</td>
</tr>
<tr>
<td>9. ( a_x = (-104 \text{ N}) / (0.420 \text{ kg}) )</td>
<td>enter values</td>
</tr>
<tr>
<td>10. ( a_x = -248 \text{ m/s}^2 )</td>
<td>division</td>
</tr>
</tbody>
</table>

And finally we calculate the acceleration in the \( y \) dimension.

<table>
<thead>
<tr>
<th>Step</th>
<th>Reason</th>
</tr>
</thead>
<tbody>
<tr>
<td>11. ( \Sigma F_y = ma_y )</td>
<td>Newton's second law</td>
</tr>
<tr>
<td>12. ( a_y = \Sigma F_y / m )</td>
<td>solve for ( a_y )</td>
</tr>
<tr>
<td>13. ( a_y = (-182 \text{ N}) / (0.420 \text{ kg}) )</td>
<td>enter values</td>
</tr>
<tr>
<td>14. ( a_y = -433 \text{ m/s}^2 )</td>
<td>division</td>
</tr>
</tbody>
</table>
5.27 - Interactive checkpoint: sledding

A child sits on a sled on a frictionless, icy hill that is inclined at 25.0° from the horizontal. The mass of the child and sled is 36.5 kg. What is the magnitude of the normal force of the hill on the child? At what rate does the child accelerate down the hill?

Answer:

\[ F_N = \square \text{N} \]
\[ a = \square \text{m/s}^2 \]

5.28 - Hooke’s law and spring force

You probably already know a few basic things about springs: You stretch them, they pull back on you. You compress them, they push back.

As a physics student, though, you are asked to study springs in a more quantitative way. Let’s consider the force of a spring using the configuration shown in Concept 1. Initially, no force is applied to the spring, so it is neither stretched nor compressed. When no force is applied, the end of the spring is at a position called the rest point (sometimes called the equilibrium point).

Then we stretch the spring. In the illustration to the right, the hand pulls to the right, so the end of the spring moves to the right, away from its rest point, and the spring pulls back to the left.

Hooke’s law is used to determine how much force the spring exerts. It states that the amount of force is proportional to how far the end of the spring is stretched or compressed away from its rest point. Stretch the end of the spring twice as far from its rest point, and the amount of force is doubled.

The amount of force is also proportional to a spring constant, which depends on the construction of the spring. A “stiff” spring has a greater spring constant than one that is easier to stretch. Stiffer springs can be made from heavier gauge materials. The units for spring constants are newtons per meter (N/m).

The equation for Hooke’s law is shown in Equation 1. The spring constant is represented by \( k \). The displacement of the end of the spring is represented by \( x \). At the rest position, \( x = 0 \). When the spring is stretched, the displacement of the end of the spring has a positive \( x \) value. When it is compressed, \( x \) is negative.

Hooke’s law calculates the magnitude of the spring force. The equation has a negative sign to indicate that the force of a spring is a restoring force, which means it acts to restore the end of the spring to its rest point. Stretch a spring and it will pull back toward the rest position; compress a spring, and it will push back toward the rest position. The direction of the force is the opposite of the direction of the displacement.

\[ F_s = -kx \]

\( F_s \) = spring force
\( k \) = spring constant
\( x \) = displacement of end from rest point
What is the force exerted by the spring?
\[ F_s = -kx \]
\[ F_s = -(4.2 \text{ N/m})(0.36 \text{ m}) \]
\[ F_s = -1.5 \text{ N (to the left)} \]

### 5.29 - Sample problem: spring force and tension

You see a block hanging from a rope attached to a spring. The block is stationary. You are asked to determine the tension in the rope and the position of the end of the spring relative to its rest point.

**Draw a diagram**

Above on the left, we draw the forces: the weight of the block, the tension forces in the rope, and the spring force. The tension forces are equal in magnitude, so we use the same variable \( T \) for each of them. Then we draw two free-body diagrams, one for the block and one for the lower end of the spring.

**Variables**

| weight    | \(-mg = -98.0 \text{ N}\) |
| tension   | \(T\) |
| spring force | \(F_s\) |
| spring constant | \(k = 535 \text{ N/m}\) |
| displacement | \(y\) |

**What is the strategy?**

1. Draw a free-body diagram.
2. Apply Newton’s second law to calculate the tension force in the rope.
3. Then apply Newton’s second law with Hooke’s law to find the position of the end of the spring.
Physics principles and equations

Newton’s second law

\[ \sum F = ma \]

Hooke’s law, applied along the \( y \) axis

\[ F_y = -ky \]

The forces sum to zero for each object because there is no acceleration.

**Step-by-step solution**

We start by determining the magnitude of tension in the rope, using the fact that the block is stationary.

<table>
<thead>
<tr>
<th>Step</th>
<th>Reason</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. ( T + (-mg) = 0 )</td>
<td>no acceleration means no net force</td>
</tr>
<tr>
<td>2. ( T = 98.0 \text{ N} )</td>
<td>enter value for weight into step 1 to determine tension</td>
</tr>
</tbody>
</table>

Since the acceleration of the end of the spring is also zero, the forces again sum to zero. We then use Hooke’s law and solve for the displacement.

<table>
<thead>
<tr>
<th>Step</th>
<th>Reason</th>
</tr>
</thead>
<tbody>
<tr>
<td>3. ( F_y + (-T) = 0 )</td>
<td>no net force</td>
</tr>
<tr>
<td>4. (-ky + (-T) = 0 )</td>
<td>Hooke's law</td>
</tr>
<tr>
<td>5. ( y = -T / k )</td>
<td>solve for ( y )</td>
</tr>
<tr>
<td>6. ( y = -(98.0 \text{ N}) / (535 \text{ N/m}) )</td>
<td>enter values</td>
</tr>
<tr>
<td>7. ( y = -0.183 \text{ m} )</td>
<td>evaluate</td>
</tr>
</tbody>
</table>

**5.30 - Air resistance**

*Air resistance:* A force that opposes motion in air.

If you parachute, or bike or ski, you have experienced air resistance. In each of these activities, you move through a fluid – air – that resists your motion. As you move through the air, you collide with the molecules that make up the atmosphere. Although air is not very dense and the molecules are very small, there are so many of them that their effects add up to a significant force. The sum of all these collisions is the force called air resistance.

Unlike kinetic friction, air resistance is not constant but increases as the speed of the object increases. The force created by air resistance is called *drag*.

The formula in Equation 1 supplies an approximation of the force of air resistance for objects moving at relatively high speeds through air. For instance, it is a relevant equation for the skysurfer shown in Concept 1, or for an airplane. The resistance is proportional to the square of the speed and to the cross sectional area of the moving object. (For the skysurfer, the board would constitute the main part of the cross sectional area.) It is also proportional to an empirically determined constant called the *drag coefficient*.

The shape of an object determines its drag coefficient. A significant change in speed can change the drag coefficient, as well. Aerospace engineers definitely earn their keep by analyzing air resistance using powerful computers. They also use wind tunnels to check their computational results.

Another interesting implication of the drag force equation is that objects will reach what is called *terminal velocity*. Terminal velocity is the maximum speed an object reaches when falling. The drag force increases with speed while the force of gravity is constant; at some point, the upward drag force equals the downward force of gravity. When this occurs, there is no net force and the object ceases to accelerate and maintains a constant speed. The equation for calculating terminal velocity is shown in Equation 2. It is derived by setting the drag force equal to the object’s weight and solving for the speed.
Research has actually determined that cats reach terminal velocity after falling six stories. In fact, they tend to slow down after six stories. Here’s why this occurs: The cat achieves terminal velocity and then relaxes a little, which expands its cross sectional area and increases its drag force. As a result, it slows down. One has to admire the cat for relaxing in such a precarious situation (or perhaps doubt its intelligence). If you think this may be an urban legend, consult the *Journal of the American Veterinary Association*, volume 191, page 1399.

### Air resistance

\[ F_D = \frac{1}{2} \rho A v^2 \]

- \( F_D \) = drag force
- \( C \) = drag coefficient for object
- \( \rho \) = air density
- \( A \) = cross-sectional area
- \( v \) = velocity

### Terminal velocity

\[ v_T = \sqrt{\frac{2mg}{C\rho A}} \]

- \( v_T \) = terminal velocity
- \( mg \) = weight

### Drag coefficients

<table>
<thead>
<tr>
<th>Object</th>
<th>Drag coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ice cream cone</td>
<td>0.34</td>
</tr>
<tr>
<td>Bowl of petunias</td>
<td>0.41</td>
</tr>
<tr>
<td>Can of soup</td>
<td>0.88</td>
</tr>
<tr>
<td>Dinner plate</td>
<td>1.11</td>
</tr>
<tr>
<td>Parachute</td>
<td>1.35</td>
</tr>
</tbody>
</table>

*Based on approximations of shape*
The drag coefficient $C$ is 0.49 and the air density $\rho$ is 1.1 kg/m$^3$. What is the skydiver's terminal velocity?

$$v_T = \sqrt{\frac{2mg}{C\rho A}}$$

$$v_T = \frac{2(650 \text{ N})}{(0.49)(1.1 \text{ kg/m}^3)(0.90 \text{ m}^2)}$$

$$v_T = 52 \text{ m/s}$$

---

**5.31 - Interactive summary problem: helicopter pilot**

In the scenario to the right, the helicopter has a mass of 1710 kg. The simulation starts paused with the helicopter 25.0 meters above the ground. When you press GO the helicopter is moving with an initial velocity of $-3.60 \text{ m/s}$. You want to determine the appropriate lift force so that it achieves zero velocity at a height of 5.00 meters. If you calculate correctly, it will attach itself to the large crate and lift it.

What force should the helicopter blades supply to allow you to accomplish this?

To solve this problem, you will need to first determine the appropriate acceleration using a motion equation, and then calculate the net force required. Hint: Make sure you consider both of the forces acting on the helicopter! Enter the force to the nearest 100 N.

When you successfully pick up the crate, notice that the acceleration decreases because the same net force is now applied to an object (helicopter plus crate) with increased mass.

If you have difficulty solving this, consult the section on motion equations and Newton's second law.

---

**5.32 - Gotchas**

An object has a speed of 20 km/h. It swerves to the left but maintains the same speed. Was a force involved? Yes. A change in speed or direction is acceleration, and acceleration requires a force.

An object is moving. A net force must be acting on it. No. Only if the object is accelerating (changing speed or direction) is there a net force. Constant velocity means there is no net force.

No acceleration means no forces are present. Close. No acceleration means no net forces. There can be a balanced set of forces and no acceleration.

"I weigh 70 kilograms." False. Kilograms measure mass, not weight.

"I weigh the same on Jupiter as I do on Mars." Not unless you dieted (lost mass) as you traveled from Jupiter to Mars. Weight is gravitational force, and Mars exerts less gravitational force.

"My mass is the same on Jupiter and Mars." Yes.

The normal force is the response force to gravity. This is too specific of a definition. The normal force appears any time two objects are brought in contact. It is not limited to gravity. For instance, if you lean against a wall, the force of the wall on you is a normal force. If you stand on the ground, the normal force of the ground is a response force to gravity.

"I push against a wall with a force of five newtons. The wall pushes back with the same force." Close, but it is better to say, "The same amount (magnitude) of force but in the opposite direction."

"I pull on the Earth with the same amount of gravitational force that the Earth exerts on me." True. You are an action-reaction pair.
5.33 - Summary

Force, and Newton's laws which describe force, are fundamental concepts in the study of physics. Force can be described as a push or pull. It is a vector quantity that is measured in newtons (1 N = 1 kg·m/s²). Net force is the vector sum of all the external forces on an object.

Free-body diagrams depict all the external forces on an object. Even though the forces may act on different parts of the object, free-body diagrams are drawn so that the forces are shown as being applied at a single point.

Newton's first law states that an object maintains a constant velocity (including remaining at rest) until a net force acts upon it.

Mass is the property of an object that determines its resistance to a change in velocity, and it is a scalar, measured in kilograms. Mass should not be confused with weight, which is a force caused by gravity, directed toward the center of the Earth.

Newton's second law states that the net force on an object is equal to its mass times its acceleration.

Newton's third law states that the forces that two bodies exert on each other are always equal in magnitude and opposite in direction.

The normal force is a force that occurs when two objects are in direct contact. It is always directed perpendicular to the surface of contact.

Tension is a force exerted by a means of connection such as a rope, and the tension force always pulls on the bodies to which the rope is attached.

Friction is a force that resists the sliding motion of two objects in direct contact. It is proportional to the magnitude of the normal force and varies according to the composition of the objects.

Static friction is the term for friction when there is no relative motion between two objects. It balances any applied pushing force that tends to slide the body, up to a maximum determined by the normal force and the coefficient of static friction between the two objects, \( \mu_s \). If the applied pushing force is greater than the maximum static friction force, then the object will move.

Once an object is in motion, kinetic friction applies. The force of kinetic friction is determined by the magnitude of the normal force multiplied by \( \mu_k \), the coefficient of kinetic friction between the two objects.

Hooke's law describes the force that a spring exerts when stretched or compressed away from its equilibrium position. The force increases linearly with the displacement from the equilibrium position. The equation for Hooke's law includes \( k \), the spring constant; a value that depends on the particular spring. The negative sign indicates that the spring force is a restoring force that points in the opposite direction as the displacement, that is, it resists both stretching and compression.

Air resistance, or drag, is a force that opposes motion through a fluid such as air. Drag increases as speed increases. Terminal velocity is reached when the drag force on a falling object equals its weight, so that it ceases to accelerate.

**Equations**

- weight = \( mg \)
- Newton's second law: \( \Sigma F = ma \)
- Newton's third law: \( F_{ab} = -F_{ba} \)
- Static friction: \( f_{s,max} = \mu_s F_N \)
- Kinetic friction: \( f_k = \mu_k F_N \)
- Hooke's law: \( F_s = -kx \)
Conceptual Problems

C.1 Can an object move if there is no net force on it? Explain.
   ☐ Yes ☐ No

C.2 Suppose you apply a force of 1 N to block A and a force of 2 N to block B. Does it follow that block B has twice the acceleration of block A? Justify your answer using Newton’s second law.
   ☐ Yes ☐ No

C.3 When a brick rests on a flat, stationary, horizontal table, there is an upward normal force on it from the table. Explain why the brick does not accelerate upward in response to this force.

C.4 A rocket in space can change course with its engines. Since in empty space there is nothing for the exhaust gases to push on, how can it accelerate?

C.5 Blocks 1 and 2, and 2 and 3 are connected by two identical thin wires. All three blocks are resting on a frictionless table. Block 1 is pulled by a constant force and all three blocks accelerate equally in a line, with block 1 leading. Are the tensions in the two wires the same or different? If the tensions are different, which has the larger magnitude? Why?
   i. Tensions are the same
   ii. Greater between blocks 1 and 2
   iii. Greater between blocks 2 and 3

C.6 Two blocks of different mass are connected by a massless rope which goes over a massless, frictionless pulley. The rope is free to move, and both of the blocks hang vertically. What is the magnitude of the tension in the rope?
   i. The weight of the heavier block
   ii. The weight of the lighter block
   iii. Their combined weight
   iv. A value between the two weights
   v. zero

C.7 Why is the frictional force proportional to the normal force, and not weight?

C.8 A college rower can easily push a small car along a flat road, but she cannot lift the car in the air. Since the mass of the car is constant, how can you explain this discrepancy?

C.9 Without friction, you would not be able to walk along a level sidewalk. Why? (Imagine being stranded in the middle of an ice rink, wearing shoes made of ice.)

C.10 If an acrobat who weighs 800 N is clinging to a vertical pole using only his hands, neither moving up nor down, can we determine the coefficient of static friction between his hands and the pole? Explain your answer.
   ☐ Yes ☐ No

C.11 State two reasons why it is easier to push a heavy object down a hill than it is to push that same object across a flat, horizontal surface.
C.12 One end of a spring is attached firmly to a wall, and a block is attached to the other end. When the spring is fully compressed, it exerts a force \( F \) on the block, and when the spring is fully extended, the force it exerts on the block is \(-F\). What is the force of the spring on the block at (a) equilibrium (neither compressed nor stretched), (b) halfway between maximum stretch and equilibrium, and (c) halfway between maximum compression and equilibrium? Carefully consider the signs in your answer, which indicate direction, and express your answers in terms of \( F \).

(a) i. \( F \)
ii. \(-F\)
iii. 0
iv. \(-F/2\)
v. \(F/2\)

(b) i. \( F \)
ii. \(-F\)
iii. 0
iv. \(-F/2\)
v. \(F/2\)

(c) i. \( F \)
ii. \(-F\)
iii. 0
iv. \(-F/2\)
v. \(F/2\)

C.13 From the example of the falling cat, we see that the cross-sectional area of a falling object affects its terminal velocity. Does an object’s mass also affect its terminal velocity? Why or why not?

- Yes
- No

Section Problems

Section 0 - Introduction

0.1 Use the simulation in the interactive problem in this section to answer the following question. If the net force on the helicopter is zero, what must the helicopter be doing?

i. Rising
ii. Falling
iii. Staying still
iv. It can be doing any of these

Section 2 - Newton’s first law

2.1 An airplane of mass 2867 kg flies at a constant horizontal velocity. The force of air resistance on it is 2225 N. What is the net force on the plane (magnitude and direction)?

i. 0 N (direction does not matter)
ii. 2225 N opposing the motion
iii. 642 N at 30° below horizontal
iv. It is impossible to say

2.2 Three children are pulling on a toy that has a mass of 1.25 kg. Child A pulls with force (5.00, 6.00, 2.50) N. Child B pulls with force (0.00, 9.20, 2.40) N. The forces are described as \((x, y, z)\) where \(z\) represents the vertical components of the force, with a downward force being negative. With what force must Child C pull for the toy to remain stationary?

\((\_\_\_, \_\_\_, \_\_\_)\) N

Section 4 - Gravitational force: weight

4.1 A weightlifter can exert an upward force of 3750 N. If a dumbbell has a mass of 225 kg, what is the maximum number of dumbbells this weightlifter could hold simultaneously if he were on the Moon? (The Moon’s acceleration due to gravity is approximately 0.166 times freefall acceleration on Earth.) The weightlifter cannot pick up a fraction of a dumbbell, so make sure your answer is an integer.

\(\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_)\) dumbbells

4.2 (a) How much does a 70.0 kg person weigh on the Earth? (b) How much would she weigh on the Moon \((g_{\text{moon}} = 0.166g)\)? (c) How much would she weigh on a neutron star where \(g_{\text{star}} = 1.43\times10^{11}g\)?

(a) \(\_\_\_\_\_\_\_)\) N
(b) \(\_\_\_\_\_\_\_)\) N
(c) \(\_\_\_\_\_\_\_)\) N

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4.3 A dog weighs 47.0 pounds on Earth. (a) What is its weight in newtons? (One newton equals 0.225 pounds.) (b) What is its mass in kilograms?

(a) ________ N  
(b) ________ kg

4.4 A dog on Earth weighs 136 N. The same dog weighs 154 N on Neptune. What is the acceleration due to gravity on Neptune?

_______ m/s²

Section 5 - Newton’s second law

5.1 When empty, a particular helicopter of mass 3770 kg can accelerate straight upward at a maximum acceleration of 1.34 m/s². A careless crewman overloads the helicopter so that it is just unable to lift off. What is the mass of the cargo?

_______ kg

5.2 A 0.125 kg frozen hamburger patty has two forces acting on it that determine its horizontal motion. A 2.30 N force pushes it to the left, and a 0.800 N force pushes it to the right. (a) Taking right to be positive, what is the net force acting on it? (b) What is its acceleration?

(a) ________ N  
(b) ________ m/s²

5.3 In the illustration, you see the graph of an object’s acceleration over time. (a) At what moment is it experiencing the most positive force? (b) The most negative force? (c) Zero force?

(a) ________ s  
(b) ________ s  
(c) ________ s

5.4 The net force on a boat causes it to accelerate at 1.55 m/s². The mass of the boat is 215 kg. The same net force causes another boat to accelerate at 0.125 m/s². (a) What is the mass of the second boat? (b) One of the boats is now loaded on the other, and the same net force is applied to this combined mass. What acceleration does it cause?

(a) ________ kg  
(b) ________ m/s²

5.5 A flea has a mass of 4.9×10⁻⁷ kg. When a flea jumps, its rear legs act like catapults, accelerating it at 2400 m/s². What force do the flea’s legs have to exert on the ground for a flea to accelerate at this rate?

_______ N

5.6 An extreme amusement park ride accelerates its riders upward from rest to 50.0 m/s in 7.00 seconds. Ignoring air resistance, what average upward force does the seat exert on a rider who weighs 1120 N?

_______ N

5.7 A giant excavator (used in road construction) can apply a maximum vertical force of 2.25×10⁵ N. If it can vertically accelerate a load of dirt at 0.200 m/s², what is the mass of that load? Ignore the mass of the excavator itself.

_______ kg

5.8 In moving a standard computer mouse, a user applies a horizontal force of 6.00×10⁻² N. The mouse has a mass of 125 g. (a) What is the acceleration of the mouse? Ignore forces like friction that oppose its motion. (b) Assuming it starts from rest, what is its speed after moving 0.159 m across a mouse pad?

(a) ________ m/s²  
(b) ________ m/s

5.9 A solar sail is used to propel a spacecraft. It uses the pressure (force per unit area) of sunlight instead of wind. Assume the sail and its spacecraft have a mass of 245 kg. If the sail has an area of 62,500 m² and achieves a velocity of 8.93 m/s in 12.0 hours starting from rest, what pressure does light of the Sun exert on the sail? To simplify the problem, ignore other forces acting on the spacecraft and assume the pressure is constant even as its distance from the Sun increases.

_______ N/m²

5.10 A tennis player strikes a tennis ball of mass 56.7 g when it is at the top of the toss, accelerating it to 68.0 m/s in a distance of 0.0250 m. What is the average force the player exerts on the ball? Ignore any other forces acting on the ball.

_______ N
5.11 There are two forces acting on a box of golf balls, \( F_1 \) and \( F_2 \). The mass of the box is 0.750 kg. When the forces act in the same direction, they cause an acceleration of 0.450 m/s\(^2\). When they oppose one another, the box accelerates at 0.240 m/s\(^2\) in the direction of \( F_2 \). (a) What is the magnitude of \( F_1 \)? (b) What is the magnitude of \( F_2 \)?

(a) \( \text{N} \)  
(b) \( \text{N} \)

5.12 A chain of roller coaster cars moving horizontally comes to an abrupt stop and the passengers are accelerated by their safety harnesses. In one particular car in the chain, the car has a mass \( M = 122 \) kg, the first passenger has a mass \( m_1 = 55.2 \) kg, and the second passenger has a mass \( m_2 = 68.8 \) kg. If the chain of cars slows from 26.5 m/s to a stop in 4.73 s, calculate the average magnitude of force exerted by their safety harnesses on (a) the first passenger and (b) the second passenger.

(a) \( \text{N} \)  
(b) \( \text{N} \)

5.13 Cedar Point’s Top Thrill Dragster Strata-Coaster in Ohio, the fastest amusement park ride in the world as of 2004, can accelerate its riders from rest to 193 km/h in 4.00 seconds. (a) What is the magnitude of the average acceleration of a rider? (b) What is the average net force on a 45.0 kg rider during these 4.00 seconds? (c) Do people really pay money for this?

(a) \( \text{m/s}^2 \)  
(b) \( \text{N} \)  
(c) \( \text{Yes} \)  

5.14 The leader is the weakest part of a fly-fishing line. A given leader can withstand 19 N of force. A trout when caught will accelerate, taking advantage of slack in the line, and some trout are strong enough to snap the line. Assume that with the line taut and the rod unable to flex further, a 1.3 kg trout is just able to snap this leader. How much time would it take this trout to accelerate from rest to 5.0 m/s if it were free of the line? Note: Trout can reach speeds like this in this interval of time.

\( \text{s} \)

5.15 A 7.6 kg chair is pushed across a frictionless floor with a force of 42 N that is applied at an angle of 22° downward from the horizontal. What is the magnitude of the acceleration of the chair?

\( \text{m/s}^2 \)

Section 9 - Interactive problem: flying in formation

9.1 Using the simulation in the interactive problem in this section, (a) what is the force required for the red ships to accelerate at the desired magnitude? (b) What force is required for the blue ships?

(a) \( \text{N} \)  
(b) \( \text{N} \)

Section 10 - Newton’s third law

10.1 A 75.0 kg man sits on a massless cart that is on a horizontal surface. The cart is initially stationary and it can move without friction or air resistance. The man throws a 5.00 kg stone in the positive direction, applying a force to it so that it has acceleration +3.50 m/s\(^2\) as measured by a nearby observer on the ground. What is the man's acceleration during the throw, as seen by the same observer? Be careful to use correct signs.

\( \text{m/s}^2 \)

10.2 Two motionless ice skaters face each other and put their palms together. One skater pushes the other away using a constant force for 0.80 s. The second skater, who is pushed, has a mass of 110 kg and moves off with a velocity of -1.2 m/s relative to the rink. If the first skater has a mass of 45 kg, what is her velocity relative to the rink after the push? (Consider any forces other than the push acting on the skaters as negligible.)

\( \text{m/s} \)

10.3 Two cubic blocks are in contact, resting on a frictionless horizontal surface. The block on the left has a mass of \( m_L = 6.70 \) kg, and the block on the right has a mass of \( m_R = 18.4 \) kg. A force of magnitude 112 N is applied to the left face of the left block, toward the right but at an upward angle of 30.0° with respect to the horizontal. It causes the left block to push on the right block. What are (a) the direction and (b) the magnitude of the force that the right block applies to the left block?

(a) i. To the left at a 30.0° angle down  
ii. To the right at a 30.0° angle up  
iii. Directly left  
iv. Directly right  

(b) \( \text{N} \)
Section 11 - Normal force

11.1 A cup and saucer rest on a table top. The cup has mass 0.176 kg and the saucer 0.165 kg. Calculate the magnitude of the normal force (a) the saucer exerts on the cup and (b) the table exerts on the saucer.

(a) ______ N
(b) ______ N

11.2 Three blocks are arranged in a stack on a frictionless horizontal surface. The bottom block has a mass of 37.0 kg. A block of mass 18.0 kg sits on top of it and an 8 kg block sits on top of the middle block. A downward vertical force of 170 N is applied to the top block. What is the magnitude of the normal force exerted by the bottom block on the middle block?

_______ N

11.3 A 22.0 kg child slides down a slide that makes a 37.0° angle with the horizontal. (a) What is the magnitude of the normal force that the slide exerts on the child? (b) At what angle from the horizontal is this force directed? State your answer as a number between 0 and 90°.

(a) ______ N
(b) ______°

11.4 A 6.00 kg box is resting on a table. You push down on the box with a force of 8.00 N. What is the magnitude of the normal force of the table on the block?

_______ N

Section 12 - Tension

12.1 An ice rescue team pulls a stranded hiker off a frozen lake by throwing him a rope and pulling him horizontally across the essentially frictionless ice with a constant force. The hiker weighs 1040 N, and accelerates across the ice at 1.10 m/s². What is the magnitude of the tension in the rope? (Ignore the mass of the rope.)

_______ N

12.2 During recess, Maria, who has mass 27.0 kg, hangs motionless on the monkey bars, with both hands gripping a horizontal bar. Assume her arms are vertical and evenly support her body. What is the tension in each of her arms?

_______ N

Section 14 - Free-body diagrams

14.1 A tugboat is towing an oil tanker on a straight section of a river. The current in the river applies a force on the tanker that is one-half the magnitude of the force that the tugboat applies. Draw a free-body diagram for the tanker when the force provided by the tugboat is directed (a) straight upstream (b) directly cross-stream, and (c) at a 30° angle to upstream. In your drawing, let the current flow in the "left" direction, and have the tugboat pull "up" when applying a cross-stream force. Label the force vectors.

14.2 A person lifts a 3.60 kg textbook (remember when they were made of paper and so heavy?) with a 52.0 N force at a 60.0° angle from the horizontal. (a) Draw a free-body diagram of the forces acting on the book, ignoring air resistance. Label the forces. (b) Draw a free-body diagram showing the net force acting on the book.

14.3 A 17.0 N force $F$ acting on a 4.00 kg block is directed at 30.0° from the horizontal, parallel to the surface of a frictionless ramp. Draw a free-body diagram of the forces acting on the block, including the normal force, and label the forces. Make sure the vectors are roughly proportional to the forces!

14.4 An apple is resting on a table. Draw free-body diagrams for the apple, table and the Earth.
Section 15 - Interactive problem: free-body diagram

15.1 Using simulation in the interactive problem in this section, what are the direction and magnitude of (a) the weight, (b) the normal force, (c) the tension, and (d) the frictional force that meet the stated requirements and give the desired acceleration?

(a) \( \text{_______ N, } \)
   i. Up
   ii. Down
   iii. Left
   iv. Right

(b) \( \text{_______ N, } \)
   i. Up
   ii. Down
   iii. Left
   iv. Right

(c) \( \text{_______ N, } \)
   i. Up
   ii. Down
   iii. Left
   iv. Right

(d) \( \text{_______ N, } \)
   i. Up
   ii. Down
   iii. Left
   iv. Right

Section 17 - Interactive problem: lifting crates

17.1 Use the helicopter in the simulation in the interactive problem in this section to find the crate with the given mass.
   i. The leftmost crate
   ii. The middle crate
   iii. The rightmost crate

Section 19 - Static friction

19.1 A piece of steel is held firmly in the jaws of a vise. A force larger than 3350 N will cause the piece of steel to start to move out of the vise. If the coefficient of friction between the steel and each of the jaws of the vise is 0.825 and each jaw applies an equal force, what is the magnitude of the normal force exerted on the steel by each jaw?
   \( \text{_______ N} \)

19.2 A wooden block of mass 29.0 kg sits on a horizontal table. A wire of negligible mass is attached to the right side of the block and goes over a pulley (also of negligible mass, and frictionless), where it is allowed to dangle vertically. When a mass of 15.5 kg is attached to the dangling wire, the block on the table just barely starts to slide. What is the coefficient of static friction between the block and the table?
   \( \text{_______} \)

19.3 The Occupational Safety and Health Administration (OSHA) suggests a minimum coefficient of static friction of \( \mu_s = 0.50 \) for floors. If Ethan, who has mass of 53 kg, stands passively, how much horizontal force can be applied on him before he will slip on a floor with OSHA's minimum coefficient of static friction?
   \( \text{_______ N} \)

19.4 A block of mass \( m \) sits on top of a larger block of mass \( 2m \), which in turn sits on a flat, frictionless table. The coefficient of static friction between the two blocks is \( \mu_s \). What is the largest possible horizontal acceleration you can give the bottom block without the top block slipping?
   \( \circ \mu_s g/2 \)
   \( \circ \mu_s g \)
   \( \circ 2\mu_s g \)
Section 20 - Kinetic friction

20.1 A 1.0 kg brick is pushed against a vertical wall by a horizontal force of 24 N. If \( \mu_s = 0.80 \) and \( \mu_k = 0.70 \) what is the acceleration of the brick?

\[
\text{\text{m/s}^2}
\]

20.2 A firefighter whose weight is 812 N is sliding down a vertical pole, her speed increasing at the rate of 1.45 m/s\(^2\). Gravity and friction are the two significant forces acting on her. What is the magnitude of the frictional force?

\[
\text{N}
\]

20.3 A plastic box of mass 1.1 kg slides along a horizontal table. Its initial speed is 3.9 m/s, and the force of kinetic friction opposes its motion, causing it to stop after 3.1 s. What is the coefficient of kinetic friction between the block and the table?

\[
\text{ Dimensionless}
\]

20.4 An old car is traveling down a long, straight, dry road at 25.0 m/s when the driver slams on the brakes, locking the wheels. The car comes to a complete stop after sliding 215 m in a straight line. If the car has a mass of 755 kg, what is the coefficient of kinetic friction between the tires and the road?

\[
\text{Dimensionless}
\]

20.5 A rescue worker pulls an injured skier lying on a toboggan (with a combined mass of 127 kg) across flat snow at a constant speed. A 2.43 m rope is attached to the toboggan at ground level, and the rescuer holds the rope taut at shoulder level. If the rescuer's shoulders are 1.65 m above the ground, and the tension in the rope is 148 N, what is the coefficient of kinetic friction between the toboggan and the snow?

\[
\text{Dimensionless}
\]

20.6 You are trying to move a chair of mass 29.0 kg by pushing it horizontally along the floor, but it is not sliding very easily. The coefficient of kinetic friction between the chair and the floor is 0.700. (a) If you push the chair with a horizontal force, what is the magnitude of the minimum force that will keep the chair moving at a constant velocity? (b) If the force on the chair is directed 30.0 degrees up from the horizontal, what is the magnitude of the minimum force that will keep the chair moving at a constant velocity? (c) What if the angle is 75.0 degrees from the horizontal?

(a) \[
\text{N}
\]

(b) \[
\text{N}
\]

(c) \[
\text{N}
\]

Section 24 - Interactive problem: forces on a sliding block

24.1 Using the simulation in the interactive problem in this section, what are the direction and magnitude of (a) the weight, (b) the normal force, (c) the frictional force, and (d) the tension that meet the stated requirements and give the desired acceleration?

(a) \[
\text{N, i. Straight up}
\]

ii. Straight down

iii. Up the plane

iv. To the right

(b) \[
\text{N, i. Straight up}
\]

ii. Straight down

iii. Up and to the left

iv. To the right

(c) \[
\text{N, i. Down the plane}
\]

ii. Up the plane

iii. To the right

iv. To the left

(d) \[
\text{N, i. Down the plane}
\]

ii. Up the plane

iii. Perpendicular to the plane

iv. Straight down
Section 25 - Sample problem: moving down a frictionless plane

25.1 A child sits on a freshly oiled, straight stair rail that is effectively frictionless and slides down it. She has a mass of 25 kg, and the rail makes an angle of 40° above the ground. If she slides 4.0 m before reaching the bottom, what is her speed there?

_______ m/s

25.2 A shipping container is hauled up a roller ramp that is effectively frictionless at a constant speed of 2.10 m/s by a 2250 N force that is parallel to the ramp. If the ramp is at a 24.6° incline, what is the container's mass?

_______ kg

Section 28 - Hooke's law and spring force

28.1 A 10.0 kg mass is placed on a frictionless, horizontal surface. The mass is connected to the end of a horizontal compressed spring which has a spring constant 339 N/m. When the spring is released, the mass has an initial, positive acceleration of 10.2 m/s². What was the displacement of the spring, as measured from equilibrium, before the block was released? Watch the sign of your answer.

_______ m

28.2 Consider a large spring, hanging vertically, with spring constant \( k = 3220 \text{ N/m} \). If the spring is stretched 25.0 cm from equilibrium and a block is attached to the end, the block stays still, neither accelerating upward nor downward. What is the mass of the block?

_______ kg

28.3 A spring with spring constant \( k = 15.0 \text{ N/m} \) hangs vertically from the ceiling. A 1.20 kg mass is attached to the bottom end of the spring, and allowed to hang freely until it becomes stationary. Then, the mass is pulled downward 10.0 cm from its resting position and released. At the moment of its release, what is (a) the magnitude of the mass's acceleration and (b) the direction? Ignore the mass of the spring.

(a) _______ m/s²
(b) i. Downward
   ii. Upward

28.4 A 5.00 kg wood cube rests on a frictionless horizontal table. It has two springs attached to it on opposite faces. The spring on the left has a spring constant of 55.0 N/m, and the spring on the right has a spring constant of 111 N/m. Both springs are initially in their equilibrium positions (neither compressed nor stretched). The block is moved toward the left 10.0 cm, compressing the left spring and stretching the right spring. (a) Calculate the resulting net force on the block. (b) Calculate the initial acceleration of the block when it is released. Use the convention that to the right is positive and to the left is negative.

(a) _______ N
(b) _______ m/s²

28.5 A man steps on his bathroom scale and obtains a reading of 243 lb. The spring in the scale is compressed by a displacement of \( \sim 0.0590 \text{ inches} \). Calculate the value of its spring constant in (a) pounds per inch (b) newtons per meter.

(a) _______ lbs/in
(b) _______ N/m

Section 30 - Air resistance

30.1 A parachutist and her parachuting equipment have a combined mass of 101 kg. Her terminal velocity is 5.30 m/s with the parachute open. Her parachute has a cross-sectional area of 35.8 m². The density of air at that altitude is 1.23 kg/m³. What is the drag coefficient of the parachutist with her parachute?

_______

30.2 A tennis ball of mass 57.0 g is dropped from the observation deck of the Empire State building (369 m). The tennis ball has a cross-sectional area of \( 3.50 \times 10^{-3} \text{ m}^2 \) and a drag coefficient of 0.600. Using 1.23 kg/m³ for the density of air, (a) what is the speed of the ball when it hits the ground? (b) What would be the final speed of the ball if you did not include air resistance in your calculations? Remember to use the appropriate sign when answering the question.

(a) _______ m/s
(b) _______ m/s

Section 31 - Interactive summary problem: helicopter pilot

31.1 Use the simulation in the interactive problem in this section to calculate the lift force required for the helicopter to pick up the crate.

_______ N

Copyright 2000-2010 Kinetic Books Co. Chapter 5 Problems
A.1 A woman is pushing a box along the ground. She is exerting a horizontal force of 156 N on the box. The box has a mass of 84.0 kg, and has an opposing horizontal frictional force of 135 N. What is the coefficient of kinetic friction between the box and the ground?

A.2 A rocket skateboard of mass 3.00 kg has an initial velocity of (5.00, 2.50) m/s. A net force of (3.40, 2.67) N is applied to it for 10.0 s. At the end of this time, what is its velocity?

(_______, _________) m/s

A.3 A popular ride at an amusement park involves standing in a cylindrical room. The room rotates and the wall presses against the rider as the floor drops down until the rider is no longer touching it. Annabel has a mass of 46.0 kg and the coefficient of static friction between the wall and her is 0.450. What is the minimum normal force exerted on her from the wall that will keep Annabel from sliding down?

_________ N

A.4 A large crate has a mass of 214 kg. A horizontal force of positive 196 N is applied to it, causing it to accelerate at 0.130 m/s² horizontally. What is the force of friction opposing the motion of the crate? Use the correct sign to indicate the direction of the force of friction. It is the sole force opposing the crate's motion in this direction.

_________ N

A.5 A ball moving through a special sticky fluid encounters a drag force whose magnitude, in newtons, is proportional to the fourth power of its velocity, expressed in meters per second. That is, $F_D = Av^4$. (a) What are the units of the coefficient “$A$”? Express your answer using the SI base units of kilograms, meters, and seconds. (b) If a ball of mass $m$ is dropped from rest into a deep container of the sticky fluid, find an expression for the terminal velocity that it reaches.

(a) $\bigcirc$ kg·m/s $\bigcirc$ kg·s²/m³ $\bigcirc$ kg·m²/s³ $\bigcirc$ kg·s/m²
(b) Submit answer on paper.

A.6 A 2.0 kg mass rests on a frictionless wedge that has an acceleration of 15 m/s² to the right. The mass remains stationary relative to the wedge, moving neither higher nor lower. (a) What is the angle of inclination, $\theta$, of the wedge? (b) What is the magnitude of the normal force exerted on the mass by the incline? (c) What would happen if the wedge were given a greater acceleration?

(a) __________°
(b) __________ N
(c) i. The block would slide up the wedge
ii. The block would remain at the same location on the wedge
iii. The block would slide down the wedge

A.7 Consider a road bicycle being pedaled along a level street. The foot pedals drive a chain that supplies the force of the biker’s legs to the rear wheel, rotating it. The bike accelerates forward, and both tires roll without slipping along the road. (a) In which direction, forward or backward, does friction exert a force on the rear tire? (b) In which direction does friction act on the front tire? (c) Explain your answers.

(a) i. Forward
ii. Backward
(b) i. Forward
ii. Backward
(c) Submit answer on paper