# A

## Acceleration

**Fields of Study**: Physics; Engineering; Mechanics; Mathematics


### ABSTRACT

*Acceleration is the rate of velocity change of a moving object, whether in a straight line or a curved or circular motion. This change of velocity is measured in meters per second, expressed as $m/s^2$. Acceleration occurs any time there is a change in speed or direction. It includes slowing down (negative acceleration) as well as speeding up. Because it involves both speed and direction, acceleration is a vector quantity.*


### KEY CONCEPTS

**acceleration**: the increase in velocity over a period of time; going faster

**air resistance**: opposition to motion due to air molecules experienced by an object passing through the air; also called drag with respect to flying machines

**centripetal**: acceleration or experienced force directed toward the focal point of curving motion or the center of a circle

**deceleration**: also called negative acceleration, the decrease of velocity over a period of time, the opposite of acceleration

**tangent**: a straight line external to a curve that touches the curve at one point only

### OVERVIEW

Galileo Galilei (1564-1642), an Italian physicist, experimented with the velocity of objects by rolling them down an inclined plane. Velocity is the rate of change in an object's position. Galileo observed that the objects gained speed as they rolled. He conducted a long-term study of the distances objects rolled and the time it took them to roll this distance. He eventually was able to show that each distance was in proportion to the time squared. For example, a ball that reaches a speed of 5 meters per second in 10 seconds has an acceleration rate of 0.5 $m/s^2$. He wrote the mathematical equation to describe how the velocity of the objects increased as they rolled— the first accurate explanation of accelerated motion.

Although the first descriptions of velocity came from Galileo, Sir Isaac Newton (1642-1727), an English physicist, took the next step and explained that some force must act upon an object to increase its velocity. For the rolling objects (or falling apples), the force was gravity. Newton's First Law of Motion states that unless an external force acts upon them, objects at rest remain at rest and objects in motion at a constant velocity continue in their direction at the same velocity.

Newton's Second Law of Motion applies to acceleration. It states that the sum of all forces (F) acting on an object is equal to the mass (m) of the object multiplied by the acceleration (a) of the object, or $F = ma$. That means that acceleration occurs when a force affects an object or mass, and the greater the mass, the greater the force needed to cause acceleration. In other words, more force is required when moving heavier objects the same distance as lighter ones. For example, a person can kick a hollow plastic ball a considerable distance without much effort but would need substantial strength to push a rock of similar size the same distance.

Acceleration changes either the speed or the direction of an object. A car that pulls onto a street is accelerating as long as it is gaining speed; once the speed levels off and becomes constant, it is no longer accelerating. However, if it rounds a curve that changes its direction, it is then accelerating, even if the speed remains constant. Negative acceleration, or deceleration, occurs when the car slows down.

**LINEAR ACCELERATION**

The term linear acceleration refers to a change in velocity without a change in direction—the object travels in a straight line. When an object moves in one direction for a given time, such as a car driving on a straight highway, it is accelerating only if its speed varies. For example, if the car is traveling at 26 m/s west (about 94 kph) and speeds up to 31 m/s west (about 112 kph), it is accelerating. But it is also accelerating if it slows to 14 m/s west (about 31 mph) when a deer crosses the road. Linear acceleration is expressed as a positive number if the car is speeding up and as a negative number if it is slowing down. Negative acceleration is generally called deceleration rather than negative acceleration.

**CENTRIPETAL ACCELERATION**

When an object rotates, or moves in a circular pattern, it changes velocity even though its speed does not change. Since velocity is a vector quantity, having both speed and direction, the velocity linear velocity vector of the circular motion is tangent to the circle and, because acceleration is always perpendicular to the velocity, the direction of the acceleration is toward the center of the circle. Thus, it is called centripetal acceleration.

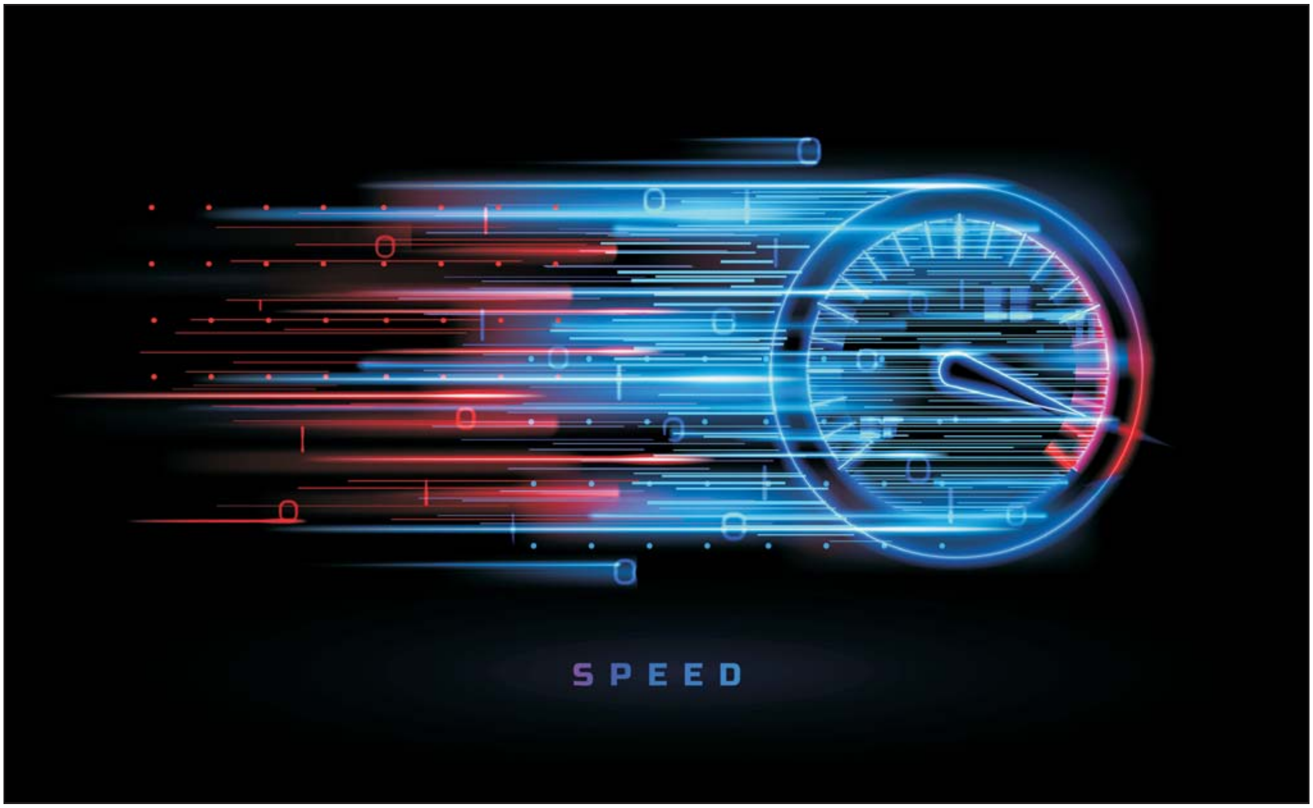
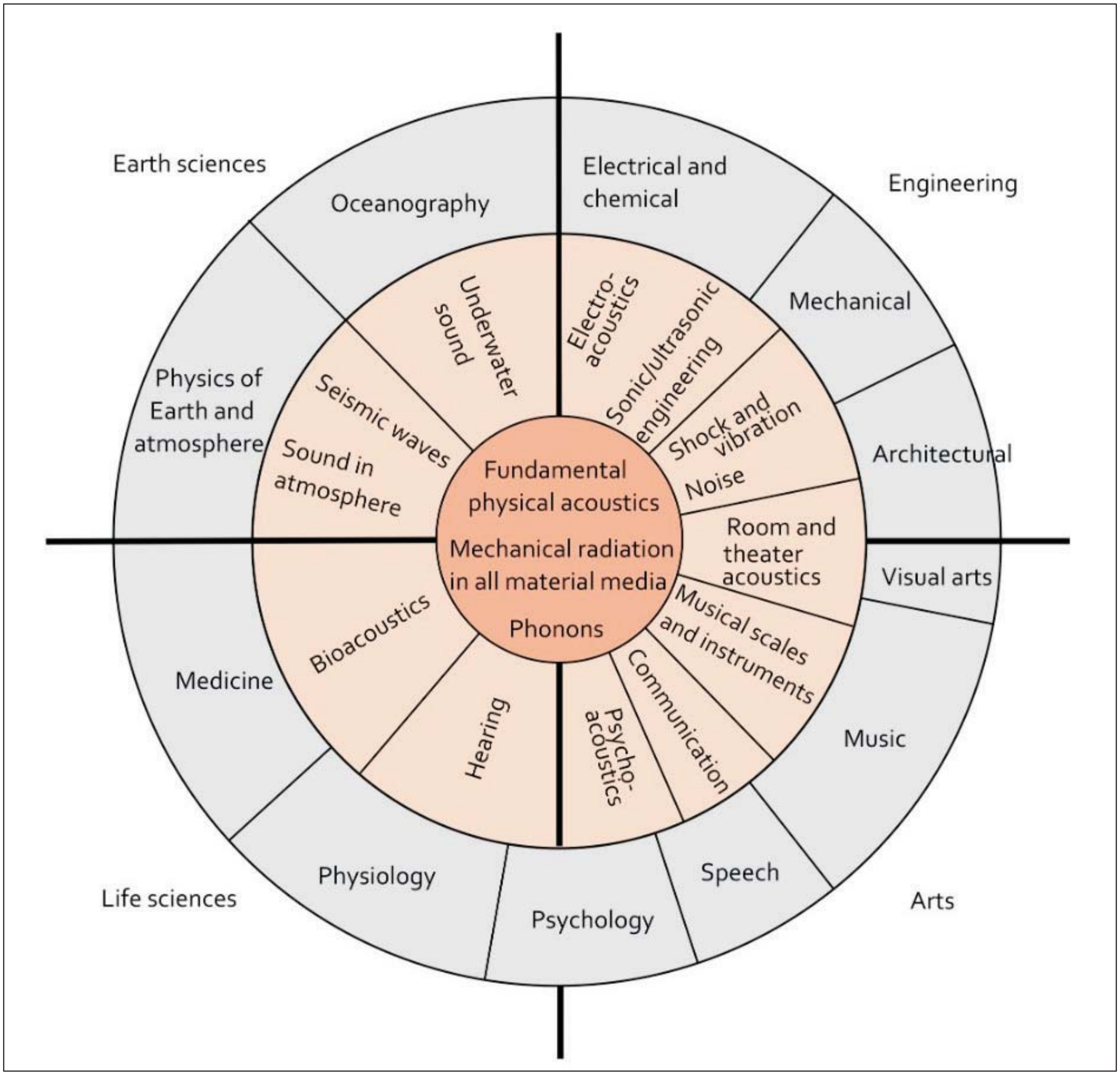



*Photo via iStock/Sensvector. [Used under license.]*




*Lindsay's Wheel of Acoustics, which shows fields within acoustics. Image by Amitchell125, via Wikimedia Commons.*

tric, are used to generate higher frequencies and greater power. Magnetostrictive devices convert magnetic energy into ultrasound by subjecting ferric material (iron or nickel) to a strong oscillating magnetic field. The field causes the material to alternately expand and contract, thus creating sound waves of the same frequency as that of the field. The resulting sound waves have frequencies between 20 Hz and 50 kHz and several thousand watts of power. Such transducers operate at the mechanical resonance frequency where the energy transfer is most efficient.

by altering its position in space. Up to 15 degrees, increasing the angle of attack enhances the lift produced by aircraft airfoils, enabling faster climbing rates, though slowing airspeed. Once the angle of attack becomes too steep, air eddies form atop the airfoil and cause large decreases in lift, which make the aircraft drop toward the ground in a stall. When a pilot's misjudgment produces a stall, the aircraft will crash unless the pilot quickly decreases the angle of attack to a safe value.

To produce appropriate lift, an airfoil must move through the air above a minimum speed that is associated with the aircraft to which it is attached. However, during landing and takeoff, safety concerns make it desirable to fly as slowly as possible. Because of these conflicting demands, aircraft have special assemblies (or parts) called high-lift devices. Two important high-lift devices are flaps and slats. A flap is the hinged portion of the back of each airfoil. In flight, it fits smoothly, in

*A NASA wake turbulence study at Wallops Island in 1990. A vortex is created by passage of an aircraft wing, revealed by smoke. Vortices are one of the many phenomena associated with the study of aerodynamics. Photo via Wikimedia Commons. [Public domain.]*

trol uses continuous decision making and hardware that are closed loop. This includes the use of thrusters, electromagnets, and reaction wheels. Passive attitude control uses open-loop environmental torques to sustain attitude, such as gravity gradient and solar sails.

The telemetry, tracking, and commanding (TT&C) subsystem involves communication with operators on the ground. Telemetry uses a radio link to transmit measurement data to those operators. It is typically used for improving spacecraft performance and for monitoring the health of the spacecraft, including the payload. Tracking and commanding deals with the spacecraft's position. Tracking is used to report the spacecraft's position to the ground station, while commanding is used to change the spacecraft's position. Some common tracking methods are the use of a beacon or a transponder, Doppler tracking, optical tracking, interferometer tracking, and radar tracking and ranging. Commanding is achieved through coded instructions that the ground station sends to the aircraft.

**PRACTICAL EXAMPLE**

A good example of aerospace design is that of the space shuttle, officially called the Space Transportation System (STS). In 1969, US president Richard Nixon established the Space Task Group to study the United States' future in space exploration. Among other things, the group envisioned a reusable spaceflight vehicle. It was not long before NASA, along with industry contractors, began the design process of such a vehicle. The process involved numerous studies, including design, engineering, cost, and risk studies. Some of the studies focused on the concepts of an orbiter, dual solid-propellant rocket motors, a reusable piloted booster, and a disposable liquid-propellant tank.

In 1972, the design of the space shuttle was moved forward. It would feature an orbiter, three main engines, two solid rocket boosters (SRBs), and an external tank (ET). The orbiter would house the crew, the SRBs would provide the shuttle's lift at the beginning of its flight, and the ET would hold fuel for the main engines. All of the components would be reusable, except for the ET, which would be jettisoned after launch. Refinements continued to be made as the project continued and systems were tested.

*The Space Shuttle Discovery in liftoff, 2007. Photo via Wikimedia Commons. [Public domain.]*

The first orbiter spacecraft, named *Enterprise*, was completed in 1976 and underwent several flight tests. However, *Enterprise* was merely a test vehicle and was not used for any actual space missions. In 1981, the first space shuttle mission took place. *Columbia* lifted off from the Kennedy Space Center and

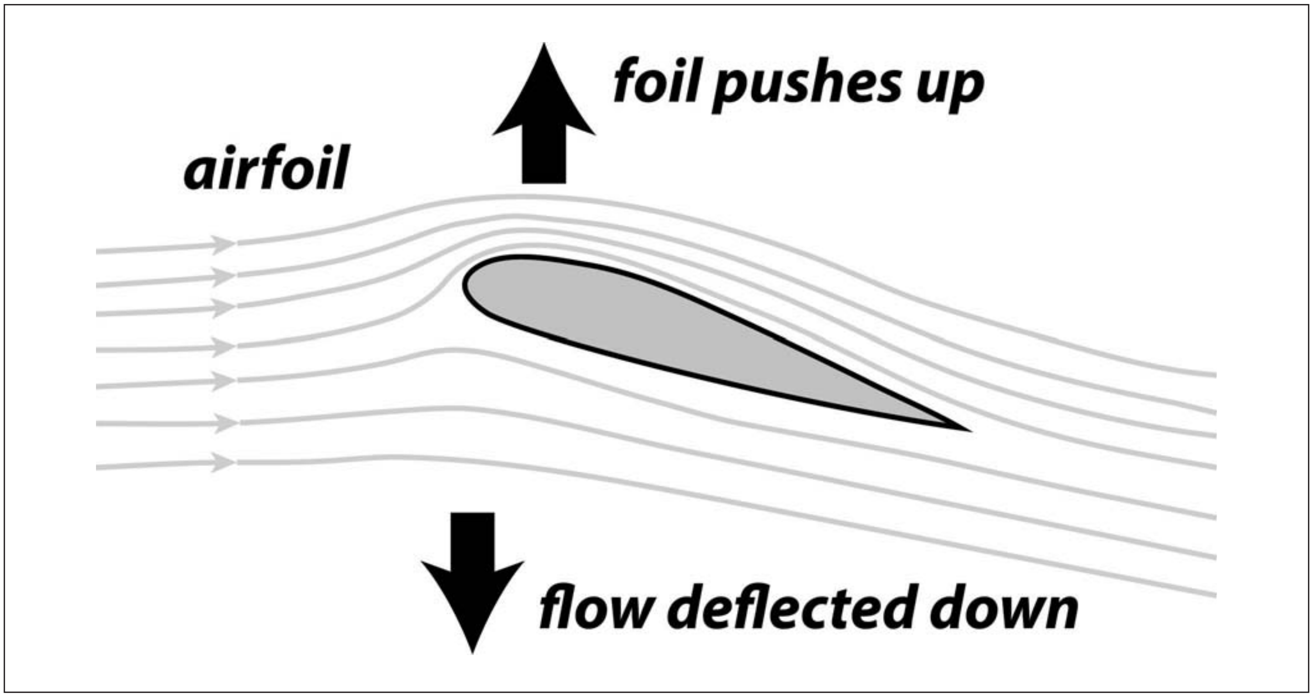



*Image via iStock/gstraub.[Used under license.]*

tests of hundreds of airfoil shapes. The NACA also developed a numbering system, or code, to describe the shapes. In the first series of tests, each of the numbers in a four-digit code was used in a prescribed set of equations to draw the airfoil shape. For example, the NACA 2412 airfoil had a maximum camber of 2 percent of its chord with the maximum camber point at 40 percent of the chord from the airfoil leading edge, and the maximum thickness was 12 percent of the chord.

Many other series of NACA airfoils were developed and tested. The 6-series airfoils were designed to provide very low drag over a set range of angle of attack by encouraging a low-friction laminar flow over part of the surface. Other series of airfoils were developed for use on propeller blades. The NACA's successor, the National Aeronautics and Space Administration (NASA), has continued to test and develop airfoils including a series of supercritical shapes that give lower drag near the speed of sound, as compared to older designs.

**MODERN AIRFOIL DESIGN**

Throughout the twentieth century, airfoil design was essentially a matter of creating a shape based on desired camber and thickness distributions, testing it in wind tunnels and then in flight. Today, airfoils can be selected from hundreds of past designs or custom-developed by specifying a desired distribution of pressure around the surface and using computers to solve for the shape that will give those pressures. Then wind-tunnel tests are done to validate the computer solution. The result is that every airplane can have a wing with a unique distribution of airfoil shapes along its span, all designed for optimum performance. The basic idea is the same as it has always been, to find the combination of camber and thickness that will give the best available mix of lift, drag, and pitching movement for the task at hand.

*—James F. Marchman III*

$$|v\mathbf{d}|^2 = (v\mathbf{f} - v\mathbf{i})^2$$

$$|v\mathbf{d}|^2 = (v\mathbf{f} - v\mathbf{i})(v\mathbf{f} - v\mathbf{i})$$

$$|v\mathbf{d}|^2 = (v\mathbf{f} \times v\mathbf{f}) - (v\mathbf{f} \times \text{vi}) - (v\mathbf{f} \times v\mathbf{i}) + (v\mathbf{i} \times v\mathbf{i})$$

$$|v\mathbf{d}|^2 = |v\mathbf{f}|^2 + |v\mathbf{i}|^2 - 2|v\mathbf{f}||v\mathbf{i}|\cos\theta$$

Of course, objects do not always travel with uniform speed. Once an object in circular motion begins to speed up or slow down, the equations above no longer work. As long as the object continues to follow a circular path, the net force acting on the object will always equal the centripetal force, but its magnitude will vary depending on the acceleration of the object (remember, force equals mass times acceleration).

**CIRCULAR MOTION IN EVERYDAY LIFE**

It is not difficult to find examples of both rotation and revolution in everyday situations. Understanding torque and rotational motion is a vital part of engineering automobiles so that the wheels are given enough force to roll the car forward. Spin on an object moving through the air dramatically affects its aerodynamics and trajectory. In tennis, topspin is a vital technique that allows a player to make the ball drop much more sharply than it would under the influence of gravity alone. Putting “English” on the cue ball in a game of billiards, or throwing a breaking ball or a curve ball in a baseball game, or bending a soccer ball into the goal in a soccer (football) match are all examples of the same effect. Although these situations may seem more complicated than the more familiar linear motion of, for instance, billiard balls just bouncing around a pool table, it is important to remember that the physical principles underpinning linear and circular motion are the same.

—*Kenrick Vezina*

**Further Reading**

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**See also**: Acceleration; Billiards; Calculus; Celestial mechanics; Centrifugation; Circular motion; Coriolis effect; Dynamics (mechanics); Flywheels; Force (physics); Inertial guidance; Linear motion; Moment of inertia; Torque; Turbines

## Angular Momentum

**Fields of Study**: Physics; Engineering; Mechanics; Mathematics

**ABSTRACT**

*Angular momentum is the tendency of an object (or a system of objects rigidly held together in some way) to keep spinning or moving in a circle. Conservation of angular momentum is one of the most fundamental principles of physics, with a wide range of applications.*

**KEY CONCEPTS**

**angular acceleration**: a change in angular velocity with time

**angular velocity**: equivalent to linear velocity, this is the change in the angular position of an object over time, measured in revolutions per unit time

**inertia**: the property of an object to resist change; an object at rest will remain at rest, while an object in motion will continue to move at a constant