

Lift is the [force](https://www.grc.nasa.gov/www/k-12/airplane/forces.html) that holds an aircraft in the air. How is lift generated? There are many explanations for the generation of lift found in encyclopedias, in basic physics textbooks, and on Web sites. Unfortunately, many of the explanations are misleading and incorrect. Theories on the generation of lift have become a source of great controversy and a topic for heated arguments for many years.

The proponents of the arguments usually fall into two camps: (1) those who support the "Bernoulli" position that lift is generated by a pressure difference across the wing, and (2) those who support the "Newton" position that lift is the reaction force on a body caused by deflecting a flow of gas. ***Notice that we place the names in quotation marks because neither Newton nor Bernoulli ever attempted to explain the aerodynamic lift of an object***. The names of these scientists are just labels for two camps.

Looking at the lives of Bernoulli and Newton we find more similarities than differences. On the figure at the top of this page we show portraits of Daniel Bernoulli, on the left, and Sir Isaac Newton, on the right. Newton worked in many areas of mathematics and physics. He developed the theories of [gravitation](https://www.grc.nasa.gov/www/k-12/airplane/wteq.html) in 1666, when he was only 23 years old. Some twenty years later, in 1686, he presented his [three laws of motion](https://www.grc.nasa.gov/www/k-12/airplane/newton.html) in the *Principia Mathematica Philosophiae Naturalis*. He and Gottfried Leibnitz are also credited with the development of the mathematics of Calculus. Bernoulli also worked in many areas of mathematics and physics and had a degree in medicine. In 1724, at age 24, he had published a mathematical work in which he investigated a problem begun by Newton concerning the flow of water from a container and several other problems involving differential equations. In 1738, his work *Hydrodynamica* was published. In this work, he applied the conservation of energy to fluid mechanics problems.

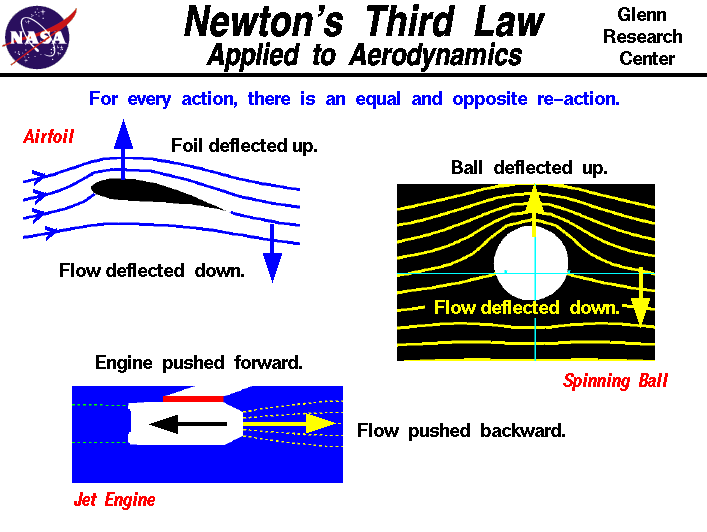
Which camp is correct? How is lift generated?

When a gas flows over an object, or when an object moves through a gas, the molecules of the gas are free to move about the object; they are not closely bound to one another as in a solid. Because the molecules move, there is a velocity associated with the gas. Within the gas, the velocity can have very different values at different places near the object.[Bernoulli's equation](https://www.grc.nasa.gov/www/k-12/airplane/bern.html), which was named for Daniel Bernoulli, Swiss Scientist relates the pressure in a gas to the local velocity; so as the velocity changes around the object, the pressure changes as well. Adding up (integrating) the [pressure variation](https://www.grc.nasa.gov/www/k-12/airplane/presar.html) times the area around the entire body determines the aerodynamic force on the body. The [lift](https://www.grc.nasa.gov/www/k-12/airplane/lift1.html) is the [component](https://www.grc.nasa.gov/www/k-12/airplane/vectpart.html) of the aerodynamic force which is perpendicular to the original flow direction of the gas. The [drag](https://www.grc.nasa.gov/www/k-12/airplane/drag1.html) is the component of the aerodynamic force which is parallel to the original flow direction of the gas. Now adding up the velocity variation around the object instead of the pressure variation also determines the aerodynamic force. The integrated velocity variation around the object produces a net [turning](https://www.grc.nasa.gov/www/k-12/airplane/right2.html) of the gas flow. From [Newton's third law](https://www.grc.nasa.gov/www/k-12/airplane/newton3.html) of motion, a turning action of the flow will result in a re-action (aerodynamic force) on the object. *So****both****"Bernoulli" and "Newton" are correct*. Integrating the effects of either the pressure or the velocity determines the aerodynamic force on an object. We can use equations developed by each of them to determine the magnitude and direction of the aerodynamic force.

What is the argument?

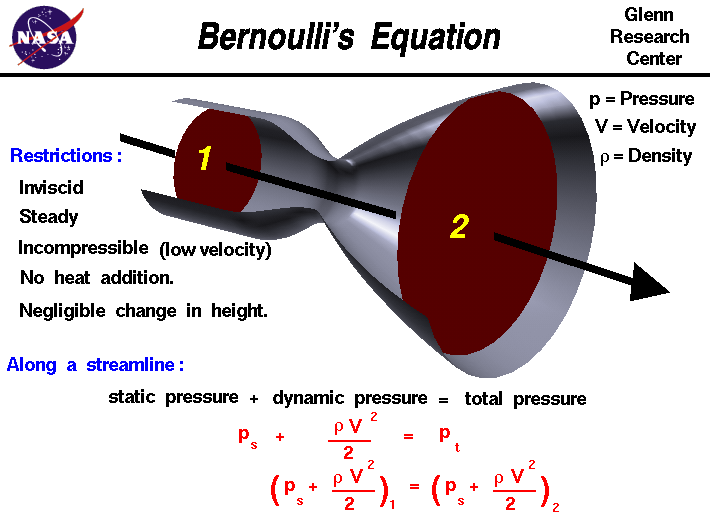
Arguments arise because people mis-apply Bernoulli and Newton's equations and because they over-simplify the description of the problem of aerodynamic lift. The most popular incorrect theory of lift arises from a mis-application of Bernoulli's equation. The theory is known as the ["equal transit time"](https://www.grc.nasa.gov/www/k-12/airplane/wrong1.html) or "longer path" theory which states that wings are designed with the upper surface longer than the lower surface, to generate higher velocities on the upper surface because the molecules of gas on the upper surface have to reach the trailing edge at the same time as the molecules on the lower surface. The theory then invokes Bernoulli's equation to explain lower pressure on the upper surface and higher pressure on the lower surface resulting in a lift force. The error in this theory involves the specification of the velocity on the upper surface. In reality, the velocity on the upper surface of a lifting wing is much higher than the velocity which produces an equal transit time. If we know the correct velocity distribution, we can use Bernoulli's equation to get the pressure, then use the pressure to determine the force. But the equal transit velocity is not the correct velocity. Another incorrect theory uses a[Venturi flow](https://www.grc.nasa.gov/www/k-12/airplane/wrong3.html) to try to determine the velocity. But this also gives the wrong answer since a wing section isn't really half a Venturi nozzle. There is also an incorrect theory which uses Newton's third law applied to the bottom surface of a wing. This theory equates aerodynamic lift to a stone [skipping](https://www.grc.nasa.gov/www/k-12/airplane/wrong2.html) across the water. It neglects the physical reality that both the lower and upper surface of a wing contribute to the turning of a flow of gas.

The real details of how an object generates lift are very complex and do not lend themselves to simplification. For a gas, we have to simultaneously conserve the [mass](https://www.grc.nasa.gov/www/k-12/airplane/mass.html), [momentum](https://www.grc.nasa.gov/www/k-12/airplane/conmo.html), and [energy](https://www.grc.nasa.gov/www/k-12/airplane/thermo1f.html) in the flow. Newton's laws of motion are statements concerning the conservation of momentum. Bernoulli's equation is derived by considering conservation of energy. So both of these equations are satisfied in the generation of lift; both are correct. The conservation of mass introduces a lot of complexity into the analysis and understanding of aerodynamic problems. For example, from the conservation of mass, a change in the velocity of a gas in one direction results in a change in the velocity of the gas in a direction perpendicular to the original change. This is very different from the motion of solids, on which we base most of our experiences in physics. The simultaneous conservation of mass, momentum, and energy of a fluid (while neglecting the effects of [air viscosity](https://www.grc.nasa.gov/www/k-12/airplane/airsim.html)) are called the [Euler Equations](https://www.grc.nasa.gov/www/k-12/airplane/eulereqs.html) after Leonard Euler. Euler was a student of Johann Bernoulli, Daniel's father, and for a time had worked with Daniel Bernoulli in St. Petersburg. If we include the effects of viscosity, we have the [Navier-Stokes Equations](https://www.grc.nasa.gov/www/k-12/airplane/nseqs.html)which are named after two independent researchers in France and in England. To truly understand the details of the generation of lift, one has to have a good working knowledge of the Euler Equations.



Sir Isaac Newton first presented his three [laws of motion](https://www.grc.nasa.gov/www/k-12/airplane/newton.html) in the "Principia Mathematica Philosophiae Naturalis" in 1686. His third law states that for every action (force) in nature there is an equal and opposite reaction. In other words, if object A exerts a force on object B, then object B also exerts an equal and opposite force on object A. Notice that the forces are exerted on different objects.

For aircraft, the principal of action and reaction is very important. It helps to explain the generation of [lift](https://www.grc.nasa.gov/www/k-12/airplane/right2.html) from an airfoil. In this problem, the air is deflected downward by the action of the airfoil, and in reaction the wing is pushed upward. Similarly, for a [spinning ball,](https://www.grc.nasa.gov/www/k-12/airplane/bball.html) the air is deflected to one side, and the ball reacts by moving in the opposite direction. A **jet engine** also produces [thrust](https://www.grc.nasa.gov/www/k-12/airplane/thrust1.html) through action and reaction. The engine produces hot exhaust gases which flow out the back of the engine. In reaction, a thrusting force is produced in the opposite direction.



In the 1700s, [Daniel Bernoulli](https://www.grc.nasa.gov/www/k-12/airplane/bernnew.html) investigated the forces present in a moving [fluid](https://www.grc.nasa.gov/www/k-12/airplane/state.html). This slide shows one of many forms of **Bernoulli's equation**. The equation appears in many physics, fluid mechanics, and airplane textbooks. The equation states that the [static pressure](https://www.grc.nasa.gov/www/k-12/airplane/pressure.html) **ps** in the flow plus the [dynamic pressure](https://www.grc.nasa.gov/www/k-12/airplane/dynpress.html), one half of the density **r** times the velocity **V** squared, is equal to a constant throughout the flow. We call this constant the total pressure **pt** of the flow.

**Molecular Scale Derivation**

We can make another interpretation of the equation by considering the [motion](https://www.grc.nasa.gov/www/k-12/airplane/kinth.html) of the gas molecules. The molecules within a fluid are in constant random motion and collide with each other and with the walls of an object in the fluid. The motion of the molecules gives the molecules a linear momentum and the fluid [pressure](https://www.grc.nasa.gov/www/k-12/airplane/pressure.html) is a measure of this momentum. If a gas is at rest, all of the motion of the molecules is random and the pressure that we detect is the **total pressure** of the gas. If the gas is set in motion or flows, some of the random components of velocity are changed in favor of the directed motion. We call the directed motion "ordered," as opposed to the disordered random motion.

We can associate a "pressure" with the momentum of the ordered motion of the gas. We call this pressure the [dynamic pressure](https://www.grc.nasa.gov/www/k-12/airplane/dynpress.html). The remaining random motion of the molecules still produces a pressure called the **static pressure**. At the molecular level, there is no distinction between random and ordered motion. Each molecule has a velocity in some direction until it collides with another molecule and the velocity is changed. But when you sum up all the velocities of all the molecules you will detect the ordered motion. From a conservation of energy and momentum, the static pressure plus the dynamic pressure is equal to the original total pressure in a flow (assuming we do not add or subtract energy in the flow). The form of the dynamic pressure is the density times the square of the velocity divided by two.

**Applications of Bernoulli's Equation**

The fluids problem shown on this slide is low speed flow through a tube with changing cross-sectional area. For a streamline along the center of the tube, the velocity decreases from station one to two. Bernoulli's equation describes the relation between velocity, density, and pressure for this flow problem. Since density is a constant for a low speed problem, the equation at the bottom of the slide relates the pressure and velocity at station two to the conditions at station one.

Along a low speed [airfoil](https://www.grc.nasa.gov/www/k-12/airplane/geom.html), the flow is incompressible and the density remains a constant. Bernoulli's equation then reduces to a simple relation between velocity and static pressure. The surface of the airfoil is a [streamline](https://www.grc.nasa.gov/www/k-12/airplane/stream.html). Since the velocity varies along the streamline, Bernoulli's equation can be used to compute the change in pressure. The static pressure integrated along the entire surface of the airfoil gives the total [aerodynamic force](https://www.grc.nasa.gov/www/k-12/airplane/presar.html) on the foil. This force can be broken down into the [lift](https://www.grc.nasa.gov/www/k-12/airplane/lift1.html)and [drag](https://www.grc.nasa.gov/www/k-12/airplane/drag1.html) of the airfoil.

Bernoulli's equation is also used on aircraft to provide a speedometer called a [pitot-static tube.](https://www.grc.nasa.gov/www/k-12/airplane/pitot.html) A pressure is quite easy to measure with a mechanical device. In a pitot-static tube, we measure the static and total pressure and can then use Bernoulli's equation to compute the velocity.

Welcome to the Beginner's Guide to Aerodynamics

Image of jet airplane

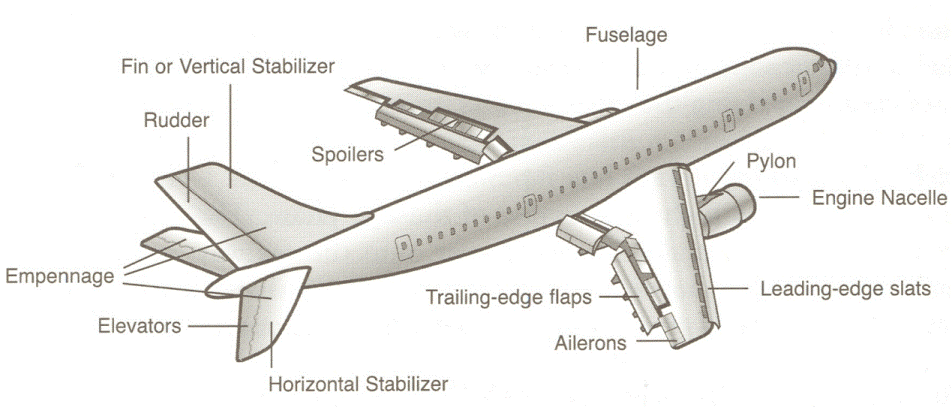
What is aerodynamics? The word comes from two Greek words: aerios, concerning the air, and dynamis, which means force. Aerodynamics is the study of forces and the resulting motion of objects through the air. Judging from the story of Daedalus and Icarus, humans have been interested in aerodynamics and flying for thousands of years, although flying in a heavier-than-air machine has been possible only in the last hundred years. Aerodynamics affects the motion of a large airliner, a model rocket, a beach ball thrown near the shore, or a kite flying high overhead. The curveball thrown by big league baseball pitchers gets its curve from aerodynamics.

Newton's basic equations of motion; the motion of a free falling object, that neglects the effects of aerodynamics; the terminal velocity of a falling object subject to both weight and air resistance; the three forces (lift, drag, and weight) that act on a glider; and finally, the four forces that act on a powered airplane. Because aerodynamics involves both the motion of the object and the reaction of the air, there are several pages devoted to basic gas properties and how those properties change through the atmosphere.

Functionality of Different Parts of Aircraft

An aircraft is composed of different parts. When you own a plane, you have to make sure that you not only look at the sub-parts and the main components of the plane, but the spare parts that will be used when one part fails.

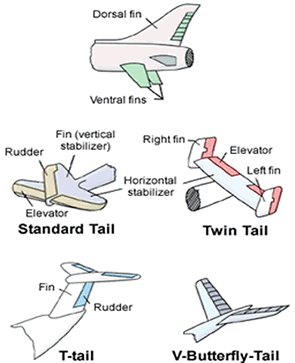
In this article, you will find different information about the parts of an aircraft, [emergent manufacturing](http://theatlasgroup.biz/) and how one part that is not working affects the whole thing. The aim of this section is to grow awareness about the importance of each part no matter how small it is.



*Structural Parts of Aircraft*

Here are the different structural parts of an Aircraft:

* **The engine.**The engine is a major component that allows the aircraft to move. Every type of aircraft is created with a special type of engine that is made in accordance to its size. During the earlier years, aircraft owners used propeller-driven engines. These are traditional engines that are no longer being used.Planes that are developed today are using jet engines. With this, it is safe to say that even modern aircraft use engines for them to be able to work. There are different types of jet engines but the two types that are widely used are turbofan and turbojet.
* **The wing.**This is an important part because it works to help in balancing and improving the aircraft’s stability when flying. This is the part that allows the plane to go up. There are two wings that are joined by a fuselage. The shape of the wings is designed that way in order to help it fly.
* **The horizontal stabilizer.** This part of the aircraft is also called the horizontal stabilizer. The main reason why this is included in the aircraft is to help in maintaining its stability when flying. The wing will not be able to do it alone without the help of this part. This is providing a counteracting force that helps when the aircraft faces disturbances while flying.
* **The fuselage.**This part is connected to the wing of the aircraft. This part actually comes in two different shapes; it may come in rectangular shapes or in cylindrical tubes. This serves as a connecting point for all the parts of the aircraft. This is where you will find the passengers and cargo.
* **The rudder.** This serves as a hinge that allows the plane to turn left. This helps in controlling the direction of the aircraft.



*Different Tail Structures*

The different parts above are basic parts of an aircraft. There are other smaller and yet very important parts that include the flap, cabin, trim tab, nose, main gear and the aileron.  
With the different descriptions given above, you can easily deduce that the main sub-structure of the aircraft is the main determinant of the performance of the whole thing. Every part is interconnected and the failure of one is going to affect everything. The rudder is one of the main components and very important when the aircraft is maneuvering. When it is not working, the whole plane will be affected and it will not be able to properly maneuver.

There is regular maintenance that has to be done in order to make sure that every part is working. This is done twice a year depending on the need of the aircraft. There are also special maintenance periods where the plane has to undergo a long check in order to replace parts that were damaged. Aside from knowing the different theories that support aircraft ownership, it is very important for you to know the importance of the basic parts and to understand how every part works for the performance of the whole aircraft.

Knowing the different functions and descriptions of the parts of the plane will allow you to know and understand the other information that includes the weight that it requires and the other requirements for its safety. This will then lead you to the conclusion on how to abide with the different rules and regulations that are given for aircraft owners.

Welcome to the Beginner's Guide to Propulsion

image of jet engine

What is propulsion? The word is derived from two Latin words: pro meaning before or forwards and pellere meaning to drive. Propulsion means to push forward or drive an object forward. A propulsion system is a machine that produces thrust to push an object forward. On airplanes, thrust is usually generated through some application of Newton's third law of action and reaction. A gas, or working fluid, is accelerated by the engine, and the reaction to this acceleration produces a force on the engine.

A general derivation of the thrust equation shows that the amount of thrust generated depends on the mass flow through the engine and the exit velocity of the gas. Different propulsion systems generate thrust in slightly different ways. We will discuss four principal propulsion systems: the propeller, the turbine (or jet) engine, the ramjet, and the rocket.

Why are there different types of engines? If we think about Newton's first law of motion, we realize that an airplane propulsion system must serve two purposes. First, the thrust from the propulsion system must balance the drag of the airplane when the airplane is cruising. And second, the thrust from the propulsion system must exceed the drag of the airplane for the airplane to accelerate. In fact, the greater the difference between the thrust and the drag, called the excess thrust, the faster the airplane will accelerate.

Some aircraft, like airliners and cargo planes, spend most of their life in a cruise condition. For these airplanes, excess thrust is not as important as high engine efficiency and low fuel usage. Since thrust depends on both the amount of gas moved and the velocity, we can generate high thrust by accelerating a large mass of gas by a small amount, or by accelerating a small mass of gas by a large amount. Because of the aerodynamic efficiency of propellers and fans, it is more fuel efficient to accelerate a large mass by a small amount. That is why we find high bypass fans and turboprops on cargo planes and airliners.

Some aircraft, like fighter planes or experimental high speed aircraft, require very high excess thrust to accelerate quickly and to overcome the high drag associated with high speeds. For these airplanes, engine efficiency is not as important as very high thrust. Modern military aircraft typically employ afterburners on a low bypass turbofan core. Future hypersonic aircraft will employ some type of ramjet or rocket propulsion. There is a special section of the Beginner's Guide which deals with compressible, or high speed, aerodynamics. This section is intended for undergraduates who are studying shock waves or isentropic flows and contains several calculators and simulators for that flow regime.

The site was prepared at NASA Glenn by the Learning Technologies Project (LTP) to provide background information on basic propulsion for secondary math and science teachers. The pages were originally prepared as teaching aids to support EngineSim, an interactive educational computer program that allows students to design and test jet engines on a personal computer. Other slides were prepared to support LTP videoconferencing workshops (http://www.grc.nasa.gov/WWW/K-12/CoE/Coemain.html) for teachers and students. And other slides were prepared as part of Power Point Presentations for the Digital Learning Network.

We have intentionally organized this site to mirror the unstructured nature of the world wide web. There are many pages here connected to one another through hyperlinks. You can then navigate through the links based on your own interest and inquiry. However, if you prefer a more structured approach, you can also take one of our Guided Tours through the site. Each tour provides a sequence of pages dealing with some aspect of propulsion.

Computer drawing of kids page link

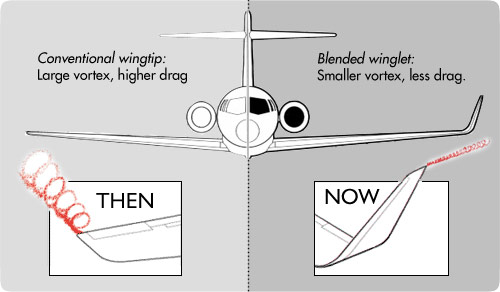
For younger students, a simpler explanation of the information on this page is available on the Kids Page.

NOTICE --- The site has recently been modified to support Section 508 of the Rehabilitation Act. Many of the pages contain mathematical equations which have been produced graphically and which are too long or complex to provide in an "ALT" tag. For these pages, we have retained the (non-compliant) graphical page and have provided a separate (compliant) text only page which contains all of the information of the original page. The two pages are connected through hyperlinks.

Can winglet designs help in conserving more fuel for airlines?

In this period where there’s fear of fuel shortage, several technological innovations for fuel conservation are starting to become a trend for airlines, especially for countries whose fuel prices are often very high. Cars and other ground vehicles are the main point of concern, but the same can also be said for aviation technology.  
Thankfully, airline researchers have found a way to increase the fuel efficiency of an aircraft, thereby saving a lot of fuel costs. All it needs is a simple modification to the wings of the aircraft in order to achieve greater fuel efficiency.

**History**The idea for winglet modifications was first conceptualized by British engineer Frederick W. Lanchester in 1897, using wing end-plates to reduce the impact of wingtip vortices. However, it only after 73 years, during the 1970s, the intensive research on this concept came to fruition. In response to the oil crisis that hit United States in 1973, NASA’s Aircraft Energy Efficiency (ACEE) looked for other methods to increase fuel efficiency for aviation purposes. It was aeronautical engineer Richard Whitcomb of the Langley Research Center that first made his research about this technology, that properly-angled vertical wingtips could drastically weaken wingtip vortices, thus eliminating unneeded drag. Less aircraft drag would then translate to better cruise efficiency, at the same time reducing fuel burn and increasing fuel efficiency for aircraft. This idea was preferred over simple wing extensions, which, while offering the same benefit, has a huge drawback of reinforcing the wings of the plane itself (which would mean increased weight) and could make the plane far too wide for airport gates.



*Modifications in Wing tip*

Whitcomb’s research was then published in 1976, which generated a spew of interest in the aviation industry, which will then lead to the winglet technology that will now be popularized in civil and military aircraft of today.

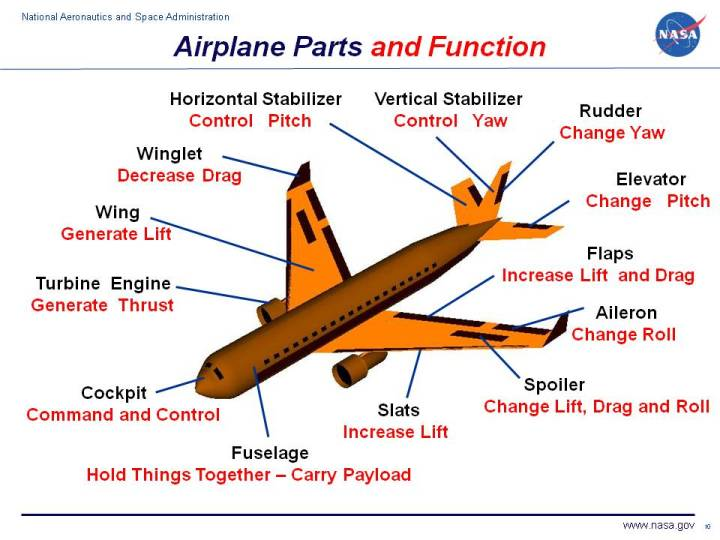
**Winglet Technology Explanation**The basis of the winglet technology can simply be explained via a paper plane construction. While most children only fold their paper planes in the most basic idea possible, others consider folding the edges of their paper wings in order to reduce drag and make the paper plane stay up in the air longer.

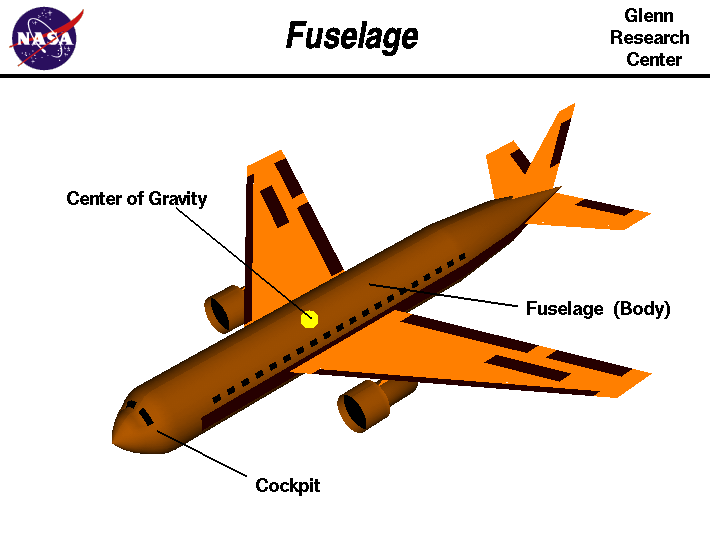


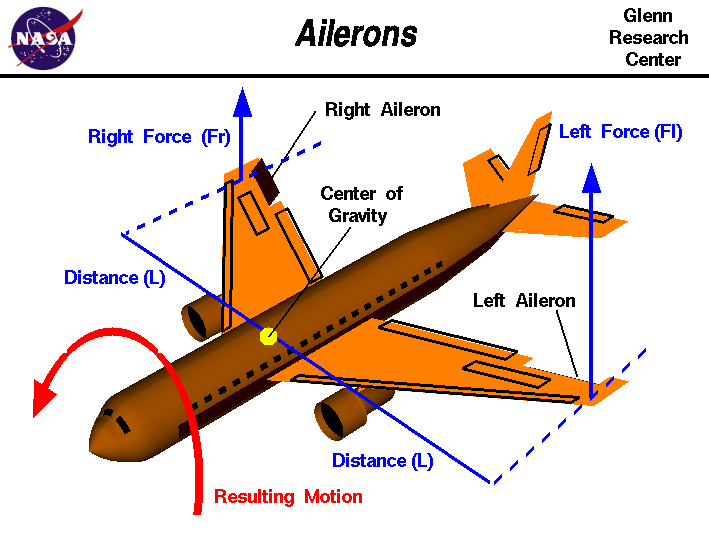
*Winglet Design*

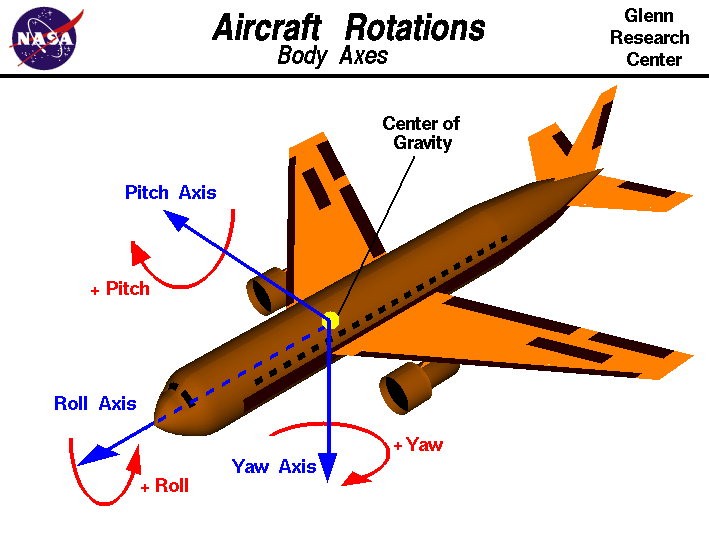
Building on this concept, the same wingtip benefit can also be applied to existing airplanes whether they are [electro-mechanical](http://theatlasgroup.biz/capabilites/electro-mechanical-systems/) or not. By placing a well angled, and properly positioned wingtip on both wings of the plane, the aircraft can achieve a huge reduction of air drag. Air drag is responsible as to why planes without wingtips experience air resistance when flying, which is then mitigated by increasing the engine’s power, effectively consuming far more fuel than normal. By contrast, less wind drag means the aircraft can fly on a much smoother cruise speed with less power, which translates to less fuel consumption, and possibly a smoother ride for the passengers.  
 **Current Winglet Applications**Ever since its development, winglets have been applied to many aircrafts of today.

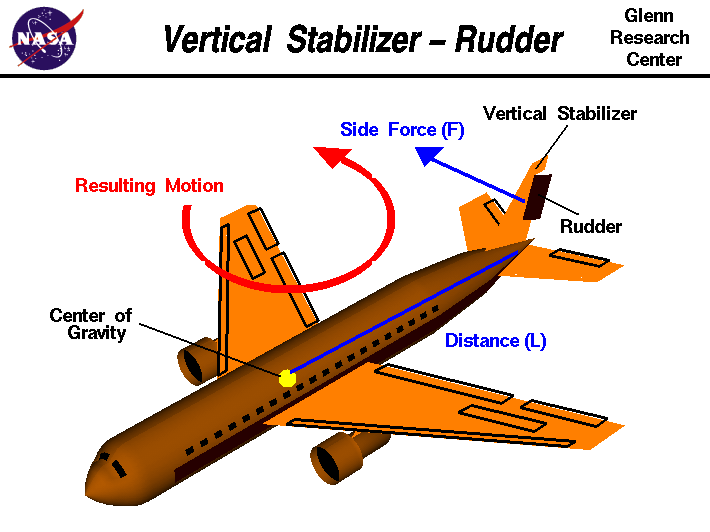
* **Composite Aircraft –**Even before NASA’s research was publicized, Burt Rutan already incorporated the winglet concept into his RutanVariEze, a glass-reinforced plastic composite homebuilt aircraft. The Rutan is considered to be the very first aircraft to incorporate winglet technology.
* **Business Aircraft –** The Learjet 28, developed by Learjet, was the very first of their line of business aircraft to incorporate winglet technology. While a prototype, Learjet developed their aircraft with no assistance from NASA whatsoever. During a series of flight tests, the winglet concept was very successful, that all future models were later equipped with winglet technology.Companies who also use quick-turn R&D also employ winglet-equipped planes, to improve on their speed.
* **Passenger Aircraft –**The Boeing Company started to use winglets with their improved model of the 747, the 747-400. In combination with an increased wingspan, it also enables the new model to carry more load.

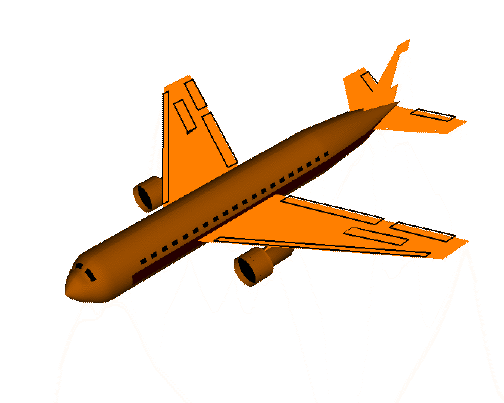


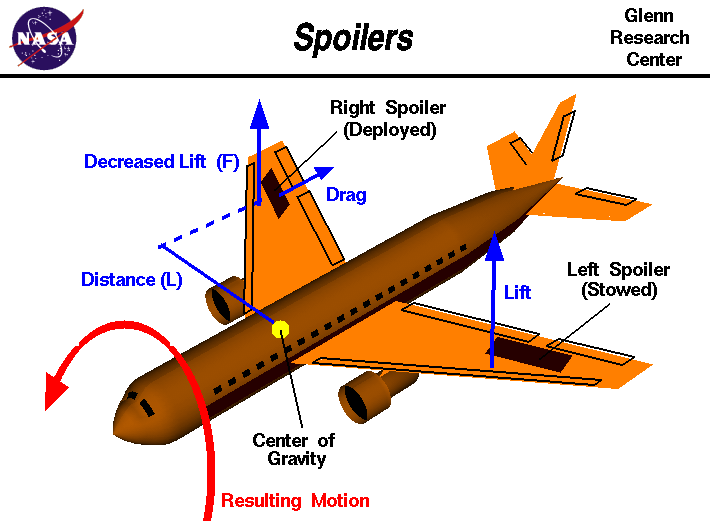


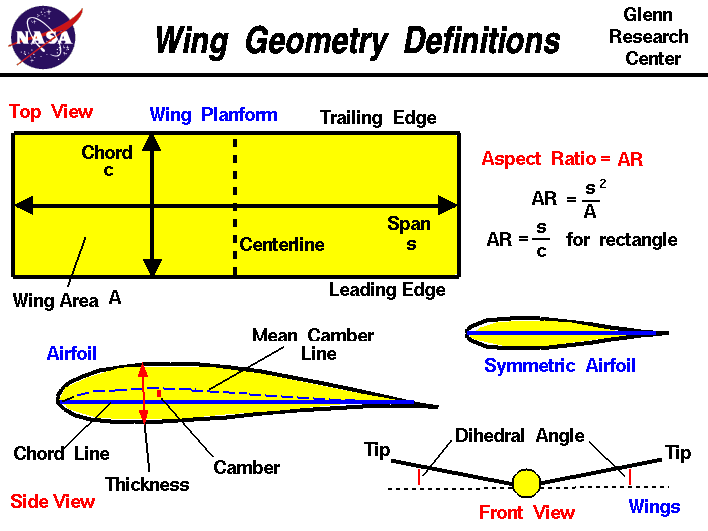


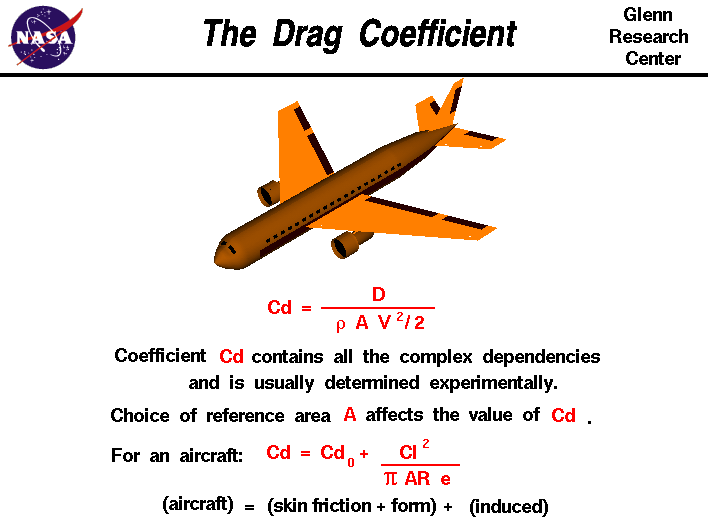


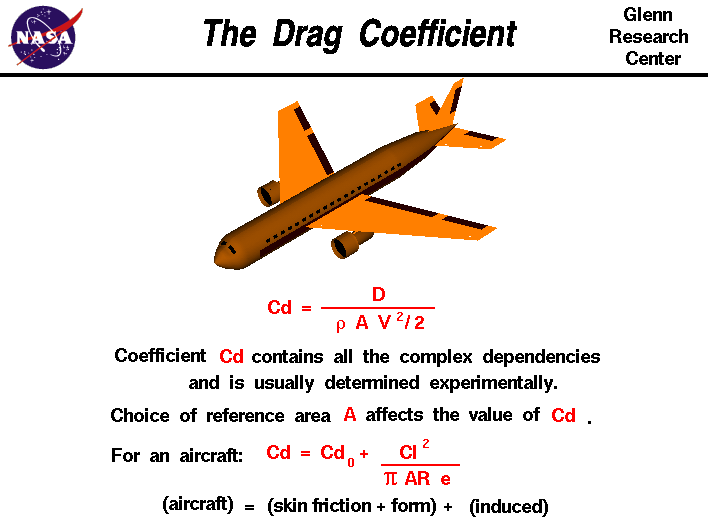


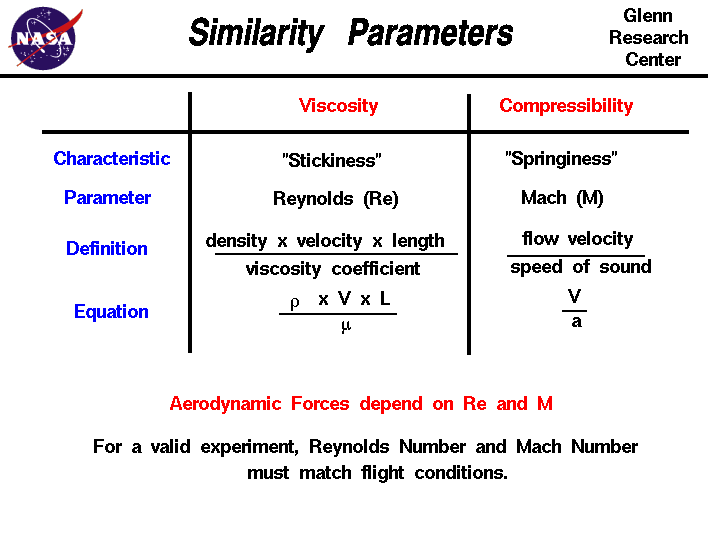


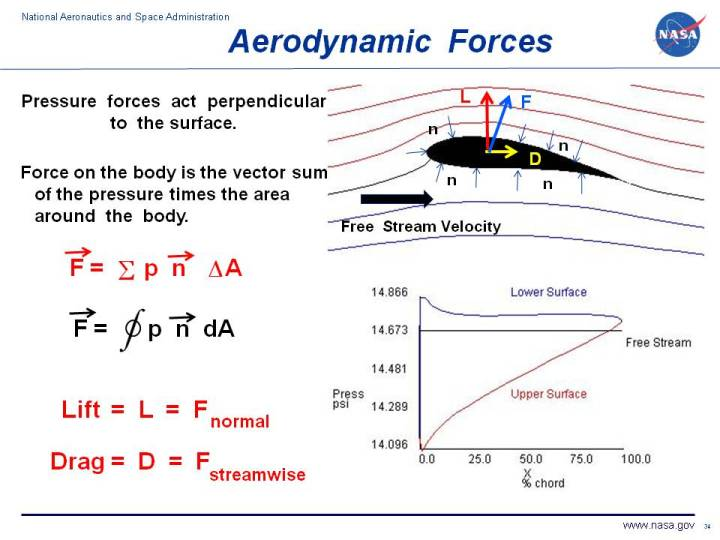


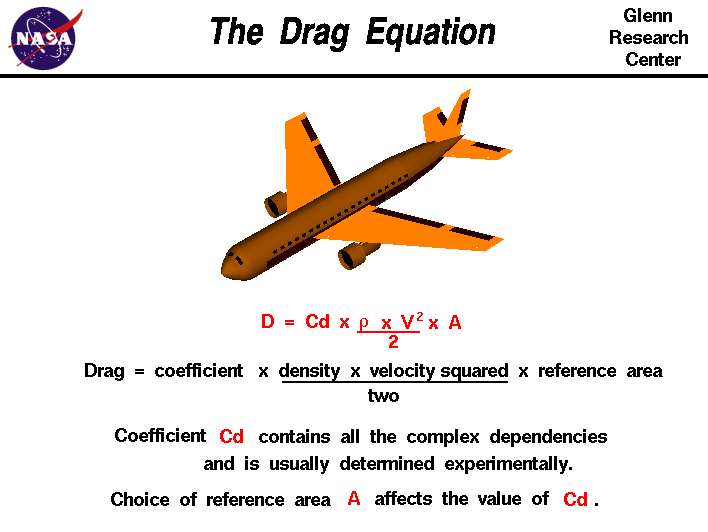


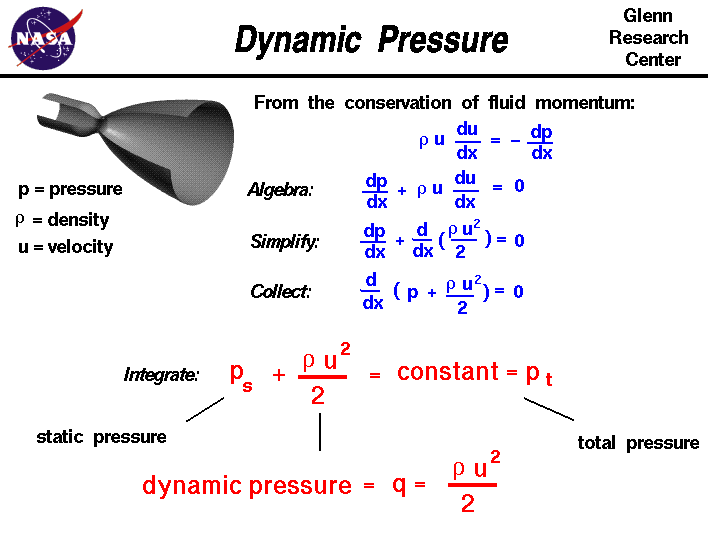


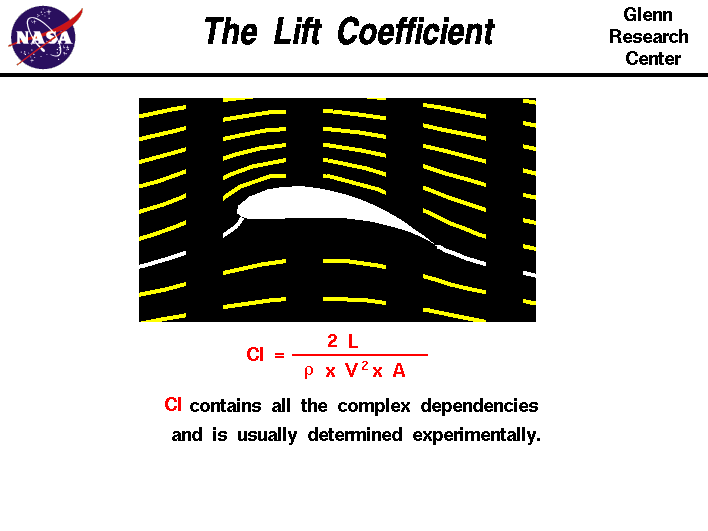












The **lift coefficient** is a number that aerodynamicists use to model all of the complex dependencies of [shape,](https://www.grc.nasa.gov/www/k-12/airplane/shape.html) [inclination,](https://www.grc.nasa.gov/www/k-12/airplane/incline.html)and [some flow conditions](https://www.grc.nasa.gov/www/k-12/airplane/airsim.html) on lift. This equation is simply a rearrangement of the [lift equation](https://www.grc.nasa.gov/www/k-12/airplane/lifteq.html) where we solve for the lift coefficient in terms of the other variables. The lift coefficient **Cl** is equal to the lift **L** divided by the quantity: density **r** times half the velocity **V** squared times the wing area **A**.

Cl = L / (A \* .5 \* r \* V^2)

The quantity one half the density times the velocity squared is called the [dynamic pressure](https://www.grc.nasa.gov/www/k-12/airplane/dynpress.html) **q**. So

Cl = L / (q \* A)

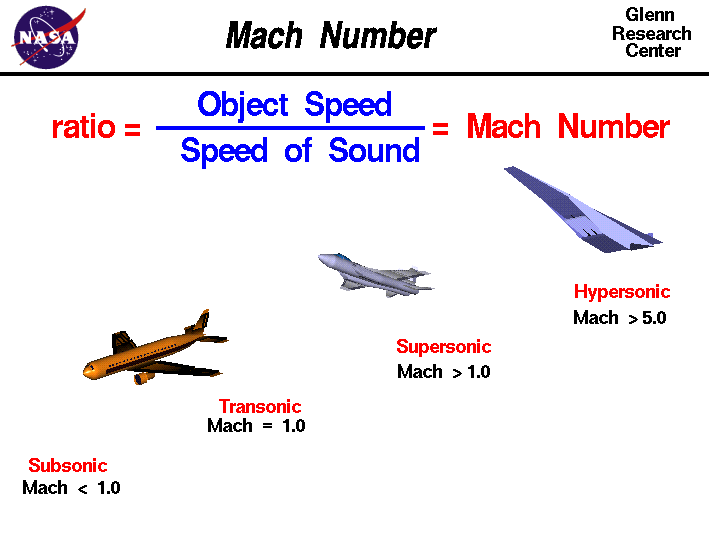
The lift coefficient then expresses the [ratio](https://www.grc.nasa.gov/www/k-12/airplane/ratio.html) of the lift force to the force produced by the dynamic pressure times the area.

Here is a way to determine a value for the lift coefficient. In a controlled environment [(wind tunnel)](https://www.grc.nasa.gov/www/k-12/airplane/tunnel1.html) we can set the velocity, density, and area and measure the lift produced. Through division, we arrive at a value for the lift coefficient. We can then predict the lift that will be produced under a different set of velocity, [density (altitude),](https://www.grc.nasa.gov/www/k-12/airplane/atmos.html) and area conditions using the [lift equation.](https://www.grc.nasa.gov/www/k-12/airplane/lifteq.html)

The lift coefficient contains the complex dependencies of object shape on lift. For three dimensional wings, the [downwash](https://www.grc.nasa.gov/www/k-12/airplane/downwash.html)generated near the [wing tips](https://www.grc.nasa.gov/www/k-12/airplane/geom.html) reduces the overall lift coefficient of the wing. The lift coefficient also contains the effects of [air viscosity and compressibility.](https://www.grc.nasa.gov/www/k-12/airplane/airsim.html) To correctly use the lift coefficient, we must be sure that the viscosity and compressibility effects are the same between our measured case and the predicted case. Otherwise, the prediction will be inaccurate.

For very low speeds (< 200 mph) the compressibility effects are negligible. At higher speeds, it becomes important to match Mach numbers between the two cases. [Mach number](https://www.grc.nasa.gov/www/k-12/airplane/mach.html) is the ratio of the velocity to the speed of sound. So it is completely incorrect to measure a lift coefficient at some low speed (say 200 mph) and apply that lift coefficient at twice the speed of sound (approximately 1,400 mph, Mach = 2.0). The compressibility of the air will alter the important physics between these two cases.

Similarly, we must match air viscosity effects, which becomes very difficult. The important matching parameter for viscosity is the Reynolds number. The [Reynolds number](https://www.grc.nasa.gov/www/k-12/airplane/boundlay.html) expresses the ratio of inertial forces to viscous forces. If the Reynolds number of the experiment and flight are close, then we properly model the effects of the viscous forces relative to the inertial forces. If they are very different, we do not correctly model the physics of the real problem and will predict an incorrect lift.



As an aircraft moves through the air, the air molecules near the aircraft are disturbed and move around the aircraft. If the aircraft passes at a low speed, typically less than 250 mph, the [density](https://www.grc.nasa.gov/www/k-12/airplane/fluden.html) of the air remains constant. But for higher speeds, some of the energy of the aircraft goes into compressing the air and locally changing the density of the air. This [compressibility effect](https://www.grc.nasa.gov/www/k-12/airplane/airsim.html) alters the amount of resulting force on the aircraft. The effect becomes more important as speed increases. Near and beyond the [speed of sound](https://www.grc.nasa.gov/www/k-12/airplane/sound.html), about 330 m/s or 760 mph, small disturbances in the flow are transmitted to other locations [isentropically](https://www.grc.nasa.gov/www/k-12/airplane/isentrop.html) or with constant entropy. But a sharp disturbance generates a [shock wave](https://www.grc.nasa.gov/www/k-12/airplane/shock.html)that affects both the lift and drag of an aircraft.

The [ratio](https://www.grc.nasa.gov/www/k-12/airplane/ratio.html) of the speed of the aircraft to the speed of sound in the gas determines the magnitude of many of the compressibility effects. Because of the importance of this speed ratio, aerodynamicists have designated it with a special parameter called the **Mach number** in honor of **Ernst Mach**, a late 19th century physicist who studied gas dynamics. The Mach number **M** allows us to define flight regimes in which compressibility effects vary.

1. [Subsonic](https://www.grc.nasa.gov/www/k-12/airplane/lowsub.html) conditions occur for Mach numbers less than one, **M < 1**. For the lowest subsonic conditions, compressibility can be ignored.
2. As the speed of the object approaches the speed of sound, the flight Mach number is nearly equal to one, **M = 1**, and the flow is said to be [transonic](https://www.grc.nasa.gov/www/k-12/airplane/hisub.html). At some places on the object, the local speed exceeds the speed of sound. Compressibility effects are most important in transonic flows and lead to the early belief in a **sound barrier**. Flight faster than sound was thought to be impossible. In fact, the sound barrier was only an increase in the drag near sonic conditions because of compressibility effects. Because of the high drag associated with compressibility effects, aircraft do not cruise near Mach 1.
3. [Supersonic](https://www.grc.nasa.gov/www/k-12/airplane/losup.html) conditions occur for Mach numbers greater than one, **1 < M < 3**. Compressibility effects are important for supersonic aircraft, and shock waves are generated by the surface of the object. For [high supersonic speeds](https://www.grc.nasa.gov/www/k-12/airplane/hisup.html), **3 < M < 5**, aerodynamic heating also becomes very important for aircraft design.
4. For speeds greater than five times the speed of sound, **M > 5**, the flow is said to be [hypersonic](https://www.grc.nasa.gov/www/k-12/airplane/lowhyper.html). At these speeds, some of the energy of the object now goes into exciting the chemical bonds which hold together the nitrogen and oxygen molecules of the air. At hypersonic speeds, the chemistry of the air must be considered when determining forces on the object. The Space Shuttle re-enters the atmosphere at [high hypersonic speeds](https://www.grc.nasa.gov/www/k-12/airplane/hihyper.html), **M ~ 25**. Under these conditions, the heated air becomes an ionized plasma of gas and the spacecraft must be insulated from the high temperatures.

For supersonic and hypersonic flows, small disturbances are transmitted downstream within a cone. The trigonometric [sine](https://www.grc.nasa.gov/www/k-12/airplane/trig.html)of the cone angle **b** is equal to the inverse of the Mach number **M** and the angle is therefore called the [Mach angle](https://www.grc.nasa.gov/www/k-12/airplane/machang.html).

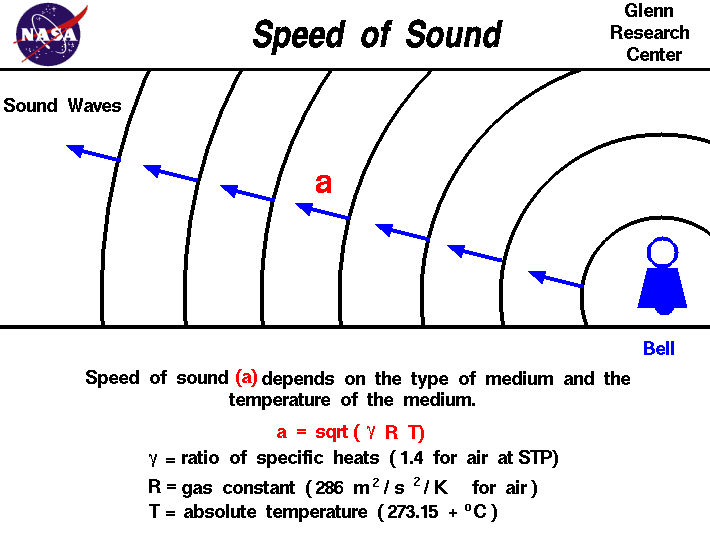
sin(b) = 1 / M

**There is no upstream influence in a supersonic flow**; disturbances are only transmitted downstream.

The Mach number appears as a [similarity parameter](https://www.grc.nasa.gov/www/k-12/airplane/airsim.html) in many of the equations for [compressible flows](https://www.grc.nasa.gov/www/k-12/airplane/isentrop.html), [shock waves](https://www.grc.nasa.gov/www/k-12/airplane/oblique.html), and[expansions](https://www.grc.nasa.gov/www/k-12/airplane/expans.html). When wind tunnel testing, you must closely match the Mach number between the experiment and flight conditions. It is completely incorrect to measure a drag coefficient at some low speed (say 200 mph) and apply that drag coefficient at twice the speed of sound (approximately 1400 mph, Mach = 2.0). The compressibility of the air alters the important physics between these two cases.

The Mach number depends on the speed of sound in the gas and the speed of sound depends on the type of gas and the temperature of the gas. The speed of sound varies from planet to planet. On Earth, the atmosphere is composed of mostly diatomic nitrogen and oxygen, and the temperature depends on the altitude in a rather complex way. Scientists and engineers have created a [mathematical model](https://www.grc.nasa.gov/www/k-12/airplane/atmos.html) of the atmosphere to help them account for the changing effects of temperature with altitude. Mars also has an atmosphere composed of mostly carbon dioxide. There is a similar[mathematical model](https://www.grc.nasa.gov/www/k-12/airplane/atmosmre.html) of the Martian atmosphere. We have created an [atmospheric calculator](https://www.grc.nasa.gov/www/k-12/airplane/atmosi.html) to let you study the variation of sound speed with planet and altitude.

Here's another JavaScript program to calculate speed of sound and Mach number for different planets, altitudes, and speed. You can use this calculator to determine the Mach number of a aircraft at a given speed and altitude on Earth or Mars.



Air is a [gas](https://www.grc.nasa.gov/www/k-12/airplane/state.html), and a very important [property](https://www.grc.nasa.gov/www/k-12/airplane/gasprop.html) of any gas is the **speed of sound** through the gas. Why are we interested in the speed of sound? The **speed of "sound"** is actually the speed of transmission of a small disturbance through a medium. **Sound** itself is a sensation created in the human brain in response to sensory inputs from the inner ear. (We won't comment on the old "tree falling in a forest" discussion!)

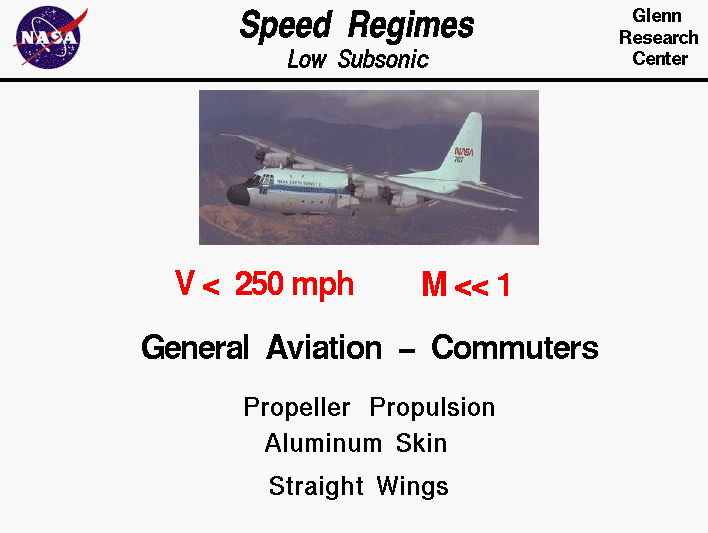
Disturbances are transmitted through a gas as a result of [collisions](https://www.grc.nasa.gov/www/k-12/airplane/kinth.html) between the randomly moving molecules in the gas. The transmission of a small disturbance through a gas is an [isentropic process](https://www.grc.nasa.gov/www/k-12/airplane/isentrop.html). The conditions in the gas are the same before and after the disturbance passes through. Because the speed of transmission depends on molecular collisions, the speed of sound depends on the [state](https://www.grc.nasa.gov/www/k-12/airplane/eqstat.html) of the gas. The speed of sound is a constant within a given gas and the value of the constant depends on the type of gas (air, pure oxygen, carbon dioxide, etc.) and the temperature of the gas. An [analysis](https://www.grc.nasa.gov/www/k-12/airplane/snddrv.html) based on conservation of [mass](https://www.grc.nasa.gov/www/k-12/airplane/mass.html) and [momentum](https://www.grc.nasa.gov/www/k-12/airplane/conmo.html) shows that the speed of sound **a** is equal to the square root of the ratio of [specific heats](https://www.grc.nasa.gov/www/k-12/airplane/specheat.html) **g** times the gas constant **R** times the temperature **T**.

a = sqrt [g \* R \* T]

*Notice that the [temperature](https://www.grc.nasa.gov/www/k-12/airplane/temptr.html) must be specified on an absolute scale (Kelvin or Rankine). The dependence on the type of gas is included in the gas constant****R****. which equals the universal gas constant divided by the molecular weight of the gas, and the ratio of specific heats.*

The speed of sound in air depends on the type of gas and the temperature of the gas. On Earth, the [atmosphere](https://www.grc.nasa.gov/www/k-12/airplane/atmosphere.html) is composed of mostly diatomic nitrogen and oxygen, and the temperature depends on the altitude in a rather complex way. Scientists and engineers have created a [mathematical model](https://www.grc.nasa.gov/www/k-12/airplane/atmos.html) of the atmosphere to help them account for the changing effects of temperature with altitude. Mars also has an atmosphere composed of mostly carbon dioxide. There is a similar[mathematical model](https://www.grc.nasa.gov/www/k-12/airplane/atmosmre.html) of the Martian atmosphere. We have created an [atmospheric calculator](https://www.grc.nasa.gov/www/k-12/airplane/atmosi.html) to let you study the variation of sound speed with planet and altitude.

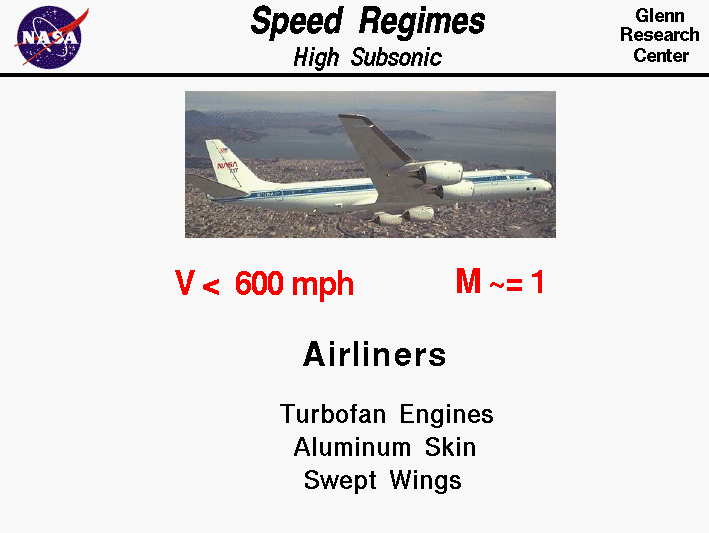
Here's a JavaScript program to calculate speed of sound and [Mach number](https://www.grc.nasa.gov/www/k-12/airplane/mach.html) for different planets, altitudes, and speed. You can use this calculator to determine the Mach number of a rocket at a given speed and altitude on Earth or Mars.



As an aircraft moves through the air, the air molecules near the aircraft are disturbed and move around the aircraft. Exactly how the air re-acts to the aircraft depends upon the ratio of the speed of the aircraft to the [speed of sound](https://www.grc.nasa.gov/www/k-12/airplane/sound.html) through the air. Because of the importance of this speed ratio, aerodynamicists have designated it with a special parameter called the [Mach number](https://www.grc.nasa.gov/www/k-12/airplane/mach.html) in honor of **Ernst Mach**, a late 19th century physicist who studied gas dynamics.

For aircraft speeds which are very much less than the speed of sound, the aircraft is said to be **subsonic**. Typical speeds for subsonic aircraft are less than 250 mph, and the Mach number **M** is much less than one, **M << 1**. For subsonic aircraft, we can neglect [compressibility effects](https://www.grc.nasa.gov/www/k-12/airplane/airsim.html) and the [air density](https://www.grc.nasa.gov/www/k-12/airplane/fluden.html) remains nearly constant.

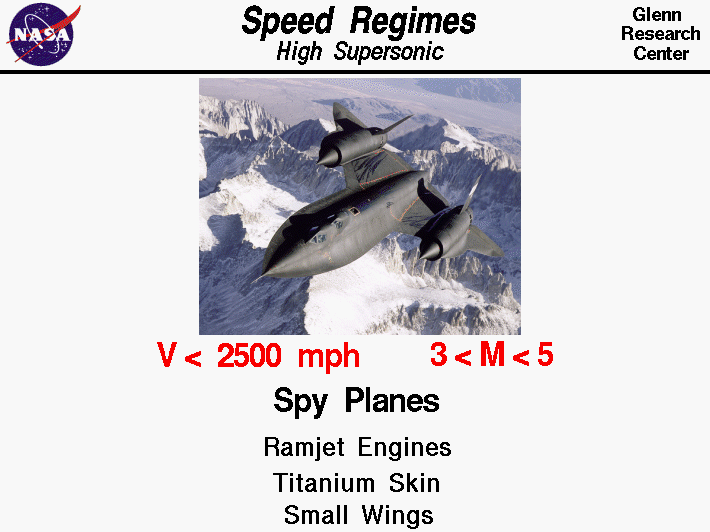
The first powered aircraft to explore this regime was the Wright Brothers' [1903 flyer](https://www.grc.nasa.gov/www/Wright/airplane/air1903.html). Modern general aviation and commuter airliners continue to fly in this speed regime. At such low speeds, [propellers](https://www.grc.nasa.gov/www/k-12/airplane/propeller.html) provide a very fuel efficient propulsion system. On the slide we show a C-130 cargo aircraft which is powered by four [turboprop engines](https://www.grc.nasa.gov/www/k-12/airplane/aturbp.html). The [wings](https://www.grc.nasa.gov/www/k-12/airplane/geom.html) of subsonic aircraft are typically [rectangular](https://www.grc.nasa.gov/www/k-12/airplane/area.html) in planform and made of light weight aluminum, although the Wrights used wood and cloth in their wing construction.



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For aircraft speeds which are very near the speed of sound, the aircraft is said to be **transonic**. Typical speeds for transonic aircraft are greater than 250 mph but less than 760 mph, and the Mach number **M** is nearly equal to one, **M ~= 1**. While the aircraft itself may be traveling less than the speed of sound, the air going around the aircraft exceeds the speed of sound at some locations on the aircraft. In the regions where the local airspeed is near or greater than the speed of sound, we encounter [compressibility effects](https://www.grc.nasa.gov/www/k-12/airplane/airsim.html) and the [air density](https://www.grc.nasa.gov/www/k-12/airplane/fluden.html) may vary because of local [shock waves](https://www.grc.nasa.gov/www/k-12/airplane/shock.html), [expansions](https://www.grc.nasa.gov/www/k-12/airplane/expans.html), or [flow choking](https://www.grc.nasa.gov/www/k-12/airplane/mflchk.html).

The first powered aircraft to explore this regime were the high performance fighters of World War II. These aircraft seemed to encounter a **sound barrier** at which drag was increasing faster than thrust. There was speculation in the mid-1940's that manned flight was not possible at speeds faster than the speed of sound, even though the muzzle velocity of rifle bullets is supersonic. Of course, the flight of the X-1A in 1947 proved that people could fly faster than sound and, until the recent retirement of the Concorde, any person with enough money can fly supersonic. As mentioned above, even though modern airliners typically fly at about **M = .85**, the flow over the wings is transonic or supersonic. Drag increases dramatically as an aircraft approaches Mach 1, so airliners use high thrust [gas turbine](https://www.grc.nasa.gov/www/k-12/airplane/turbine.html) propulsion systems. On the slide we show a DC-8 airliner which is powered by four [turbofan engines](https://www.grc.nasa.gov/www/k-12/airplane/aturbf.html). The [wings](https://www.grc.nasa.gov/www/k-12/airplane/geom.html) of airliners are typically [swept](https://www.grc.nasa.gov/www/k-12/airplane/area.html) in planform to reduce the transonic drag. For Mach numbers less than 2.0, the frictional heating of the airframe is low enough that light weight aluminum is used for the structure.

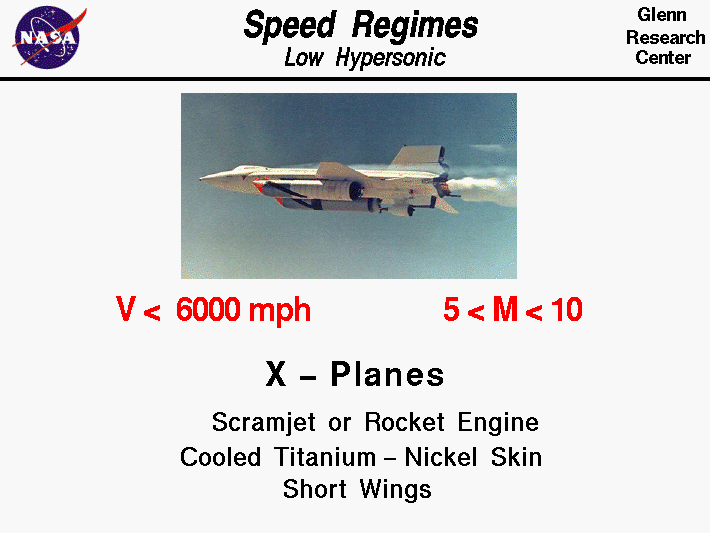


As an aircraft moves through the air, the air molecules near the aircraft are disturbed and move around the aircraft. Exactly how the air re-acts to the aircraft depends upon the ratio of the speed of the aircraft to the [speed of sound](https://www.grc.nasa.gov/www/k-12/airplane/sound.html) through the air. Because of the importance of this speed ratio, aerodynamicists have designated it with a special parameter called the [Mach number](https://www.grc.nasa.gov/www/k-12/airplane/mach.html) in honor of **Ernst Mach**, a late 19th century physicist who studied gas dynamics.

For aircraft speeds which are greater than the speed of sound, the aircraft is said to be **supersonic**. There are some very special aircraft which fly in the **high supersonic** regime in which aircraft skin [temperature](https://www.grc.nasa.gov/www/k-12/airplane/temptr.html) becomes high enough that special materials must be used, but the temperature is still low enough that the air molecules remain intact. Typical speeds for high supersonic aircraft are greater than 1500 mph but less than 2500 mph. The Mach number **M** is then greater than three, but less than five, **3 < M < 5**. In addition to the high temperatures, we encounter [compressibility effects](https://www.grc.nasa.gov/www/k-12/airplane/airsim.html) and the local[air density](https://www.grc.nasa.gov/www/k-12/airplane/fluden.html) varies because of [shock waves](https://www.grc.nasa.gov/www/k-12/airplane/shock.html), and [expansions](https://www.grc.nasa.gov/www/k-12/airplane/expans.html).

The only aircraft to cruise in this regime were the XB-70 and the SR-71/YF-12. An SR-71 is shown on the figure. Both of these aircraft employed very specialized [inlet systems](https://www.grc.nasa.gov/www/k-12/airplane/inlet.html) to bring high speed air into the engine. The XB-70 employed six special [afterburning turbine engines](https://www.grc.nasa.gov/www/k-12/airplane/turbine.html) while the SR-71 used an integrated [turbo-ramjet](https://www.grc.nasa.gov/www/k-12/airplane/ramjet.html). Because [lift](https://www.grc.nasa.gov/www/k-12/airplane/lift1.html) and [drag](https://www.grc.nasa.gov/www/k-12/airplane/drag1.html) depend on the square of the [velocity](https://www.grc.nasa.gov/www/k-12/airplane/vel.html), these aircraft did not require large [wing area](https://www.grc.nasa.gov/www/k-12/airplane/geom.html) in cruising flight. Like any supersonic aircraft, the wings are [swept](https://www.grc.nasa.gov/www/k-12/airplane/area.html) in planform to reduce drag.

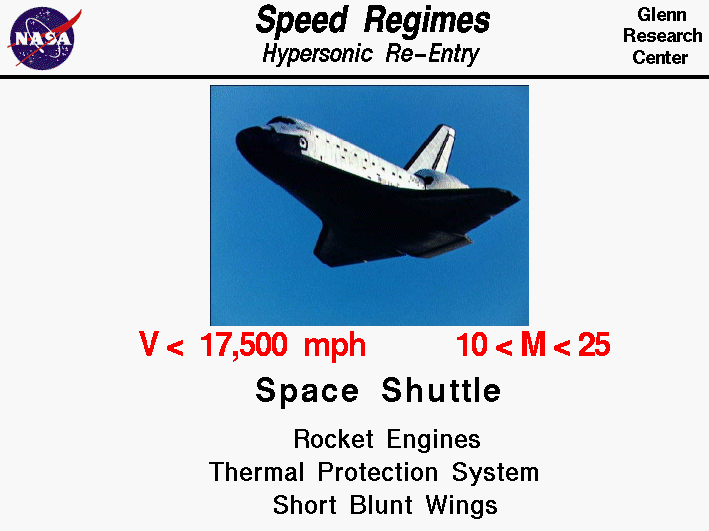
As any metal is heated, it begins to lose strength. The amount of the loss depends on the type of metal. For Mach numbers greater than 2.5, the frictional heating of the airframe by the air becomes high enough that light weight aluminum can not be used for the structure. The SR-71 was made largely of titanium, which has good high temperature characteristics, but is still light enough for aircraft structures. During heating, any metal expands. To allow for the expansion, slip joints are used in many places on the SR-71. On the ground, the SR-71 fuel tanks leak, and they do not seal until the aircraft heats up during flight.



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For aircraft speeds which are much greater than the speed of sound, the aircraft is said to be **hypersonic**. Typical speeds for hypersonic aircraft are greater than 3000 mph and Mach number **M** greater than five, **M > 5**. We are going to define a[high hypersonic](https://www.grc.nasa.gov/www/k-12/airplane/hihyper.html) regime at **M > 10**to account for re-entry aerodynamics. The chief characteristic of hypersonic aerodynamics is that the [temperature](https://www.grc.nasa.gov/www/k-12/airplane/temptr.html) of the flow is so great that the chemistry of the diatomic molecules of the [air](https://www.grc.nasa.gov/www/k-12/airplane/state.html) must be considered. At low hypersonic speeds, the molecular bonds vibrate, which changes the magnitude of the forces generated by the air on the aircraft. At high hypersonic speeds, the molecules break apart producing an electrically charged plasma around the aircraft. Large variations in [air density](https://www.grc.nasa.gov/www/k-12/airplane/fluden.html) and [pressure](https://www.grc.nasa.gov/www/k-12/airplane/pressure.html) occur because of [shock waves](https://www.grc.nasa.gov/www/k-12/airplane/shock.html), and [expansions](https://www.grc.nasa.gov/www/k-12/airplane/expans.html).

The only manned aircraft to fly in the low hypersonic regime were the X-15 and the Space Shuttle during re-entry. The X-15 is shown on the figure. The X-15 used a [rocket](https://www.grc.nasa.gov/www/k-12/airplane/rocket.html) propulsion system to achieve sustained Mach 6 flight. Recently, an un-manned X-43A used a [scramjet](https://www.grc.nasa.gov/www/k-12/airplane/scramjet.html), or supersonic combustion [ramjet](https://www.grc.nasa.gov/www/k-12/airplane/ramjet.html), to make two hypersonic flights; one at Mach 7, the other at Mach 10. Because of the pressure losses associated with the [terminal shock](https://www.grc.nasa.gov/www/k-12/airplane/normal.html) of the [inlet](https://www.grc.nasa.gov/www/k-12/airplane/inlet.html), a ramjet has very limited performance beyond Mach 5. Because [lift](https://www.grc.nasa.gov/www/k-12/airplane/lift1.html) and [drag](https://www.grc.nasa.gov/www/k-12/airplane/drag1.html) depend on the square of the [velocity](https://www.grc.nasa.gov/www/k-12/airplane/vel.html), hypersonic aircraft do not require a large [wing area](https://www.grc.nasa.gov/www/k-12/airplane/geom.html). For Mach numbers greater than 5, the frictional heating of the airframe by the air becomes so high that very special nickel alloys are required for the structure. For some proposed hypersonic aircraft, the skin is actively cooled by circulating fuel through the skin to absorb the heat.

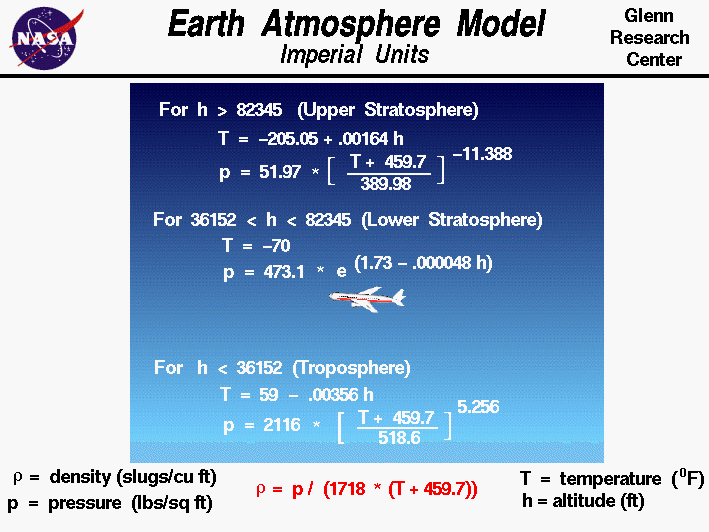


As an aircraft moves through the air, the air molecules near the aircraft are disturbed and move around the aircraft. Exactly how the air re-acts to the aircraft depends upon the ratio of the speed of the aircraft to the [speed of sound](https://www.grc.nasa.gov/WWW/BGH/sound.html) through the air. Because of the importance of this speed ratio, aerodynamicists have designated it with a special parameter called the [Mach number](https://www.grc.nasa.gov/WWW/BGH/mach.html) in honor of **Ernst Mach**, a late 19th century physicist who studied gas dynamics.

As a spacecraft **re-enters** the earth's atmosphere, it is traveling very much faster than the speed of sound. The aircraft is said to be **hypersonic**. Typical low earth orbit re-entry speeds are near 17,500 mph and the Mach number **M** is nearly twenty five, **M < 25**. The chief characteristic of re-entry aerodynamics is that the [temperature](https://www.grc.nasa.gov/WWW/BGH/temptr.html) of the flow is so great that the chemical bonds of the diatomic molecules of the [air](https://www.grc.nasa.gov/WWW/BGH/state.html) are broken. The molecules break apart producing an electrically charged plasma around the aircraft. The [air density](https://www.grc.nasa.gov/WWW/BGH/fluden.html) is very low because re-entry occurs many miles above the earth's surface. Strong [shock waves](https://www.grc.nasa.gov/WWW/BGH/shock.html) are generated on the lower surface of the spacecraft.

The only manned aircraft to currently fly in this regime are the American Space Shuttle, the Russian Soyuz spacecraft, and the Chinese Shenzhou spacecraft. The figure shows the Shuttle after it has passed through the re-entry regime. The Shuttle uses a [rocket](https://www.grc.nasa.gov/WWW/BGH/rocket.html) propulsion system to get into orbit, but during re-entry the aircraft is actually an un-powered glider. Small steering rockets are used for maneuvering early in the re-entry because the low density of the air at altitudes above 50 miles makes aerodynamic surfaces ineffective. The heat is so great during re-entry that a special **thermal protection system** is used to keep the spacecraft intact. On the Shuttle, special silicon tiles are placed on the aluminum skin to insulate the skin. On the leading edge of the wings, carbon-cabon composite material is used to withstand the heat. The high forces and high heat dictate that the Shuttle has short, blunt wings. The Shuttle flies at a high angle of attack during re-entry to generate drag to dissipate speed. It executes hypersonic "S-turn" maneuvers to kill off speed during re-entry. The [lift](https://www.grc.nasa.gov/WWW/BGH/lift1.html) of the wings is only important in the final flare maneuver at touchdown.

The Soyuz, Shenzhou, and all of the early Apollo, Gemini, and Mercury spacecraft used a thermal protection system that is different than the Space Shuttle. Each of these spacecraft use an **ablative**, or "burning", heat shield. The heat shield is made of special ceramic materials and is designed to slowly burn away as it encounters the high temperature plasma flow aft of the bow [shock wave](https://www.grc.nasa.gov/WWW/BGH/normal.html). The change of phase from solid to liquid to gas and the [convection](https://www.grc.nasa.gov/WWW/BGH/gasprop.html) of the flow away from the spacecraft help to protect the astronauts from the heat of re-entry.



The Earth's [atmosphere](https://www.grc.nasa.gov/www/k-12/airplane/atmosphere.html)is an extremely thin sheet of [air](https://www.grc.nasa.gov/www/k-12/airplane/airprop.html) extending from the surface of the Earth to the edge of space, about 60 miles above the surface of the Earth. If the Earth were the size of a basketball, a tightly held pillowcase would represent the thickness of the atmosphere. [Gravity](https://www.grc.nasa.gov/www/k-12/airplane/wteq.html) holds the atmosphere to the Earth's surface. Within the atmosphere, very complex chemical, [thermodynamic](https://www.grc.nasa.gov/www/k-12/airplane/thermo.html), and [fluid dynamics](https://www.grc.nasa.gov/www/k-12/airplane/gasprop.html) effects occur. The atmosphere is not uniform; fluid properties are constantly changing with time and place. We call this change the weather.

Variations in air properties extend upward from the surface of the Earth. The sun [heats](https://www.grc.nasa.gov/www/k-12/airplane/heat.html) the surface of the Earth, and some of this heat goes into warming the air near the surface. The heated air is then [diffused or convected](https://www.grc.nasa.gov/www/k-12/airplane/gasprop.html) up through the atmosphere. Thus the air [temperature](https://www.grc.nasa.gov/www/k-12/airplane/temptr.html) is highest near the surface and decreases as altitude increases. The [speed of sound](https://www.grc.nasa.gov/www/k-12/airplane/sound.html)depends on the temperature and also decreases with increasing altitude. The [pressure](https://www.grc.nasa.gov/www/k-12/airplane/pressure.html) of the air can be related to the weight of the air over a given location. As we increase altitude through the atmosphere, there is some air below us and some air above us. But there is always less air above us than was present at a lower altitude. Therefore, air pressure decreases as we increase altitude. The air [density](https://www.grc.nasa.gov/www/k-12/airplane/fluden.html) depends on both the temperature and the pressure through the [equation of state](https://www.grc.nasa.gov/www/k-12/airplane/eqstat.html) and also decreases with increasing altitude.

Aerodynamic forces directly [depend](https://www.grc.nasa.gov/www/k-12/airplane/presar.html) on the air density. To help aircraft designers, it is useful to define a **standard atmosphere**model of the variation of properties through the atmosphere. There are actually several different models available--a standard or average day, a hot day, a cold day, and a tropical day. The models are updated every few years to include the latest atmospheric data. The model was developed from atmospheric measurements that were averaged and curve fit to produce the given equations. The model assumes that the pressure and temperature change only with altitude. The particular model shown here was developed in the early sixties, and the curve fits are given for Imperial units. Curve fits are also available in [metric units.](https://www.grc.nasa.gov/www/k-12/airplane/atmosmet.html)

The model has three zones with separate curve fits for the troposphere, the lower stratosphere, and the upper stratosphere. The troposphere runs from the surface of the Earth to 36,152 feet. In the troposphere, the temperature decreases linearly and the pressure decreases exponentially. The rate of temperature decrease is called the **lapse rate**. For the temperature **T**and the pressure **p**, the Imperial units curve fits for the troposphere are:

T = 59 - .00356 \* h

p = 2116 \* [(T + 459.7)/ 518.6]^5.256

where the temperature is given in Fahrenheit degrees, the pressure in pounds/square feet, and **h** is the altitude in feet. The lower stratosphere runs from 36,152 feet to 82,345 feet. In the lower stratosphere the temperature is constant and the pressure decreases [exponentially.](https://www.grc.nasa.gov/www/k-12/airplane/function.html) The Imperial units curve fits for the lower stratosphere are:

T = -70

p = 473.1 \* exp(1.73 - .000048 \* h)

The upper stratosphere model is used for altitudes above 82,345 feet. In the upper stratosphere the temperature increases slightly and the pressure decreases exponentially. The Imperial units curve fits for the upper stratosphere are:

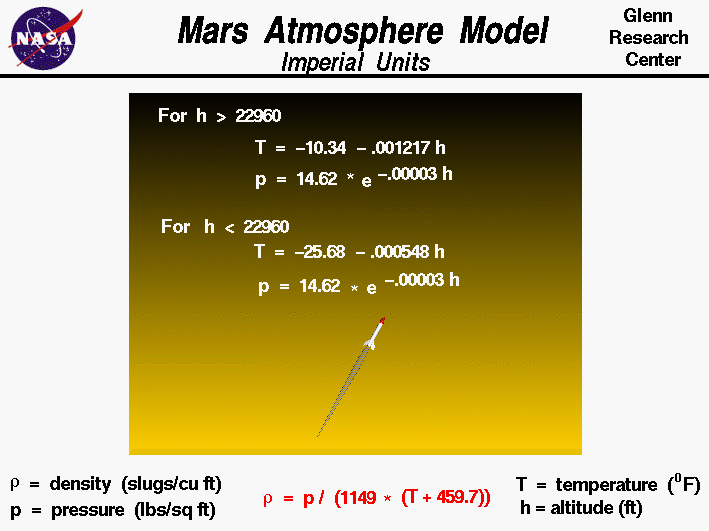
T = -205.05 + .00164 \* h

p = 51.97 \* [(T + 459.7)/ 389.98]^-11.388

In each zone the density **r** is derived from the [equation of state](https://www.grc.nasa.gov/www/k-12/airplane/eqstat.html).

r = p / [1718 \* (T + 459.7)]

This is the atmosphere model used in the [FoilSim](https://www.grc.nasa.gov/www/k-12/airplane/foil3.html)and [EngineSim](https://www.grc.nasa.gov/www/k-12/airplane/ngnsim.html)computer simulators. An [interactive simulation](https://www.grc.nasa.gov/www/k-12/airplane/atmosi.html) for the atmosphere model is also available. With the applet, you can change altitude and see the effects on pressure and temperature.



The Martian atmosphere is an extremely thin sheet of [gas,](https://www.grc.nasa.gov/www/k-12/airplane/gasprop.html) principally carbon dioxide, that extends from the surface of Mars to the edge of space. The Martian atmosphere is less dense than the Earth's [atmosphere,](https://www.grc.nasa.gov/www/k-12/airplane/atmosphere.html)but there are many similarities.[Gravity](https://www.grc.nasa.gov/www/k-12/airplane/wteq.html) holds the atmosphere to the Martian surface. Within the atmosphere, very complex chemical, [thermodynamic](https://www.grc.nasa.gov/www/k-12/airplane/thermo.html), and [fluid dynamics](https://www.grc.nasa.gov/www/k-12/airplane/gasprop.html) effects occur. The atmosphere is not uniform; fluid properties are constantly changing with time and place, producing weather on Mars just like on Earth.

Variations in atmospheric properties extend upward from the surface of Mars. The sun [heats](https://www.grc.nasa.gov/www/k-12/airplane/heat.html) the surface, and some of this heat goes into warming the gas near the surface. The heated gas is then [diffused or convected](https://www.grc.nasa.gov/www/k-12/airplane/gasprop.html) up through the atmosphere. Thus, the gas [temperature](https://www.grc.nasa.gov/www/k-12/airplane/temptr.html) is highest near the surface and decreases as altitude increases. The [speed of sound](https://www.grc.nasa.gov/www/k-12/airplane/sound.html) depends on the temperature and also decreases with increasing altitude. As with the Earth, the [pressure](https://www.grc.nasa.gov/www/k-12/airplane/pressure.html) in the atmosphere decreases with altitude. The [density](https://www.grc.nasa.gov/www/k-12/airplane/fluden.html) of the atmosphere depends on both the temperature and the pressure through the [equation of state](https://www.grc.nasa.gov/www/k-12/airplane/eqstat.html) and also decreases with increasing altitude.

Aerodynamic forces directly [depend](https://www.grc.nasa.gov/www/k-12/airplane/presar.html) on the gas density. To help spacecraft designers, it is useful to define a mathematical model of the atmosphere to capture the effects of altitude. The model shown here was developed from measurements of the Martian atmosphere made by the Mars Global Surveyor in April 1996. The information on the Martian atmosphere was gathered by Jonathon Donadee of Canfield (Ohio) Middle School during a cyber-mentoring program in 1999. The data was curve fit to produce equations by Dave Hiltner of St. John's Jesuit High School as part of a shadowing program in May 1999. The curve fits are given for Imperial units. These curve fits are also available in [metric units.](https://www.grc.nasa.gov/www/k-12/airplane/atmosmrm.html)

The model has two zones with separate curve fits for the lower atmosphere and the upper atmosphere. The lower atmosphere runs from the surface of Mars to 22,960 feet. In the lower atmosphere, the temperature decreases linearly and the pressure decreases exponentially. The rate of temperature decrease is called the **lapse rate**. For the temperature **T** and the pressure **p**, the Imperial units curve fits for the lower atmosphere are:

T = -25.68 - .000548 \* h

p = 14.62 \* exp(-00003 \* h)

where the temperature is given in Fahrenheit degrees, the pressure in pounds/square feet, and **h** is the altitude in feet. The upper stratosphere model is used for altitudes above 22,960 feet. In the upper atmosphere the temperature decreases linearly and the pressure decreases exponentially. The Imperial units curve fits for the upper atmosphere are:

T = -10.34 - .001217 \* h

p = 14.62 \* exp(-00003 \* h)

In each zone the density **r** is derived from the [equation of state](https://www.grc.nasa.gov/www/k-12/airplane/eqstat.html).

r = p / [1149 \* (T + 459.7)]

Comparing this equation with the similar equation of state for the [Earth's atmosphere](https://www.grc.nasa.gov/www/k-12/airplane/atmos.html), you will notice that the gas constants are different, 1149 for Mars and 1718 for Earth. These numbers are different because the Martian atmosphere is almost entirely composed of carbon dioxide, while the Earth's atmosphere is a mixture of 78% nitrogen and 21% oxygen.

This is the atmosphere model used in the [FoilSim](https://www.grc.nasa.gov/www/k-12/airplane/foil3.html) simulator. The model is also available in an [interactive atmosphere simulation](https://www.grc.nasa.gov/www/k-12/airplane/atmosi.html) program. With the applet, you can change altitude and see the effects on pressure and temperature. You can also compare the Martian atmosphere to the atmosphere on Earth.