Newton's Laws of Motion

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CHAPTER 1 Newton's Laws of Motion

CHAPTER OUTLINE

The sprinter in this photo is pushing off from the blocks at the start of a race. The blocks provide a counter force so she can take off in a hurry. With great effort, she will go from motionless to top speed in just a few seconds. She won't slow down until she crosses the finish line. By then, she will be going so fast that it will take her almost as much time to come to a full stop as it did to run the race.

No doubt you've experienced motions like these, even if you've never run a race. But do you know what explains these motions? For example, do you know why it's as hard to stop running as it is to start? These and other aspects of motion are explained by three laws of motion. The laws were developed by Sir Isaac Newton in the late 1600s. You'll learn about Newton's laws of motion in this chapter and how and why objects move as they do.

1.1 Newton's First Law

Lesson Objectives

- State Newton's first law of motion.
- Define inertia, and explain its relationship to mass.

Lesson Vocabulary

- inertia
- Newton's first law of motion

Introduction

The amusement park ride pictured in **Figure** 1.1 keeps changing direction as it zooms back and forth. Each time it abruptly switches direction, the riders are forced to the opposite side of the car. What force causes this to happen? In this lesson, you'll find out.

FIGURE 1.1
Amusement park rides like this one are exciting because of the strong forces the riders feel.

Force and Motion

Newton's first law of motion states that an object's motion will not change unless an unbalanced force acts on the object. If the object is at rest, it will stay at rest. If the object is in motion, it will stay in motion and its velocity will remain the same. In other words, neither the direction nor the speed of the object will change as long as the net force acting on it is zero. You can watch a video about Newton's first law at this URL: http://videos.howstuffworks.com/discovery/29382-assignment-discovery-newtons-first-law-video.htm.

Look at the pool balls in **Figure** 1.2. When a pool player pushes the pool stick against the white ball, the white ball is set into motion. Once the white ball is rolling, it rolls all the way across the table and stops moving only after it crashes into the cluster of colored balls. Then, the force of the collision starts the colored balls moving. Some may roll until they bounce off the raised sides of the table. Some may fall down into the holes at the edges of the table. None of these motions will occur, however, unless that initial push of the pool stick is applied. As long as the net force on the balls is zero, they will remain at rest.

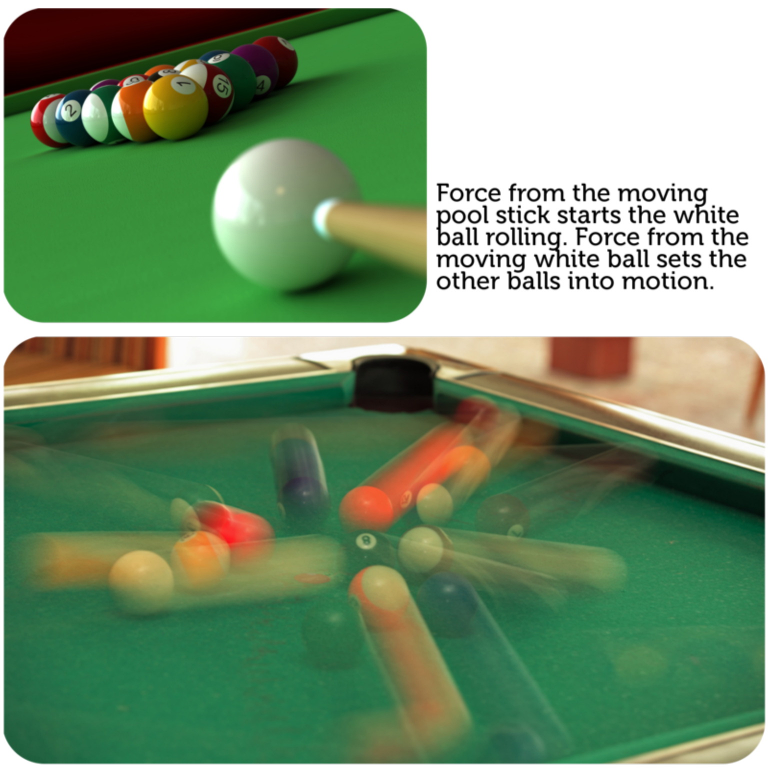

FIGURE 1.2
Pool balls remain at rest until an unbalanced force is applied to them. After they are in motion, they stay in motion until another force opposes their motion.

Inertia

Newton's first law of motion is also called the law of inertia. **Inertia** is the tendency of an object to resist a change in its motion. If an object is already at rest, inertia will keep it at rest. If the object is already moving, inertia will keep it moving.

Think about what happens when you are riding in a car that stops suddenly. Your body moves forward on the seat. Why? The brakes stop the car but not your body, so your body keeps moving forward because of inertia. That's why it's important to always wear a seat belt. Inertia also explains the amusement park ride in **Figure** 1.1. The car keeps changing direction, but the riders keep moving in the same direction as before. They slide to the opposite side of the car as a result. You can see an animation of inertia at this URL: http://www.physicsclassroom.com/mmedia/newtlaws/cci.cfm.

Inertia and Mass

The inertia of an object depends on its mass. Objects with greater mass also have greater inertia. Think how hard it would be to push a big box full of books, like the one in **Figure** 1.3. Then think how easy it would be to push the box if it was empty. The full box is harder to move because it has greater mass and therefore greater inertia.

FIGURE 1.3
The tendency of an object to resist a change in its motion depends on its mass. Which box has greater inertia?

Overcoming Inertia

To change the motion of an object, inertia must be overcome by an unbalanced force acting on the object. Until the soccer player kicks the ball in **Figure** 1.4, the ball remains motionless on the ground. However, when the ball is kicked, the force on it is suddenly unbalanced. The ball starts moving across the field because its inertia has been overcome.

FIGURE 1.4
Force must be applied to overcome the inertia of a soccer ball at rest.

Once objects start moving, inertia keeps them moving without any additional force being applied. In fact, they won't stop moving unless another unbalanced force opposes their motion. What if the rolling soccer ball is not kicked by another player or stopped by a fence or other object? Will it just keep rolling forever? It would if another unbalanced force did not oppose its motion. Friction — in this case rolling friction with the ground — will oppose the motion of the rolling soccer ball. As a result, the ball will eventually come to rest. Friction opposes the motion of all moving objects, so, like the soccer ball, all moving objects eventually come to a stop even if no other forces oppose their motion.

Lesson Summary

- Newton's first law of motion states that an object's motion will not change unless an unbalanced force acts on the object. If the object is at rest, it will stay at rest. If the object is in motion, it will stay in motion.
- Inertia is the tendency of an object to resist a change in its motion. The inertia of an object depends on its mass. Objects with greater mass have greater inertia. To overcome inertia, an unbalanced force must be applied to an object.

Lesson Review Questions

Recall

1. State Newton's first law of motion.
2. Define inertia.
3. How does an object's mass affect its inertia?

Apply Concepts

4. Assume you are riding a skateboard and you run into a curb. Your skateboard suddenly stops its forward motion. Apply the concept of inertia to this scenario, and explain what happens next.

Think Critically

5. Why is Newton's first law of motion also called the law of inertia?

Points to Consider

In this lesson, you read that the mass of an object determines its inertia. You also learned that an unbalanced force must be applied to an object to overcome its inertia, whether it is moving or at rest. An unbalanced force causes an object to accelerate.

- Predict how the mass of an object affects its acceleration when an unbalanced force is applied to it.
- How do you think the acceleration of an object is related to the strength of the unbalanced force acting on it?

1.2 Newton's Second Law

Lesson Objectives

- State Newton's second law of motion.
- Identify the relationship between acceleration and weight.

Lesson Vocabulary

- Newton's second law of motion

Introduction

A car's gas pedal, like the one in **Figure** 1.5, is sometimes called the accelerator. That's because it controls the acceleration of the car. Pressing down on the gas pedal gives the car more gas and causes the car to speed up. Letting up on the gas pedal gives the car less gas and causes the car to slow down. Whenever an object speeds up, slows down, or changes direction, it accelerates. Acceleration is a measure of the change in velocity of a moving object. Acceleration occurs whenever an object is acted upon by an unbalanced force.

FIGURE 1.5
The car pedal on the right controls the amount of gas the engine gets. How does this affect the car's acceleration?

Acceleration, Force, and Mass

Newton determined that two factors affect the acceleration of an object: the net force acting on the object and the object's mass. The relationships between these two factors and motion make up **Newton's second law of motion**.

This law states that the acceleration of an object equals the net force acting on the object divided by the object's mass. This can be represented by the equation:

$$\text{Acceleration} = \frac{\text{Net force}}{\text{Mass}}, \text{ or}$$
$$a = \frac{F}{m}$$

You can watch a video about how Newton's second law of motion applies to football at this URL: http://science360.gov/obj/video/58e62534-e38d-430b-bfb1-c505e628a2d4.

Direct and Inverse Relationships

Newton's second law shows that there is a direct relationship between force and acceleration. The greater the force that is applied to an object of a given mass, the more the object will accelerate. For example, doubling the force on the object doubles its acceleration. The relationship between mass and acceleration, on the other hand, is an inverse relationship. The greater the mass of an object, the less it will accelerate when a given force is applied. For example, doubling the mass of an object results in only half as much acceleration for the same amount of force.

Consider the example of a batter, like the boy in **Figure** 1.6. The harder he hits the ball, the greater will be its acceleration. It will travel faster and farther if he hits it with more force. What if the batter hits a baseball and a softball with the same amount of force? The softball will accelerate less than the baseball because the softball has greater mass. As a result, it won't travel as fast or as far as the baseball.

FIGURE 1.6
Hitting a baseball with greater force gives it greater acceleration. Hitting a softball with the same amount of force results in less acceleration. Can you explain why?

Calculating Acceleration

The equation for acceleration given above can be used to calculate the acceleration of an object that is acted on by an unbalanced force. For example, assume you are pushing a large wooden trunk, like the one shown in **Figure** 1.7. The trunk has a mass of 10 kilograms, and you are pushing it with a force of 20 newtons. To calculate the acceleration of the trunk, substitute these values in the equation for acceleration:

$$a = \frac{F}{m} = \frac{20\text{ N}}{10\text{ kg}} = \frac{2\text{ N}}{\text{kg}}$$

Recall that one newton (1 N) is the force needed to cause a 1-kilogram mass to accelerate at 1 m/s^2. Therefore, force can also be expressed in the unit kg·m/s^2. This way of expressing force can be substituted for newtons in the solution to the problem:

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

Why are there no kilograms in the final answer to this problem? The kilogram units in the numerator and denominator of the fraction cancel out. As a result, the answer is expressed in the correct units for acceleration: m/s^2.

FIGURE 1.7

This empty trunk has a mass of 10 kilograms. The weights also have a mass of 10 kilograms. If the weights are placed in the trunk, what will be its mass? How will this affect its acceleration?

You Try It!

Problem: Assume that you add the weights to the trunk in **Figure** 1.7. If you push the trunk and weights with a force of 20 N, what will be the trunk's acceleration?

Need more practice? You can find additional problems at this URL: http://www.auburnschools.org/ajhs/lmcrowe/Week%2014/WorksheetPracticeProblemsforNewtons2law.pdf.

Acceleration and Weight

Newton's second law of motion explains the weight of objects. Weight is a measure of the force of gravity pulling on an object of a given mass. It's the force (F) in the acceleration equation that was introduced above:

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

This equation can also be written as:

$$F = m \times a$$

The acceleration due to gravity of an object equals 9.8 m/s^2, so if you know the mass of an object, you can calculate its weight as:

$$F = m \times 9.8\text{ m/s}^2$$

As this equation shows, weight is directly related to mass. As an object's mass increases, so does its weight. For example, if mass doubles, weight doubles as well. You can learn more about weight and acceleration at this URL: http://www.nasa.gov/mov/192448main_018_force_equals_mass_time.mov.

Problem Solving

Problem: Daisy has a mass of 35 kilograms. How much does she weigh?

Solution: Use the formula: $F = m \times 9.8\ \text{m/s}^2$.

$F = 35\ \text{kg} \times 9.8\ \text{m/s}^2 = 343.0\ \text{kg} \cdot \text{m/s}^2 = 343.0\ \text{N}$

You Try It!

Problem: Daisy's dad has a mass is 70 kg, which is twice Daisy's mass. Predict how much Daisy's dad weighs. Then calculate his weight to see if your prediction is correct.

Helpful Hints

The equation for calculating weight ($F = m \times a$) works only when the correct units of measurement are used.

- Mass must be in kilograms (kg).
- Acceleration must be in m/s^2.
- Weight (F) is expressed in $\text{kg}\cdot\text{m/s}^2$ or in newtons (N).

Lesson Summary

- Newton's second law of motion states that the acceleration of an object equals the net force acting on the object divided by the object's mass.
- Weight is a measure of the force of gravity pulling on an object of a given mass. It equals the mass of the object (in kilograms) times the acceleration due to gravity ($9.8\ \text{m/s}^2$).

Lesson Review Questions

Recall

1. State Newton's second law of motion.
2. Describe how the net force acting on an object is related to its acceleration.
3. If the mass of an object increases, how is its acceleration affected, assuming the net force acting on the object remains the same?
4. What is weight?

Apply Concepts

5. Tori applies a force of 20 newtons to move a bookcase with a mass of 40 kg. What is the acceleration of the bookcase?
6. Ollie has a mass of 45 kilograms. What is his weight in newtons?

Think Critically

7. If you know your weight in newtons, how could you calculate your mass in kilograms? What formula would you use?

Points to Consider

Assume that a 5-kilogram skateboard and a 50-kilogram go-cart start rolling down a hill. Both are moving at the same speed. You and a friend want to stop before they plunge into a pond at the bottom of the hill.

- Which will be harder to stop: the skateboard or the go-cart?
- Can you explain why?

1.3 Newton's Third Law

Lesson Objectives

- State Newton's third law of motion.
- Describe momentum and the conservation of momentum.

Lesson Vocabulary

- law of conservation of momentum
- momentum
- Newton's third law of motion

Introduction

Look at the skateboarders in **Figure** 1.8. When they push against each other, it causes them to move apart. The harder they push together, the farther apart they move. This is an example of Newton's third law of motion.

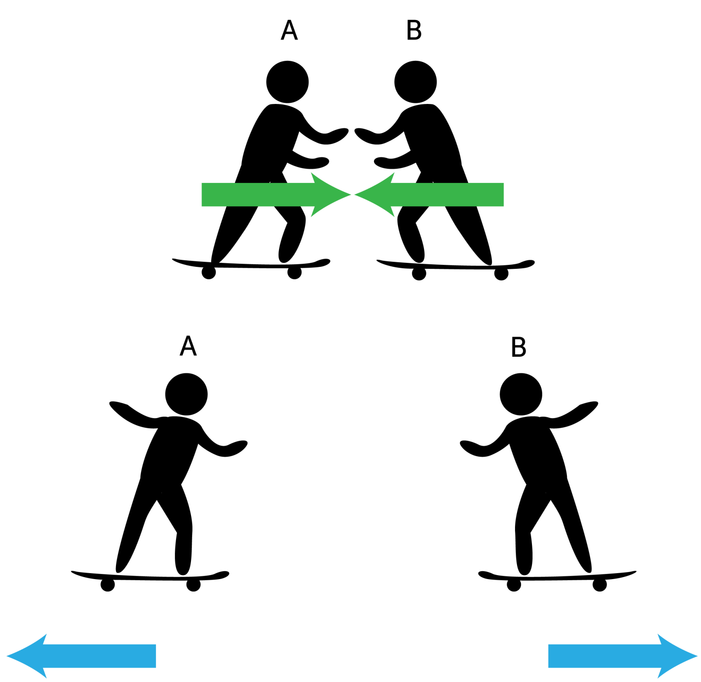

FIGURE 1.8
A and B move apart by first pushing together.

Action and Reaction

Newton's third law of motion states that every action has an equal and opposite reaction. This means that forces always act in pairs. First an action occurs, such as the skateboarders pushing together. Then a reaction occurs that is equal in strength to the action but in the opposite direction. In the case of the skateboarders, they move apart, and the distance they move depends on how hard they first pushed together. You can see other examples of actions and reactions in **Figure** 1.9. You can watch a video about actions and reactions at this URL: http://www.nasa.gov/mov/192449main_019_law_of_action.mov.

FIGURE 1.9

Each example shown here includes an action and reaction.

You might think that actions and reactions would cancel each other out like balanced forces do. Balanced forces, which are also equal and opposite, cancel each other out because they act on the same object. Action and reaction forces, in contrast, act on different objects, so they don't cancel each other out and, in fact, often result in motion. For example, in **Figure** 1.9, the kangaroo's action acts on the ground, but the ground's reaction acts on the kangaroo. As a result, the kangaroo jumps away from the ground. One of the action-reaction examples in the figure above does not result in motion. Do you know which one it is?

Momentum

What if a friend asked you to play catch with a bowling ball, like the one pictured in **Figure** 1.10? Hopefully, you would refuse to play! A bowling ball would be too heavy to catch without risk of injury — assuming you could even throw it. That's because a bowling ball has a lot of mass. This gives it a great deal of momentum. **Momentum** is a property of a moving object that makes the object hard to stop. It equals the object's mass times its velocity. It can be represented by the equation:

$$\text{Momentum} = \text{Mass} \times \text{Velocity}$$

This equation shows that momentum is directly related to both mass and velocity. An object has greater momentum if it has greater mass, greater velocity, or both. For example, a bowling ball has greater momentum than a softball when both are moving at the same velocity because the bowling ball has greater mass. However, a softball moving at a very high velocity — say, 100 miles an hour — would have greater momentum than a slow-rolling bowling ball. If an object isn't moving at all, it has no momentum. That's because its velocity is zero, and zero times anything is zero.

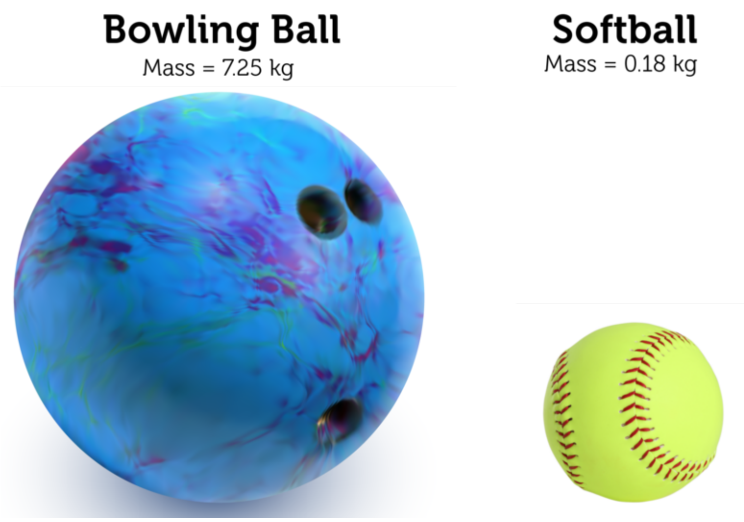

FIGURE 1.10
A bowling ball and a softball differ in mass. How does this affect their momentum?

Calculating Momentum

Momentum can be calculated by multiplying an object's mass in kilograms (kg) by its velocity in meters per second (m/s). For example, assume that a golf ball has a mass of 0.05 kg. If the ball is traveling at a velocity of 50 m/s, its momentum is:

$$\text{Momentum} = 0.05 \text{ kg} \times 50 \text{ m/s} = 2.5 \text{ kg} \cdot \text{m/s}$$

Note that the SI unit for momentum is kg·m/s.

Problem Solving

Problem: What is the momentum of a 40-kg child who is running straight ahead with a velocity of 2 m/s?

Solution: The child has momentum of: 40 kg × 2 m/s = 80 kg·m/s.

You Try It!

Problem: Which football player has greater momentum?

Player A: mass = 60 kg; velocity = 2.5 m/s

Player B: mass = 65 kg; velocity = 2.0 m/s

Conservation of Momentum

When an action and reaction occur, momentum is transferred from one object to the other. However, the combined momentum of the objects remains the same. In other words, momentum is conserved. This is the **law of conservation of momentum**.

Consider the example of a truck colliding with a car, which is illustrated in **Figure** 1.11. Both vehicles are moving in the same direction before and after the collision, but the truck is moving faster than the car before the collision occurs. During the collision, the truck transfers some of its momentum to the car. After the collision, the truck is moving slower and the car is moving faster than before the collision occurred. Nonetheless, their combined momentum is the same both before and after the collision. You can see an animation showing how momentum is conserved in a head-on collision at this URL: http://www.physicsclassroom.com/mmedia/momentum/cthoi.cfm.

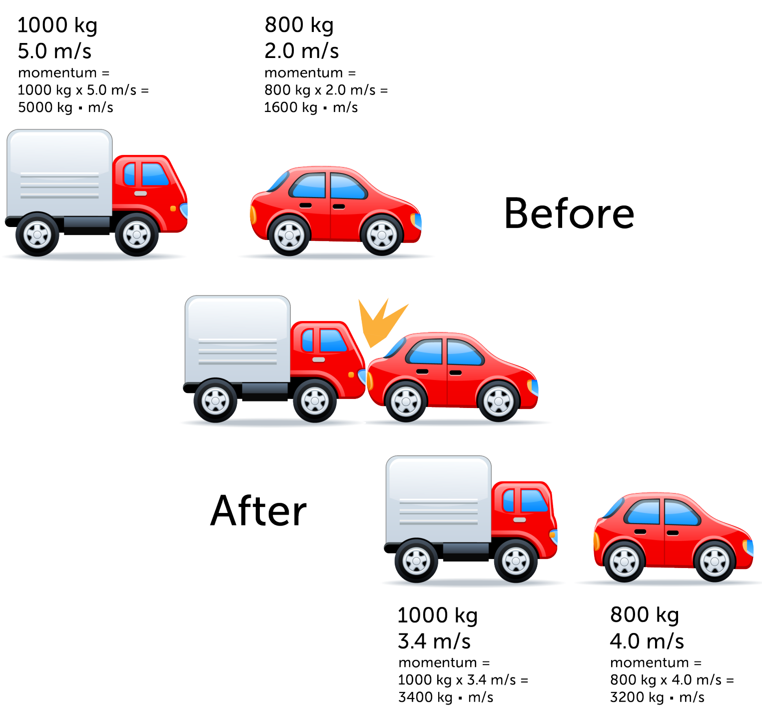

FIGURE 1.11
How can you tell momentum has been conserved in this collision?

Lesson Summary

- Newton's third law of motion states that every action has an equal and opposite reaction.
- Momentum is a property of a moving object that makes it hard to stop. It equals the object's mass times its velocity. When an action and reaction occur, momentum may be transferred from one object to another, but their combined momentum remains the same. This is the law of conservation of momentum.

Lesson Review Questions

Recall

1. State Newton's third law of motion.
2. Define momentum.
3. If you double the velocity of a moving object, how is its momentum affected?

Apply Concepts

4. A large rock has a mass of 50 kg and is rolling downhill at 3 m/s. What is its momentum?
5. Create a diagram to illustrate the transfer and conservation of momentum when a moving object collides with a stationary object.

Think Critically

6. The reaction to an action is an equal and opposite force. Why doesn't this yield a net force of zero?
7. Momentum is a property of an object, but it is different than a physical or chemical property, such as boiling point or flammability. How is momentum different?

Points to Consider

In this chapter, you learned about forces and motions of solid objects, such as balls and cars. In the next chapter, "Fluid Forces," you will learn about forces in fluids, which include liquids and gases.

- How do fluids differ from solids?
- What might be examples of forces in fluids? For example, what force allows some objects to float in water?

1.4 References

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