# How Rockets Work

Whether flying a small model rocket or launching a giant cargo rocket to Mars, the principles of how rockets work are exactly the same. Understanding and applying these principles means mission success.

In the early days of rocketry, the flight of a fire arrow or other rocket device was largely a matter of chance. It might fly; it might skitter about, shooting sparks and smoke; or it might explode. Through centuries of trial and error, rockets became more reliable. However, real advancements in rocketry depended upon a scientific and mathematical understanding of motion. That came in the seventeenth century with the works of scientists such as Galileo and Isaac Newton.

Galileo conducted a wide range of experiments involving motion. Through studies of inclined planes, Galileo concluded that moving objects did not need the continuous application of force (in the absence of friction and drag) to keep moving. Galileo discovered the principle of inertia, that all matter, because of its mass, resists changes in motion. The more mass, the more resistance.

Isaac Newton, born the year Galileo died, advanced Galileo's discoveries and those of others by proposing three basic laws of motion. These laws are the foundation of all rocket science. Understand the laws and you know just about everything you need to build successful rockets. Apply the laws and you become a "rocket scientist.

## "Newton's Laws of Motion

In his master work entitled Philosophia Naturalis Principia Mathematica (usually referred to as Principia), Isaac Newton stated his laws of motion. For the most part, the laws were known intuitively by rocketeers, but their statement in clear form elevated rocketry to a science. Practical application of Newton's laws makes the difference between failure and success. The laws relate force and direction to all forms of motion.

## In simple language, Newton's Laws of Motion:

**First Law**
Objects at rest remain at rest and objects in motion remain in motion in a straight line unless acted upon by an unbalanced force.

**Second Law**
Force equals mass times acceleration (or f = ma).

**Third Law**
For every action there is an equal and opposite reaction.

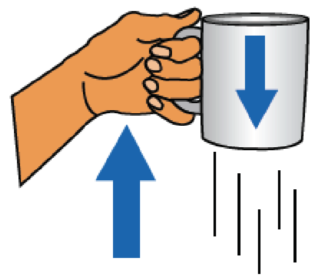
Before looking at each of these laws in detail, a few terms should be explained.

*Rest* and *Motion*, as they are used in the first law, can be confusing. Both terms are relative. They mean rest or motion in relation to surroundings. You are at rest when sitting in a chair. It doesn't matter if the chair is in the cabin of a jet plane on a cross-country flight. You are still considered to be at rest because the airplane cabin is moving along with you. If you get up from your seat on the airplane and walk down the aisle, you are in relative motion because you are changing your position inside the cabin.

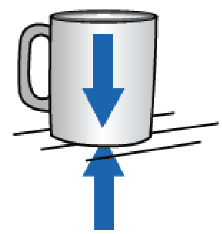
*Force* is a push or a pull exerted on an object. Force can be exerted in many ways, such as muscle power, movement of air, and electromagnetism, to name a few. In the case of rockets, force is usually exerted by burning rocket propellants that expand explosively.

*Unbalanced Force* refers to the sum total or net force exerted on an object. The forces on a coffee cup sitting on a desk, for example, are in balance. Gravity is exerting a downward force on the cup. At the same time, the structure of the desk exerts an upward force, preventing the cup from falling. The two forces are in balance.

Reach over and pick up the cup. In doing so, you unbalance the forces on the cup. The weight you feel is the force of gravity acting on the mass of the cup. To move the cup upward, you have to exert a force greater than the force of gravity. If you hold the cup steady, the force of gravity and the muscle force you are exerting are in balance.

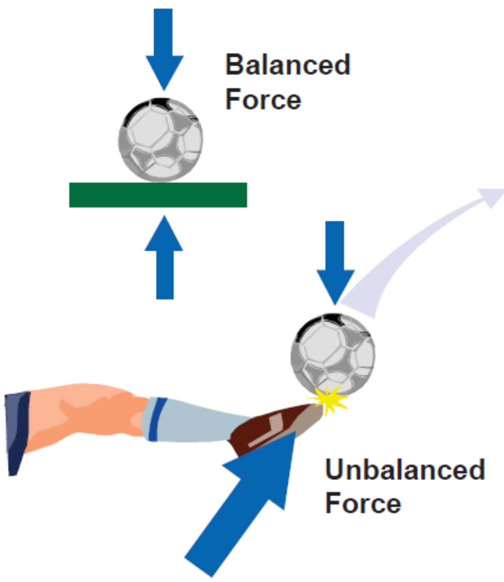


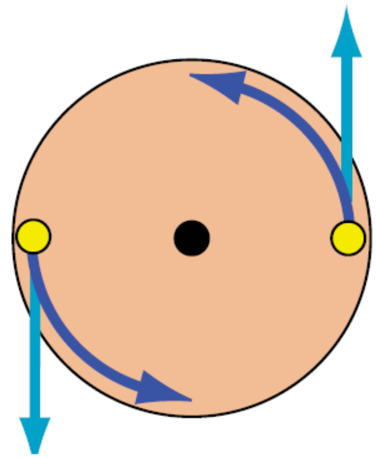
Unbalanced force



Balanced forces

Unbalanced force also refers to other motions. The forces on a soccer ball at rest on the playing field are balanced. Give the ball a good kick, and the forces become unbalanced. Gradually, air drag (a force) slows the ball, and gravity causes it to bounce on the field. When the ball stops bouncing and rolling, the forces are in balance again. Take the soccer ball into  deep space, far away from any star or other significant gravitational field, and give it a kick. The kick is an unbalanced force exerted on the ball that gets it moving. Once the ball is no longer in contact with the foot, the forces on the ball become balanced again, and the ball will travel in a straight line forever. How can you tell if forces are balanced or unbalanced? If the soccer ball is at rest, constant speed and in a straight line, the forces are balanced. If the ball is accelerating or changing its direction, the forces are unbalanced.

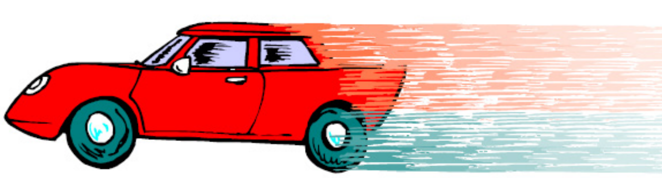


Top view of two riders on a carousel. The carousel platform exerts unbalanced forces on the riders, preventing them from going in straight lines. Instead, the platform continually accelerates the riders in a counterclockwise direction.

*Mass* is the amount of matter contained in an object. The object does not have to be solid. It could be the amount of air contained in a balloon or the amount of water in a glass. The important thing about mass is that unless you alter it in some way, it remains the same whether the object is on Earth, in Earth orbit, or on the Moon. Mass just refers to the quantity of matter contained in the object. (Mass and weight are often confused. They are not the same thing. Weight is a force and is the product of mass times the acceleration of gravity.)

*Acceleration* relates to motion. It means a change in motion. Usually, change refers to increasing speed, like what occurs when you step on the accelerator pedal of a car. Acceleration also means changing direction.



This is what happens on a carousel. Even though the carousel is turning at a constant rate, the continual change in direction of the horses and riders (circular motion) is an acceleration.

*Action* is the result of a force. A cannon fires, and the cannon ball flies through the air. The movement of the cannon ball is an action. Release air from an inflated balloon. The air shoots out the nozzle. That is also an action. Step off a boat onto a pier. That, too, is an action.

*Reaction* is related to action. When the cannon fires, and the cannon ball flies through the air, the cannon itself recoils backward. That is a reaction. When the air rushes out of the balloon, the balloon shoots the other way, another reaction. Stepping off a boat onto to a pier causes a reaction. Unless the boat is held in some way, it moves in the opposite direction. (Note: The boat example is a great demonstration of the action/reaction principle, providing you are not the one stepping off the boat!)

## Newton's First Law

This law is sometimes referred to as Galileo's law of inertia because Galileo discovered the principle of inertia. This law simply points out that an object at rest, such as a rocket on a launch pad, needs the exertion of an unbalanced force to cause it to lift off. The amount of the thrust (force) produced by the rocket engines has to be greater than the force of gravity holding it down. As long as the thrust of the engines continues, the rocket accelerates. When the rocket runs out of propellant, the forces become unbalanced again. This time, gravity takes over and causes the rocket to fall back to Earth. Following its "landing," the rocket is at rest again, and the forces are in balance.

There is one very interesting part of this law that has enormous implications for spaceflight. When a rocket reaches space, atmospheric drag (friction) is greatly reduced or eliminated. Within the atmosphere, drag is an important unbalancing force. That force is virtually absent in space. A rocket traveling away from Earth at a speed greater than 11.186 kilometers per second (6.95 miles per second) or 40,270 kph (25,023 mph) will eventually escape Earth's gravity. It will slow down, but Earth's gravity will never slow it down enough to cause it to fall back to Earth. Ultimately, the rocket (actually its payload) will travel to the stars. No additional rocket thrust will be needed. Its inertia will cause it to continue to travel outward. Four spacecraft are actually doing that as you read this. Pioneers 10 and 11 and Voyagers 1 and 2 are on journeys to the stars!

## Newton's Third Law

(It is useful to jump to the third law and come back to the second law later.) This is the law of motion with which many people are familiar. It is the principle of action and reaction. In the case of rockets, the action is the force produced by the expulsion of gas, smoke, and flames from the nozzle end of a rocket engine. The reaction force propels the rocket in the opposite direction.When a rocket lifts off, the combustion products from the burning propellants accelerate rapidly out of the engine. The rocket, on the other hand, slowly accelerates skyward. It would appear that something is wrong here if the action and reaction are supposed to be equal. They are equal, but the mass of the gas, smoke, and flames being propelled by the engine is much less than the mass of the rocket being propelled in the opposite direction.

Even though the force is equal on both, the effects are different. Newton's first law, the law of inertia, explains why. The law states that it takes a force to change the motion of an object. The greater the mass, the greater the force required to move it.

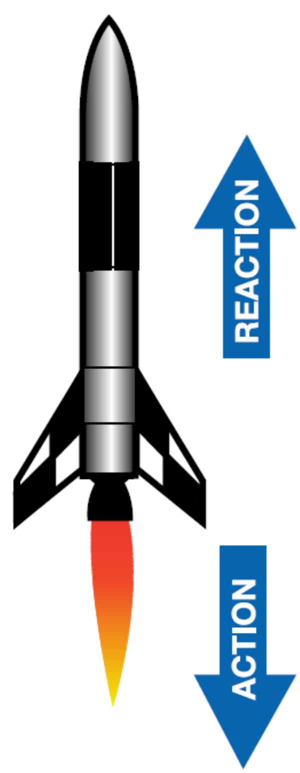
## Newton's Second Law

The second law relates force, acceleration, and mass. The law is often written as the equation:

$$f = ma$$

The force or thrust produced by a rocket engine is directly proportional to the mass of the gas and particles produced by burning rocket propellant times the acceleration of those combustion products out the back of the engine. This law only applies to what is actually traveling out of the engine at the moment and not the mass of the rocket propellant contained in the rocket that will be consumed later.

The implication of this law for rocketry is that the more propellant (m) you consume at any moment and the greater the acceleration (a)of the combustion products out of thenozzle, the greater the thrust (f).



## A Taste of Real Rocket Science

Naturally, launching rockets into space is more complicated than Newton's laws of motion imply. Designing rockets that can actually lift off Earth and reach orbital velocities or interplanetary space is an extremely complicated process.

Newton's laws are the beginning, but many other things come into play. For example, air pressure plays an important role while the rocket is still in the atmosphere. The internal pressure produced by burning rocket propellants inside the rocket engine combustion chamber has to be greater than the outside pressure to escape through the engine nozzle. In a sense, the outside air is like a cork in the engine. It takes some of the pressure generated inside the engine just to exceed the ambient outside pressure. Consequently, the velocity of combustion products passing through the opening or throat of the nozzle is reduced. The good news is that as the rocket climbs into space, the ambient pressure becomes less and less as the atmosphere thins and the engine thrust increases.

Another important factor is the changing mass of the rocket. As the rocket is gaining thrust as it accelerates upward due to outside pressure changes, it is also getting a boost due to its changing mass. Every bit of rocket propellant burned has mass. As the combustion products are ejected by the engine, the total mass of the vehicle lessens. As it does its inertia, or resistance to change in motion, becomes less. As a result, upward acceleration of the rocket increases.

In practical terms, Newton's second law can be rewritten as this:

$$\mathbf{f = m_{\mathit{exit}}V_{\mathit{exit}} + (p_{\mathit{exit}} - p_{\mathit{ambient}})A_{\mathit{exit}}}$$

("A" refers to the area of the engine throat.)

When the rocket reaches space, and the exit pressure minus the ambient pressure becomes zero, the equation becomes:

$$\mathbf{f = m_{\mathit{exit}}V_{\mathit{exit}}}$$

In real rocket science, many other things also come into play.

- Even with a low acceleration, the rocket will gain speed over time because acceleration accumulates.

- Not all rocket propellants are alike. Some produce much greater thrust than others because of their burning rate and mass. It would seem obvious that rocket scientists would always choose the more energetic propellants. Not so. Each choice a rocket scientist makes comes with a cost. Liquid hydrogen and liquid oxygen are very energetic when burned, but they both have to be kept chilled to very low temperatures. Furthermore, their mass is low, and very big tanks are needed to contain enough propellant to do the job.

## In Conclusion...

Newton's laws of motion explain just about everything you need to know to become a rocket scientist. However, knowing the laws is not enough. You have to know how to apply them, such as:

- How can you create enough thrust to exceed the weight of the rocket?

- What structural materials and propellant combinations should you use?

- How big will the rocket have to be?

- How can you make the rocket go where you want it to?

- How can you bring it back to Earth safely?