5.1 Newton's First Law

Sir Isaac Newton, an English physicist and mathematician, was one of the most brilliant scientists in history. Before the age of thirty he had made many important discoveries in physics and had even invented a new kind of mathematics called calculus. Newton's three laws of motion are probably the most widely used natural laws in all of science. The laws explain the relationships between the forces acting on an object, the object's mass, and its motion. This section discusses Newton's first law.

Force changes motion

Force changes an object's motion

Imagine you are playing miniature golf. It is your turn. What do you do to move the golf ball toward the hole? Do you yell at the ball? Of course not! You hit the ball with the golf club to get it rolling. In physics, "hit the ball" means the golf club applies a force to the ball. This force is what changes the ball from being at rest to being in motion (Figure 5.1). *Motion can change only through the action of a force.* This statement is the beginning of Newton's first law.

Why do things stop moving after awhile?

What happens next? The ball rolls some distance, slows down, and eventually stops. For a long time, scientists thought the natural state of all things was to be at rest (stopped). They believed that force had to keep being applied to keep an object moving, even if it was moving at a constant speed. Things stopped moving because being stopped was the natural state of being. Scientists thought constant motion required a constant supply of force. *They were wrong*!

The real explanation

The golf ball stops because the force of friction keeps acting on it until there is no longer any motion. Suppose the golf course were perfectly level and had no friction. After being hit with the golf club, the ball would keep moving in a straight line at a constant speed *forever*. The ball would neither slow down nor change direction *unless another force acted on it*. In a world without friction, the golf ball would just keep going forever once the force from the club acted on it. Being stopped or moving with constant speed and direction are *both* natural states of motion and *neither one requires any force to sustain it*.

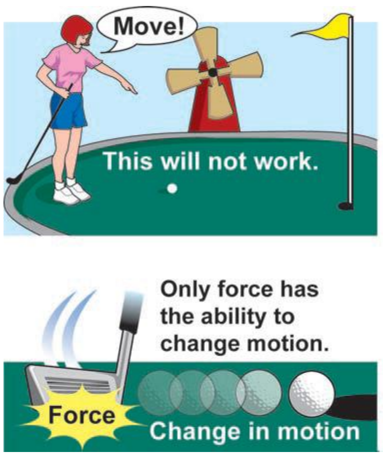


Figure 5.1: *Force is the only action that has the ability to change motion. Without force, the motion of an object cannot be started or changed.*

The first law: The law of inertia

Newton's first law

Newton's first law says objects continue the motion they already have *unless* they are acted on by a net force (the sum of all forces acting on an object at any given time). When the net force is zero, objects at rest stay at rest, and objects that are moving keep moving in the same direction with the same speed.

When the net force is zero, objects at rest stay at rest and objects in motion keep moving with the same speed and direction.

Force is required to change Motion

The first law says there can be no change in motion without a net force. *That includes slowing down!* It takes a net force (often friction) to make things slow down. If forces are truly balanced, a moving object will keep moving forever with the same speed, in the same direction.

Balanced and unbalanced forces

Changes in motion come from **unbalanced forces**. Forces are "unbalanced" when the net force is not exactly zero. Forces are "balanced" when they add up to zero net force. Forces are always balanced in equilibrium. A rolling golf ball is not in equilibrium because friction is an unbalanced force.

Inertia

The first law is often called the "law of inertia" because **inertia** is the property of an object that resists changes in motion. Inertia comes from mass. Objects with more mass have more inertia. To understand inertia, imagine moving a bowling ball and a golf ball which are at rest (Figure 5.2). A golf ball has a mass of 0.05 kilogram, and the average bowling ball has a mass of 5 kilograms. A bowling ball has 100 times the mass of a golf ball, so it has 100 times the inertia. Which needs more force to start moving? Of course, the bowling ball needs more force to move at the same speed as the golf ball (assuming the forces act for the same length of time). The bowling ball needs more force because a bowling ball has more inertia than a golf ball. The greater an object's inertia, the greater the force needed to change its motion.

The net force

Multiple forces

When you hit a golf ball, the force from the club is not the only force that acts on the ball (Figure 5.3). The ball's weight, the normal force from the ground, and friction are also acting. Which force determines how the ball moves?

Net force causes motion

You are right if you answered "all forces together." There is almost always more than one force present because gravity acts on all objects. The first law is written in terms of the *net force* because that is what affects motion. Individual forces only matter in that they contribute to the net force.

Adding forces

Recall that force is a vector. When adding up forces, the *directions* of the forces matter. To find the net force, you must include positive and negative signs to account for the directions of the forces.

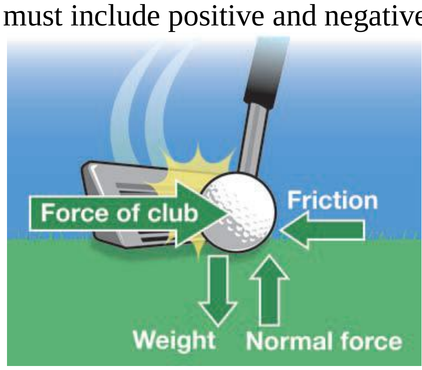


Figure 5.3: *Four forces act on a golf ball. The net force determines how it moves.*

5.2 Newton's Second Law

Newton's first law says that a force is needed to change an object's motion. But what kind of change happens? The answer is *acceleration*. According to Newton's second law, the amount of acceleration depends on both the force and the mass.

The three main ideas of the second law

What is the second law about?

Newton's first law tells us that motion cannot change without a net force. The second law tells us exactly what kind of change is caused by unbalanced forces. The second law answers questions like: "How much force does it take to change the speed of a 1,000 kg car from 0 to 55 mph?" Anyone who does anything involving motion needs to understand the second law.

The three main ideas

There are three main ideas related to the second law.
1. Acceleration is the result of unbalanced forces.
2. A larger force makes a proportionally larger acceleration.
3. Acceleration is inversely proportional to mass.

Unbalanced forces cause acceleration

The first law tells us things in motion can continue to move even without any net force. This is true as long as the motion is at a constant speed and in a straight line. The second law says that any unbalanced force results in acceleration. We know that acceleration causes changes in velocity (speed or direction). Putting these two ideas together tells us two things about force and motion:

(1) Unbalanced forces cause changes in speed, direction, or both;
and
(2) any time there is a change in speed or direction, there must be an unbalanced force acting.

Force and motion connect through acceleration

The second law is the connection between force, mass, and motion. The connection occurs through *acceleration*, which results in *changes* in speed and/or direction. In fact, the unit of force (newton) is defined by the second law (Figure 5.4).

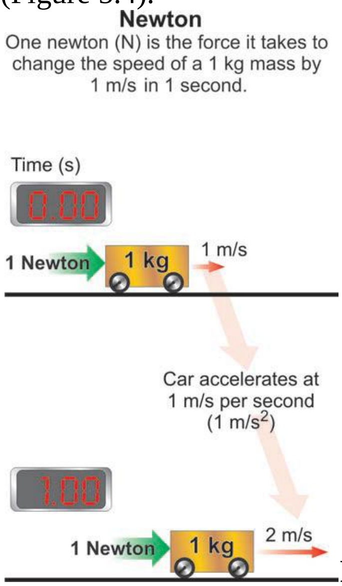


Figure 5.4: *The newton, a unit of force, is defined in terms of the acceleration it can create.*

Acceleration and force

Acceleration is proportional to force

The second law says that acceleration is *proportional* to force. What does that mean? It means that all other things being equal, if the force doubles, the acceleration also doubles. If the force is reduced by half, the acceleration is also reduced by half (Figure 5.5).

Example: A robot mail cart

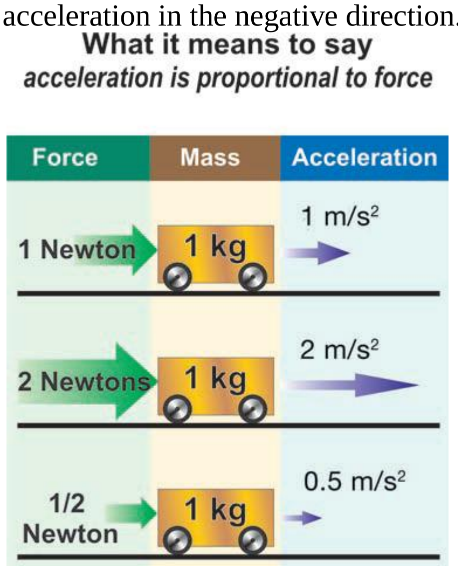
Here is an example. Two engineers are each asked to design an battery-operated motor for a robot mail cart. The cart is supposed to drive around to people's offices and stop so they can collect their mail. One engineer chooses a motor that produces a force of 50 newtons. The other chooses a motor that produces a force of 100 newtons.

The acceleration of the mail cart

The robot with the smaller motor goes from rest to a top speed of 4 m/s in 4 seconds. The acceleration is 1 m/s^2. The robot with the larger motor accelerates to the same top speed (4 m/s) in 2 seconds. Its acceleration is 2 m/s^2. Both robots have the same top speed. The one with the bigger motor accelerates to its top speed twice as fast because it uses twice as much force. Of course, the one with the bigger motor drains its batteries faster too. There is always a trade-off between performance and battery life.

Acceleration is in the direction of the net force

Another important factor of the second law is that the acceleration is always in the same direction as the net force. A force in the positive direction causes acceleration in the positive direction. A force in the negative direction causes acceleration in the negative direction. A sideways net force causes a sideways acceleration.



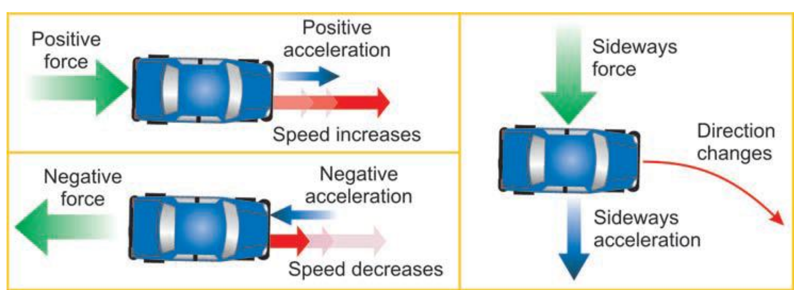


Figure 5.5: *"Acceleration is proportional to force" means that if force is increased or decreased, acceleration will be increased or decreased by the same factor*

Acceleration and mass

Mass and acceleration

The greater the mass, the smaller the acceleration for a given force (Figure 5.6). That means acceleration is *inversely proportional* to mass. When the forces stay the same, increasing mass decreases the acceleration. For example, an object with twice the mass will have half the acceleration if the same force is applied. An object with half the mass will have twice the acceleration.

Why mass reduces acceleration

Acceleration decreases with mass because mass creates inertia. Remember, inertia is the property of matter that resists changes in motion (acceleration). More mass means more inertia, and therefore more resistance to acceleration.

Newton’s second law

Force causes acceleration, and mass resists acceleration. **Newton’s second law** relates the force on an object, the mass of the object, and the object’s acceleration.

The acceleration caused by a force is proportional to force and inversely proportional to mass.

The formula for the second law

The relationships between force, mass, and acceleration are combined in the formula for Newton’s second law.

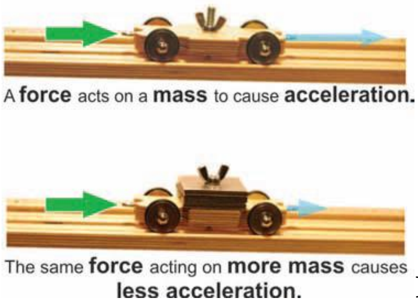


Figure 5.6: *How acceleration is affected by mass*

NEWTON'S SECOND LAW

a=f/m a=acceleration m/s^2 , f=force (N), m=mass (kg)

Applying the second law

Writing the second law

You can use Newton’s second law to calculate force, mass, or acceleration if two of the three values are known. As you solve problems, keep in mind the concepts shown in Figure 5.7. Larger force leads to larger acceleration. Larger mass leads to smaller acceleration.

Net force and the second law

Newton’s second law explains the effect of the *net force* on motion. You must consider all the forces that are acting and add them up to find the net force. Then you use the net force to calculate any acceleration. You can also use the second law to work in the other direction, calculating net force from a given mass and acceleration.
To use Newton’s second law properly, keep the following important ideas in mind.

1. The *net* force is what causes acceleration.
2. If there is *no* acceleration, the net force *must* be zero.
3. If there *is* acceleration, there *must* also be a net force.
4. The force unit of newtons is based on kilograms, meters, and seconds.

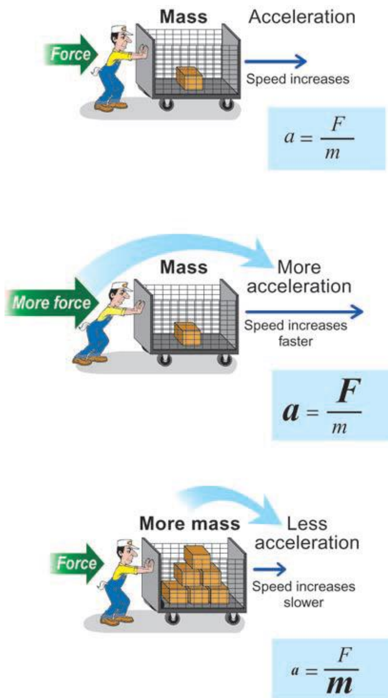


Figure 5.7: *More force causes more acceleration, and more mass causes less acceleration*

5.3 Newton's Third Law

Newton's first and second laws apply to the motion of an *individual* object. However, all forces must be applied *by* something. Think about throwing a basketball (Figure 5.10). You feel the ball push back against your hand as you throw it. You know you apply a force to the ball to make it move. Where does the force against your hand come from?

Forces always come in matched pairs

An imaginary skateboard contest

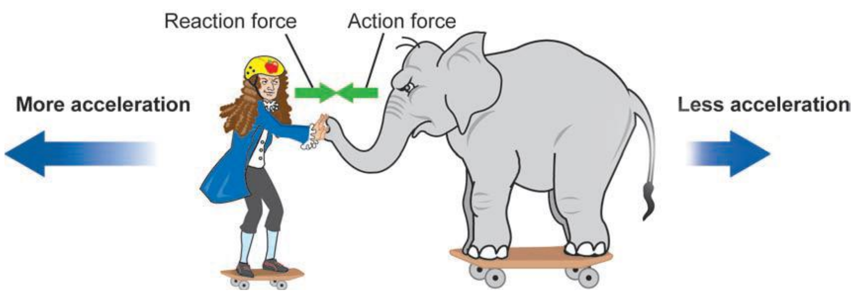
Imagine a skateboard contest between Isaac Newton and an elephant. They can only push against each other, not against the ground. The one whose skateboard moves the fastest wins. The elephant knows he is much stronger and pushes off Newton with a huge force thinking he will surely win. But will he?

The winner

Newton flies away with a great speed and the puzzled elephant moves backward with a much smaller speed. Newton wins—and will always win this contest against the elephant. No matter how hard the elephant pushes, Newton will always move away faster. Why?

Forces always come in pairs

It takes force to make both Newton and the elephant move. Newton wins because *forces always come in pairs*. The elephant pushes against Newton and that *action* force pushes Newton away. The elephant's force against Newton creates a *reaction* force against the elephant. The action and reaction forces are equal in strength. Newton has much less mass so he has much more acceleration.



The third law: Action and reaction

The first and second laws

The first two laws of motion apply to individual objects. The first law says an object will remain at rest or in motion at a constant velocity unless acted upon by a net force. The second law states that acceleration equals the force on an object divided by the mass of the object.

The third law

The third law of motion deals with pairs of objects. This is because *all forces come in pairs*. **Newton's third law** states that every action force creates a reaction force that is equal in strength and opposite in direction.

Every action force creates a reaction force that is equal in strength and opposite in direction.

Force pairs

There can never be a single force, alone, without its action-reaction partner. Forces *only* come in action-reaction pairs. In the skateboard contest, the force exerted by the elephant (action) moved Newton since it acted on Newton. The reaction force acting back on the elephant was what moved the elephant.

The labels *action* and *reaction*

The words *action* and *reaction* are just labels. It does not matter which force is called action and which is called reaction. You simply choose one to call the action and then call the other one the reaction (Figure 5.11).

Why action and reaction forces do not cancel each other out

Why don't action and reaction forces cancel each other out? The reason is *action and reaction forces act on different objects*. For example, think again about throwing a ball. When you throw a ball, you apply the action force to the ball, creating the ball's acceleration. The reaction is the ball pushing back against your hand. The action acts on the ball and the reaction acts on your hand. The forces do not cancel each other out because they act on different objects. You can only cancel out forces acting on the same object (Figure 5.12).

Action and reaction forces

A skateboard example

Think carefully about propelling a skateboard with your foot. Your foot presses backward against the ground (Figure 5.13). The force acts *on* the ground. However, *you* move, so a force must act on you, too. Why do you move? What force acts on you? You move because the action force of your foot against the ground creates a reaction force of the ground against your foot. You "feel" the ground because you sense the reaction force pressing on your foot. The reaction force is what makes you move because it acts on *you*.

Draw diagrams

When sorting out action and reaction forces, it is helpful to draw diagrams. Draw each object apart from the other. Represent each force as an arrow in the appropriate direction. Here are some guidelines to help you sort out action and reaction forces:

- Both are always there whenever any force appears.
- They always have the exact same strength.
- They always act in opposite directions.
- They always act on different objects.
- Both are real forces and can cause changes in motion.

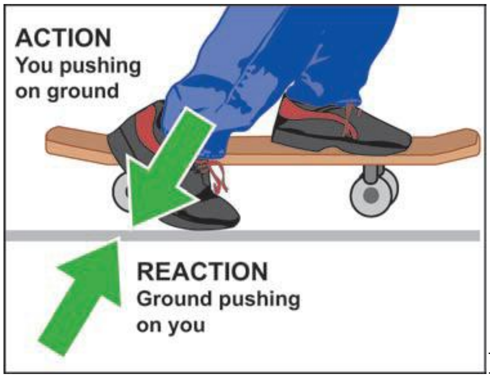


Figure 5.13: *You move forward because of the reaction force of the ground on your foot.*

Collisions

The effect of forces

Newton's third law tells us that any time two objects hit each other, they exert equal and opposite forces on each other. However, the *effect* of the force is not always the same. Imagine two hockey players moving at the same speed toward each other, one with twice the mass of the other. The force on each during the collision is the same strength, but they do not have the same change in motion.

More mass results in less acceleration

The person with more mass has more inertia. More force is needed to change his motion. Because of his greater inertia, the more massive skater will have a smaller change in motion during the collision. The forces on each skater are always exactly equal and opposite. The two skaters have different changes in motion because they have different amounts of inertia, *not because the forces are different*.

Auto collisions

The same is true of vehicles in a collision. When a large truck hits a small car, the forces are equal (Figure 5.14). However, the small car experiences a much greater change in velocity much more rapidly than the big truck.

Safety features

Riding in a vehicle with a large mass does not guarantee passengers will be safe in a collision. Large SUVs are more likely to roll over during accidents. Auto manufacturers conduct crash tests to help them improve the design of cars. Safety features such as seat belts, airbags, and antilock brakes help make cars safer (Figure 5.15).

Figure 5.14: *The car has less inertia, so it accelerates more and may become more damaged than the truck*

Figure 5.15: *Safety features help passengers avoid injury during a collision*