Newton's Laws of Motion

Newton's laws of motion are three separate statements that explain how and why objects move or stay at rest. When a player hits a puck on an air hockey table, as in **Figure 1**, Newton's laws describe what happens to the puck before, during, and after the collision with the paddle. Newton's laws also describe the forces the objects exert on each other. You can use these three laws to explain the motion of many types of objects experiencing and exerting different types of forces.

Figure 1 Newton's laws of motion describe what happens to a puck on an air hockey table.

Newton's First Law of Motion

If you watch a puck move across an air hockey table, you will notice that it moves at a relatively constant velocity. This is because the puck floats on a cushion of air and moves with very little friction acting on it. In fact, the net force on the puck is virtually zero. In addition, when the puck is at rest and no one hits it, the puck will remain at rest. This example demonstrates **Newton's first law of motion**.

> **Newton's First Law of Motion**
>
> If the external net force on an object is zero, the object will remain at rest or continue to move at a constant velocity.

Some important implications of Newton's first law are the following:

- A net force is not required for an object to maintain a constant velocity.
- A net force is required to change the velocity of an object in magnitude, direction, or both.
- External forces are required to change the motion of an object. Internal forces have no effect on an object's motion.

Inertia and Mass

Galileo introduced the concept of inertia, and Newton used this concept to develop his first law of motion. **Inertia** is the property of matter that causes an object to resist any changes in motion. This means that an object at rest will stay at rest unless a net force acts on it. In addition, if an object is in motion, it will maintain a constant velocity unless a net force acts on it. The concept of inertia is closely related to Newton's first law.

inertia a measure of an object's resistance to change in velocity

Some objects have more inertia than others. In fact, objects that have more mass have more inertia. The degree to which an object resists a change in motion depends on the magnitude of the object's mass. **Mass** is a measure of the amount of matter in an object. The SI unit for mass is the kilogram (kg). Objects that contain a small amount of matter have a smaller mass and less inertia than objects that contain a large amount of matter. For example, a basketball has a mass of approximately 0.62 kg, and a volleyball has a mass of approximately 0.28 kg. If you hit each one with an equal force, the heavier ball (basketball) changes its motion less than the lighter ball (volleyball). Inertia is directly proportional to the mass of the object.

mass a measure of the amount of matter in an object

Newton's Second Law of Motion

Newton's second law of motion explains the relationship between mass, acceleration, and net force.

Newton's Second Law of Motion

If the net external force on an object is not zero, the object will accelerate in the direction of the net force. The magnitude of the acceleration is directly proportional to the magnitude of the net force and inversely proportional to the object's mass.

The acceleration of an object with mass m is then given by

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

Newton's second law is often written in the equivalent form

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

Recall from Section 2.1 that the net force, or total force, on an object is the sum of all the individual external forces, $\vec{F}_{net} = \vec{F}_{total} = \Sigma\vec{F}$. In most cases, more than one force acts on an object at any given time. To determine the total force, you add all these forces together. That resulting vector sum is the force $\Sigma\vec{F}$ in Newton's second law, as shown in **Figure 2**. Newton's second law, $\Sigma\vec{F} = m\vec{a}$, indicates that the acceleration of an object, $\vec{a}$, is always parallel to the net force, $\Sigma\vec{F}$, acting on the object (Figure 2). However, since acceleration and velocity might be in different directions, velocity and net force need not be in the same direction. For example, you can be moving forward in a car while applying the brakes. You and the car are still moving forward, but you are accelerating backward.
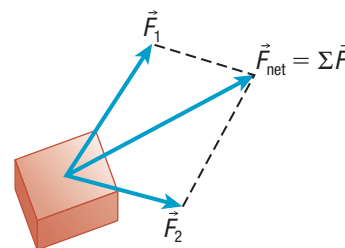
Figure 2 When several forces act on an object, the vector sum of these forces determines the acceleration, according to Newton's second law.

THE NEWTON

You can write the newton in terms of the SI units for mass (kilograms) and acceleration (metres per second squared):

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

$N = kg{\cdot}m/s^2$

The value of the newton as a unit of force is therefore

$$1\ N = 1\ kg{\cdot}m/s^2$$

In the following Tutorial, you will use the equation for Newton's second law of motion to predict how several different forces act on an object.

The following Sample Problem models how to calculate the acceleration of an object.

Sample Problem 1: Calculating Acceleration and Direction

Two tugboats are pulling a 4.2×10^3 kg barge into a harbour (**Figure 3**). The first tugboat exerts a constant force of 1.8×10^3 N [E 37° N]. The second tugboat exerts a constant force of 1.3×10^3 N [E 12° S]. Calculate the acceleration (magnitude and direction) of the barge. Assume there is no friction acting on the barge.
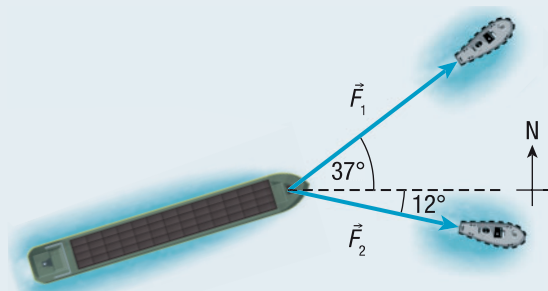
Figure 3

Given: $m = 4.2 \times 10^3$ kg; $F_1 = 1.8 \times 10^3$ N; $F_2 = 1.3 \times 10^3$ N; $\theta_1 = $ [E 37° N]; $\theta_2 = $ [E 12° S]
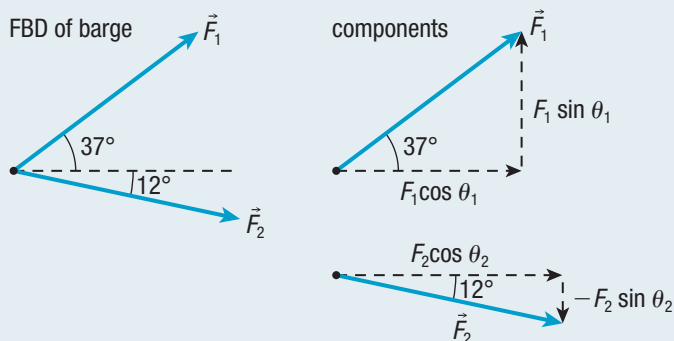
Required: the acceleration of the barge, a; the angle at which the barge moves, θ

Analysis: Use north and east as positive for components. Break the force into its components using $\Sigma F_x = F_1 \cos \theta_1 + F_2 \cos \theta_2$ and $\Sigma F_y = F_1 \sin \theta_1 + (-F_2 \sin \theta_2)$. Draw an FBD.

Use $\theta = \tan^{-1}\left(\dfrac{\Sigma F_y}{\Sigma F_x}\right)$ to determine the direction of the force.

Use $|\Sigma \vec{F}| = \sqrt{(F_x)^2 + (F_y)^2}$ to calculate the magnitude of the force. Use $\Sigma \vec{F} = m\vec{a}$ to calculate the acceleration.

Solution:

FBD of barge

components

$$\Sigma F_x = F_1 \cos \theta_1 + F_2 \cos \theta_2$$
$$= (1.8 \times 10^3 \text{ N})\cos 37° + (1.3 \times 10^3 \text{ N})\cos 12°$$
$$\Sigma F_x = 2.7 \times 10^3 \text{ N}$$

$$\Sigma F_y = F_1 \sin \theta_1 + (-F_2 \sin \theta_2)$$
$$= (1.8 \times 10^3 \text{ N})\sin 37° + (-(1.3 \times 10^3 \text{ N})\sin 12°)$$
$$\Sigma F_y = 8.13 \times 10^2 \text{ N (one extra digit carried)}$$

The direction of the force is

$$\theta = \tan^{-1}\left(\frac{\Sigma F_y}{\Sigma F_x}\right)$$
$$= \tan^{-1}\left(\frac{8.13 \times 10^2 \text{ N}}{2.7 \times 10^3 \text{ N}}\right)$$
$$\theta = 17°$$

The magnitude is

$$|\Sigma \vec{F}| = \sqrt{(F_x)^2 + (F_y)^2}$$
$$= \sqrt{(2.7 \times 10^3 \text{ N})^2 + (8.13 \times 10^2 \text{ N})^2}$$
$$= 2.82 \times 10^3 \text{ N}$$
$$|\Sigma \vec{F}| = 2.8 \times 10^3 \text{ N}$$

The acceleration of the barge is

$$\Sigma \vec{F} = m\vec{a}$$
$$\vec{a} = \frac{\Sigma \vec{F}}{m}$$
$$= \frac{2.82 \times 10^3 \text{ N } [\text{E } 17° \text{ N}]}{4.2 \times 10^3 \text{ kg}}$$
$$\vec{a} = 0.67 \text{ m/s}^2 \, [\text{E } 17° \text{ N}]$$

Statement: The acceleration of the barge is 0.67 m/s² [E 17° N].

Practice

1. For each of the following, determine the acceleration of the mass. Assume no other forces act on the object other than the ones given. **T/I**
   (a) a mass of 1.2×10^2 kg with a force of 1.5×10^2 N [N] and a force of 2.2×10^2 N [W] acting on it [ans: 2.2 m/s² [N 56° W]]
   (b) a mass of 26 kg with a force of 38 N [N 24° E] and a force of 52 N [N 36° E] acting on it [ans: 3.4 m/s² [N 31° E]]

2. Two students push horizontally on a large, 65 kg trunk. The trunk moves east with an acceleration of 2.0 m/s². One student pushes with a force of 2.2×10^2 N [E 42° S]. The force of friction acting on the trunk is 1.9×10^2 N [W]. Determine the force that the other student applies to the trunk. **T/I** [ans: 2.1×10^2 N [E 43° N]]

3. Two ropes are used to lift a 1.5×10^2 kg beam with a force of gravity of 1.47×10^3 N [down] acting on it. One rope exerts a force of tension of 1.8×10^3 N [up 30.0° left] on the beam, and the other rope exerts a force of tension of 1.8×10^3 N [up 30.0° right] on the beam. Calculate the acceleration of the beam. **T/I** [ans: 11 m/s² [up]]

Newton's Third Law of Motion

Newton's first two laws of motion deal with a single object and the forces acting on it. **Newton's third law of motion** deals with the forces that two objects exert on each other.

> **Newton's Third Law of Motion**
>
> For every action force, there exists a simultaneous reaction force that is equal in magnitude but opposite in direction.

Newton's third law is also known as the action–reaction principle. For example, if you push east on a wall, the wall exerts a simultaneous force west on you, causing you to move away from the wall. Newton's third law states that action–reaction forces always come in pairs. According to Newton's third law, these two equal and opposite forces must always act on different objects. In Tutorial 2, you will use the equation for Newton's second law of motion to demonstrate Newton's third law of motion.

Tutorial 2 / Solving Problems Related to Newton's Third Law

The following Sample Problem shows how to use Newton's second law of motion to calculate the acceleration of two objects in an action–reaction pair.

Sample Problem 1: Calculating Acceleration Due to Newton's Third Law

The person on roller blades in **Figure 4** is pushing on a refrigerator that sits on a cart on a level floor. Assume no force of friction exists on either the person or the refrigerator. The person has a mass of 60.0 kg, and the refrigerator has a mass of 1.2×10^2 kg. The force exerted by the person on the refrigerator is 1.8×10^2 N [forward]. Calculate the refrigerator's acceleration and the person's acceleration.

Figure 4

Given: $m_{person} = 60.0$ kg; $m_{refrigerator} = 1.2 \times 10^2$ kg; $\vec{F}_a = 1.8 \times 10^2$ N [forward]

Required: $\vec{a}_{refrigerator}$; $\vec{a}_{person}$

Analysis: The forces acting on the refrigerator are gravity, the normal force, and the force applied by the person on the refrigerator. The floor is level, so gravity and the normal force cancel each other. Use Newton's second law to determine the refrigerator's acceleration, $\vec{a} = \dfrac{\Sigma \vec{F}}{m}$. Use the same equation to determine the person's acceleration. The action force of the person on the refrigerator is equal to the reaction force of the refrigerator on the person in magnitude but opposite in direction.

Solution: $\vec{a}_{refrigerator} = \dfrac{\Sigma \vec{F}}{m}$

$= \dfrac{1.8 \times 10^2 \text{ N [forward]}}{1.2 \times 10^2 \text{ kg}}$

$\vec{a}_{refrigerator} = 1.5 \text{ m/s}^2 \text{ [forward]}$

$\vec{a}_{person} = \dfrac{\Sigma \vec{F}}{m}$

$= \dfrac{1.8 \times 10^2 \text{ N [backward]}}{60.0 \text{ kg}}$

$\vec{a}_{person} = 3.0 \text{ m/s}^2 \text{ [backward]}$

Statement: The acceleration of the refrigerator is 1.5 m/s² [forward], and the acceleration of the person is 3.0 m/s² [backward].

Practice

1. Use Newton's third law to explain the motion of each of the following objects. Identify the action and reaction forces and their directions. K/U T/I A
   (a) a rocket leaving a launch pad
   (b) an airplane flying at a constant velocity
   (c) a runner's foot pushing straight down on the ground

2. A swimmer with a mass of 56 kg pushes horizontally against the pool wall toward the east for 0.75 s with a constant force. Having started from rest, the swimmer glides to a maximum speed of 75 cm/s. Neglecting friction, determine the magnitude of
   (a) the (constant) acceleration [ans: 1.0 m/s² [W]]
   (b) the force exerted by the swimmer on the wall [ans: 56 N [E]]
   (c) the force exerted by the wall on the swimmer [ans: 56 N [W]]
   (d) the displacement of the swimmer from the wall after 1.50 s K/U T/I A [ans: 0.84 m [W]]

3. A boy is floating on an air mattress in a swimming pool. The mass of the boy is 32.5 kg, and the mass of the mattress is 2.50 kg. T/I
   (a) Calculate the upward force of the water on the mattress. [ans: 3.4 × 10² N]
   (b) Calculate the force that the boy exerts on the mattress. [ans: 3.2 × 10² N]
   (c) Calculate the upward force of the mattress on the boy. [ans: 3.2 × 10² N]

4. A projectile launcher fires a projectile horizontally from a platform, which rests on a flat, icy, frictionless surface. Just after the projectile is fired and while it is moving through the launcher, the projectile has an acceleration of 25 m/s². At the same time, the launcher has an acceleration of 0.25 m/s². The mass of the projectile is 0.20 kg. Calculate the mass of the launcher. K/U T/I A [ans: 20 kg]

The Gravitational Force

Earth's force of gravity is something you are quite familiar with from everyday life. However, Newton realized that gravity is an attractive force between all objects, including the motion of the planets and stars. As mentioned in Section 2.1, the gravitational force is weak when the objects are far apart and/or small. However, Earth is so much more massive than any other nearby objects that the strongest gravitational attraction on objects around you is toward Earth.

You know that if you allow an object to fall, it will accelerate downward (in the absence of air resistance). The acceleration due to gravity near Earth's surface varies depending on the distance from Earth's surface. At or near Earth's surface, the

acceleration due to gravity is $\vec{g} = 9.8$ m/s² [down] (to two significant digits) when the object is in free fall. When an object is in free fall, it is moving toward Earth with only the force of gravity acting on it. In other words, we are assuming that air resistance is negligible.
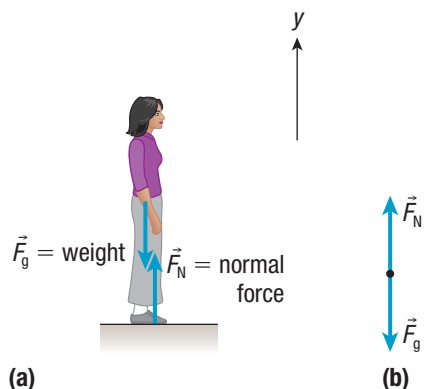
Weight and the Normal Force

According to Newton's second law, when an object is in free fall, $\Sigma\vec{F} = m\vec{a}$, where $\vec{a} = \vec{g}$. Since the only force acting on the object is gravity, then $\Sigma\vec{F} = \vec{F}_g$. Therefore, the force of gravity is given by $\vec{F}_g = m\vec{g}$.

Another name for the gravitational force is **weight**. The weight, $\vec{F}_g$, of an object is a force and is therefore measured in newtons (N). It is often convenient to indicate a force that is directed downward by making the force negative, so when solving problems you will often use $F_g = -mg$. The negative sign here indicates that the force is in the negative y-direction, or down, toward the centre of Earth.

As you can see in **Figure 5**, in addition to the gravitational force, another force acting on the person is the normal force exerted by the floor on her feet. The person in Figure 5 is at rest with an acceleration of zero. Using Newton's second law for components of the force and acceleration along y, you see that

$$\Sigma F = -mg + F_N$$
$$ma = -mg + F_N$$
$$0 = -mg + F_N$$
$$F_N = mg$$

(a)   (b)

Figure 5 (a) The person standing still has two forces acting on her. (b) The FBD of the person in (a) shows all the forces acting on her.

In this case, the normal force is equal in magnitude and opposite in direction to the person's weight. This raises two common misconceptions in physics, which need to be cleared up at this point.

First, the normal force is not the reaction force to gravity. The reaction force to the force of gravity is another force of gravity. The normal force is the reaction force to the object applying a force to the surface.

Second, since the normal force is not the reaction force to gravity, the normal force is not always equal in magnitude and opposite in direction to the force of gravity. If someone pushed down on the shoulders of the person in Figure 5, the normal force would increase, but the force of gravity on the person remains the same. If the person in Figure 5 were standing on a ramp, the normal force would be perpendicular to the ramp and no longer vertical, but gravity would still point straight down.

weight the gravitational force exerted by Earth on an object

UNIT TASK **BOOKMARK**
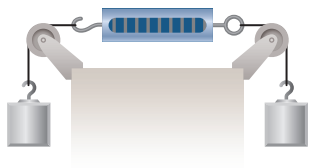
You can apply what you have learned about Newton's laws of motion to the Unit Task on page 146.

Summary

- Newton's first law states that when the external net force on an object is zero, the object will remain at rest or continue moving at a constant velocity.
- Inertia causes matter to resist changes in motion.
- Newton's second law states that when the net external force on an object is not zero, the object will accelerate in the direction of the net force. The magnitude of the acceleration is directly proportional to the magnitude of the net force and inversely proportional to the mass: $\vec{a} = \dfrac{\Sigma \vec{F}}{m}$; also $\Sigma \vec{F} = m\vec{a}$.
- Newton's third law states that for every action force, there exists a simultaneous reaction force that is equal in magnitude and opposite in direction.
- Earth's force of gravity on an object is the object's weight. The force of gravity at Earth's surface is determined using the equation $\vec{F}_g = m\vec{g}$.

Questions

1. A snowboarder is sliding downhill when she suddenly encounters a rough patch. Use Newton's first law of motion to describe and explain what will likely happen to the snowboarder. K/U T/I

2. You are sitting on a bus moving at 50 km/h [E] when you toss a ball in front of you and straight up into the air. The ball reaches a height close to your eyes. Will the ball hit you in the face? Explain. K/U

3. A child is sliding across the ice on a sled with an initial velocity of 4.2 m/s [E]. The combined mass of the child and the sled is 41 kg. There is a constant force of friction between the ice and the sled of 25 N. K/U A
   (a) Calculate the child's acceleration across the ice.
   (b) How long will it take the child to stop?

4. An object moves with an acceleration of magnitude 12 m/s² while it is subjected to a force of magnitude 2.2×10^2 N. Determine the mass of the object. K/U T/I A

5. Your friend's car has broken down, so you volunteer to push it with your own car to the nearest repair shop, which is 2.0 km away. You carefully move your car so that the bumpers of the two cars are in contact. You then slowly accelerate to a speed of 2.5 m/s over the course of 1.0 min. The mass of your friend's car is 1.2×10^3 kg. K/U T/I A
   (a) Calculate the normal force between the two bumpers.
   (b) You then maintain the speed of 2.5 m/s. How long does it take you to reach the repair shop?

6. Two forces act on a 250 kg mass, 150 N [E] and 350 N [S 45° W]. Calculate the acceleration of the mass. T/I

7. In each of the examples below, identify an action–reaction pair of forces. K/U T/I A
   (a) A tennis racquet hits a tennis ball, exerting a force on the ball.
   (b) A car is moving at high speed and runs into a tree, exerting a force on the tree.
   (c) Two cars are moving in opposite directions and collide head-on.
   (d) A person leans on a wall, exerting a force on the wall.
   (e) A mass hangs by a string attached to the ceiling, and the string exerts a force on the mass.
   (f) A bird sits on a telephone pole, exerting a force on the pole.

8. Two 5.2 kg masses are suspended as shown in **Figure 6**. K/U T/I

Figure 6

   (a) Determine the tension in each string.
   (b) Determine the reading on the spring scale.
   (c) How would your answers to (a) and (b) change if you replaced one mass with your hand and held everything at rest? Explain your answer.

9. An athlete with a mass of 62 kg jumps and lands on the ground on his feet. The ground exerts a total force of 1.1×10^3 N [backward 55° up] on his feet. Calculate the acceleration of the athlete. T/I