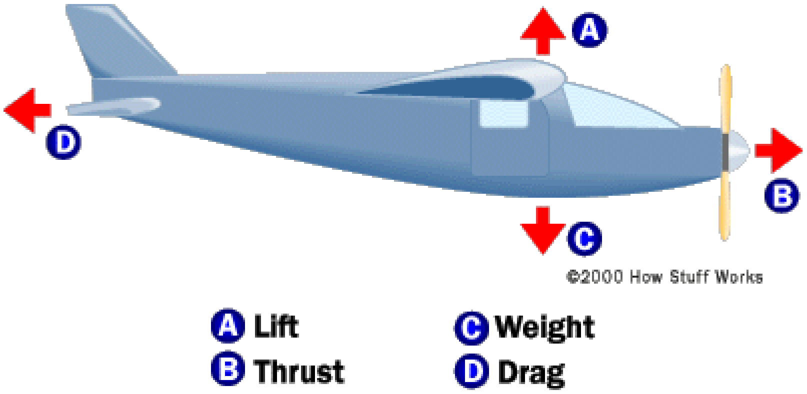
How Airplanes Work

I happen to fly a lot on business. For me, personally, airplanes are one of the most amazing things that I see on a daily basis. When I get on a 747, I am boarding a gigantic vehicle capable of carrying 500 or 600 people. A 747 weighs up to 870,000 pounds at takeoff. Yet it rolls down the runway and, as though by magic, lifts itself into the air and can fly up to 7,000 nautical miles without stopping. It is truly incredible when you think about it!

If you have ever wondered what allows a 747 -- or any airplane for that matter -- to fly, then read on. In this article, we will walk through the theory of flight and talk about the different parts of a standard airplane, and then you can explore tons of links to learn even more.

Aerodynamic Forces

Before we dive into how wings keep airplanes up in the air, it's important that we take a look at four basic aerodynamic forces: lift, weight, thrust and drag.



Straight and Level Flight

In order for an airplane to fly straight and level, the following relationships must be true:

- **Thrust = Drag**
- **Lift = Weight**

If, for any reason, the amount of drag becomes larger than the amount of thrust, the plane will slow down. If the thrust is increased so that it is greater than the drag, the plane will speed up.

Similarly, if the amount of lift drops below the weight of the airplane, the plane will descend. By increasing the lift, the pilot can make the airplane climb.

Thrust

Thrust is an aerodynamic force that must be created by an airplane in order to overcome the drag (notice that thrust and drag act in opposite directions in the figure above). Airplanes create thrust using propellers, jet engines or rockets. In the figure above, the thrust is being created with a propeller, which acts like a very powerful version of a household fan, pulling air past the blades.

Now, let's look at drag.

Drag

Drag is an aerodynamic force that resists the motion of an object moving through a fluid (air and water are both fluids). If you stick your hand out of a car window while moving, you will experience a very simple demonstration of this effect. The amount of drag that your hand creates depends on a few factors, such as the size of your hand, the speed of the car and the density of the air. If you were to slow down, you would notice that the drag on your hand would decrease.

We see another example of drag reduction when we watch downhill skiers in the Olympics. You'll notice that, whenever they get the chance, they will squeeze down into a tight crouch. By making themselves "smaller," they decrease the drag they create, which allows them to move faster down the hill.

If you've ever wondered why, after takeoff, a passenger jet always retracts its landing gear (wheels) into the body of the airplane, the answer (as you may have already guessed) is to reduce drag. Just like the downhill skier, the pilot wants to make the aircraft as small as possible to reduce drag. The amount of drag produced by the landing gear of a jet is so great that, at cruising speeds, the gear would be ripped right off of the plane.

But what about the other two aerodynamic forces, weight and lift?

Weight and Lift

Weight

This one is the easiest. Every object on earth has weight (including air). A 747 can weigh up to 870,000 pounds (that's 435 tons!) and still manage to get off the runway. (See the table below for more 747 specs.)

Lift

Lift is the aerodynamic force that holds an airplane in the air, and is probably the trickiest of the four aerodynamic forces to explain without using a lot of math. On airplanes, most of the lift required to keep the plane aloft is created by the wings (although some is created by other parts of the structure).

A principal concept in aerodynamics is the idea that **air is a fluid**. Let's investigate that concept more closely.

A Few Words About Fluid

As we mentioned, a principal concept in aerodynamics is the idea that **air is a fluid**. Like all gases, air flows and behaves in a similar manner to water and other liquids. Even though air, water and pancake syrup may seem like very different substances, they all conform to the same set of mathematical relationships. In fact, basic aerodynamic tests are sometimes performed underwater.

747-400 Facts

- **Length**: 232 feet (~ 71 meters)
- **Height**: 63 feet (~ 19 meters)
- **Wingspan**: 211 feet (~ 64 meters)
- **Wing area**: 5,650 square feet (~ 525 square meters)
- **Max. takeoff weight**: 870,000 pounds (~ 394,625 kilograms)
- **Max. landing weight**: 630,000 pounds (~ 285,763 kilograms) (explains why planes may need to dump fuel for emergency landings)
- **Engines**: four turbofan engines, 57,000 pounds of thrust each
- **Fuel capacity**: up to 57,000 gallons (~ 215,768 liters)
- **Max. range**: 7,200 nautical miles
- **Cruising speed**: 490 knots
- **Takeoff distance**: 10,500 feet (~ 3,200 meters)

Another important concept is the fact that **lift can exist only in the presence of a moving fluid**. This is also true for drag. It doesn't matter if the object is stationary and the fluid is moving, or if the fluid is still and the object is moving through it. What really matters is the **relative difference in speeds between the object and the fluid**.

Consequently, neither lift nor drag can be created in space (where there is no fluid). This explains why spacecraft don't have wings unless the spaceship spends at least some of its time in air. The space shuttle is a good example of a spacecraft that spends most of its time in space, where there is no air that can be used to create lift. However, when the shuttle re-enters the earth's atmosphere, its stubby wings produce enough lift to allow the shuttle to glide to a graceful landing.

Popular (and Imperfect) Explanations of Lift Creation

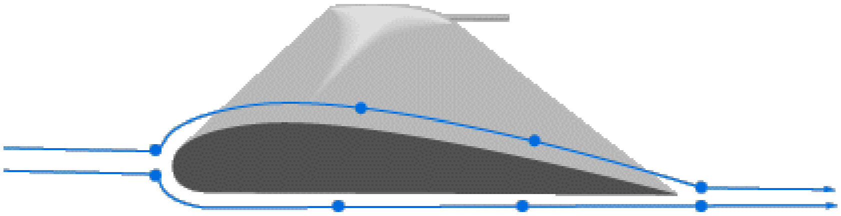
If you read any college-level aerodynamics textbook, you will find plenty of mathematical methods for calculating lift. Unfortunately, none of these explanations are particularly satisfying unless you have a Ph.D. in mathematics.

There are many simplified explanations of lift that appear on the Internet and in some textbooks. Two of the most popular explanations today are the **Longer Path explanation** (also known as the **Bernoulli** or **equal transit time** explanation) and the **Newtonian explanation** (also known as the **momentum transfer** or **air deflection** explanation). While many versions of these explanations are fundamentally flawed, they can still contribute to an intuitive understanding of how lift is created.

The Longer Path Explanation

What is it?

The Longer Path explanation holds that the top surface of a wing is more curved than the bottom surface. Air particles that approach the leading edge of the wing must travel either over or under the wing. Let's assume that two nearby particles split up at the leading edge, and then come back together at the trailing edge of the wing. Since the particle traveling over the top goes a longer distance in the same amount of time, it must be traveling faster.



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Bernoulli's equation, a fundamental of fluid dynamics, states that as the speed of a fluid flow increases, its pressure decreases. The Longer Path explanation deduces that this faster moving air develops a lower pressure on the top surface, while the slower moving air maintains a higher pressure on the bottom surface. This pressure difference essentially "sucks" the wing upward (or pushes the wing upward, depending on your point of view).

Why is it not entirely correct?

There are several flaws in this theory, although this is a very common explanation found in high school textbooks and even encyclopedias:

1. The assumption that the two air particles described above rejoin each other at the trailing edge of the wing is groundless. In fact, these two air particles have no "knowledge" of each other's presence at all, and there is no logical reason why these particles should end up at the rear of the wing at the same moment in time.
2. For many types of wings, the top surface is longer than the bottom. However, many wings are symmetric (shaped identically on the top and bottom surfaces). This explanation also predicts that planes should not be able to fly upside down, although we know that many planes have this ability.

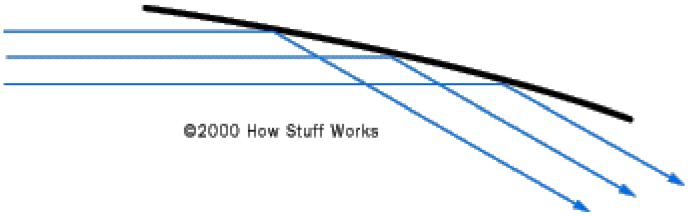
Why is it not entirely wrong?

The Longer Path explanation is correct in more than one way. First, the air on the top surface of the wing actually does move faster than the air on the bottom -- in fact, it is moving faster than the speed required for the top and bottom air particles to reunite, as many people suggest. Second, the overall pressure on the top of a lift-producing wing is lower than that on the bottom of the wing, and it is this net pressure difference that creates the lifting force.

The Newtonian Explanation

What is it?

Isaac Newton stated that for every action there is an equal, and opposite, reaction (Newton's Third Law). You can see a good example of this by watching two skaters at an ice rink. If one pushes on the other, both move -- one due to the action force and the other due to the reaction force.



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In the late 1600s, Isaac Newton theorized that air molecules behave like individual particles, and that the air hitting the bottom surface of a wing behaves like shotgun pellets bouncing off a metal plate. Each individual particle bounces off the bottom surface of the wing and is deflected downward. As the particles strike the bottom surface of the wing, they impart some of their momentum to the wing, thus incrementally nudging the wing upward with every molecular impact.

Note: Actually, Newton's theories on fluids were developed for naval warfare, in order to help decrease the resistance that ships encounter in the water -- the goal was to build a faster boat, not a better airplane. Still, the theories are applicable, since water and air are both fluids.

Why is it not entirely correct?

The Newtonian explanation provides a pretty intuitive picture of how the wing turns the air flowing past it, with a couple of exceptions:

1. The top surface of the wing is left completely out of the picture. The top surface of a wing contributes greatly to turning the fluid flow. When only the bottom surface of the wing is considered, the resulting lift calculations are very inaccurate.
2. Almost a hundred years after Newton's theory of ship hulls, a man named Leonhard Euler noticed that fluid moving toward an object will actually deflect before it even hits the surface, so it doesn't get a chance to bounce off the surface at all. It seemed that air did not behave like individual shotgun pellets after all. Instead, air molecules interact and influence each other in a way that is difficult to predict using simplified methods. This influence also extends far beyond the air immediately surrounding the wing.

Why is it not entirely wrong?

While a pure Newtonian explanation does not produce accurate estimates of lift values in normal flight conditions (for example, a passenger jet's flight), it predicts lift for certain flight regimes very well. For hypersonic flight conditions (speeds exceeding five times the speed of sound), the Newtonian theory holds true. At high speeds and very low air densities, air molecules behave much more like the pellets that Newton spoke of. The space shuttle operates under these conditions during its re-entry phase.

Unlike the Longer Path explanation, the Newtonian approach predicts that the air is deflected downward as it passes the wing. While this may not be due to molecules bouncing off the bottom of the wing, the air is certainly deflected downward, resulting in a phenomenon called **downwash**. (See NASA: Glenn Research Center for more on downwash.)

Likewise, predicting the amount of lift created by wings has been an equally challenging task for engineers and designers in the past. In fact, for years, we have relied heavily on experimental data collected 70 to 80 years ago to aid in our initial designs of wings.

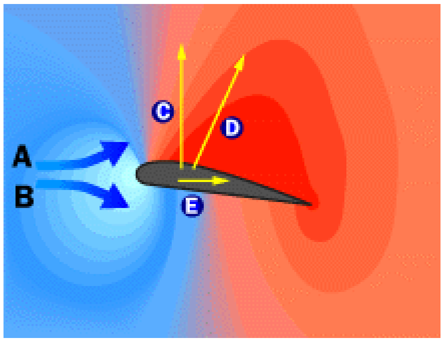
Consider This

It is important to realize that, unlike in the two popular explanations described earlier, lift depends on significant contributions from both the top and bottom wing surfaces. While neither of these explanations is perfect, they both hold some nuggets of validity. Other explanations hold that the unequal pressure distributions cause the flow deflection, and still others state that the exact opposite is true. In either case, it is clear that this is not a subject that can be explained easily using simplified theories.

How Lift is Created

Pressure Variations Caused By Turning a Moving Fluid

Lift is a force on a wing (or any other solid object) immersed in a moving fluid, and it acts perpendicular to the flow of the fluid. (Drag is the same thing, but acts parallel to the direction of the fluid flow). The net force is created by pressure differences brought about by variations in speed of the air at all points around the wing. These velocity variations are caused by the disruption and turning of the air flowing past the wing. The measured pressure distribution on a typical wing looks like the following diagram:



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A. Air approaching the top surface of the wing is compressed into the air above it as it moves upward. Then, as the top surface curves downward and away from the airstream, a low-pressure area is developed and the air above is pulled downward toward the back of the wing.

B. Air approaching the bottom surface of the wing is slowed, compressed and redirected in a downward path. As the air nears the rear of the wing, its speed and pressure gradually match that of the air coming over the top. The overall pressure effects encountered on the bottom of the wing are generally less pronounced than those on the top of the wing.

C. Lift component

D. Net force

E. Drag component

When you sum up all the pressures acting on the wing (all the way around), you end up with a net force on the wing. A portion of this lift goes into lifting the wing (**lift component**), and the rest goes into slowing the wing down (**drag component**). As the amount of airflow turned by a given wing is increased, the speed and pressure differences between the top and bottom surfaces become more pronounced, and this increases the lift. There are many ways to increase the lift of a wing, such as increasing the angle of attack or increasing the speed of the airflow. These methods and others are discussed in more detail later in this article.

Calculating Lift Based on Experimental Test Results

In 1915, the U.S. Congress created the National Advisory Committee on Aeronautics (NACA -- a precursor of NASA). During the 1920s and 1930s, NACA conducted extensive wind tunnel tests on hundreds of **airfoil** shapes (wing cross-sectional shapes). The data collected allows engineers to predictably calculate the amount of lift and drag that airfoils can develop in various flight conditions.

The **lift coefficient** of an airfoil is a number that relates its lift-producing capability to air speed, air density, wing area and **angle of attack** -- the angle at which the airfoil is oriented with respect to the oncoming air flow (we'll discuss this in greater detail later in the article). The lift coefficient of a given airfoil depends upon the angle of attack.

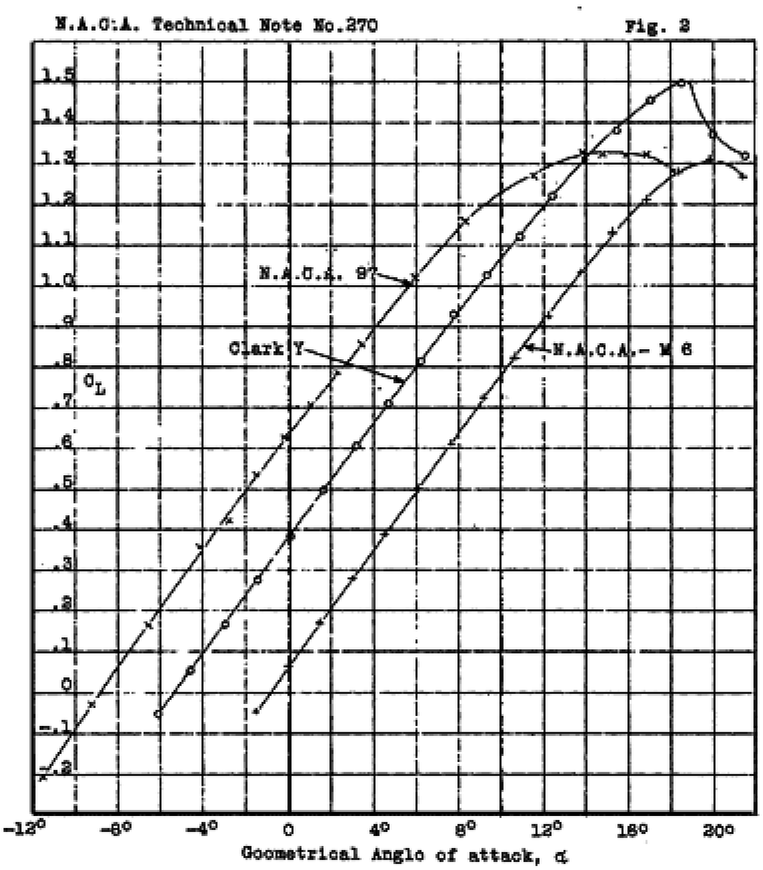


Image courtesy NASA

The lift-curve slope of a NACA airfoil

Here is the standard equation for calculating lift using a lift coefficient:

$$L = C_l \times \frac{1}{2} \times \rho \times V^2 \times A$$

L = lift
Cl = lift coefficient
(rho) = air density
V = air velocity
A = wing area

As an example, let's calculate the lift of an airplane with a wingspan of 40 feet and a chord length of 4 feet (wing area = 160 sq. ft.), moving at a speed of 100 mph (161 kph) at sea level (that's 147 feet, or 45 meters, per second!). Let's assume that the wing has a constant cross-section using an NACA 1408 airfoil shape, and that the plane is flying so that the angle of attack of the wing is 4 degrees.

We know that:

- **A** = 160 square feet
- **(rho)** = 0.0023769 slugs / cubic foot (at sea level on a standard day)
- **V** = 147 feet per second
- **Cl** = 0.55 (lift coefficient for NACA 1408 airfoil at 4 degrees AOA)

So let's calculate the lift:

- **Lift** = 0.55 x .5 x .0023769 x 147 x 147 x 160
- **Lift = 2,260 lbs**

Try your hand at airfoil design on NASA's Web site using a virtual wind tunnel.

Calculating Lift Using Computer Simulations

In the years since NACA's experimental data was collected, engineers have used this information to calculate the lift (and other aerodynamic forces) produced by wings and other objects in fluid flows. In recent years, however, computing power has increased such that wind tunnel experiments can now be simulated on an average personal computer.

Software packages, such as FLUENT, have been developed to create simulated fluid flows in which solid objects can be virtually immersed. The applications of this type of software range from simulating the air flowing over a wing, to mapping the airflow through a computer case to ensure that there is enough cool air passing over the CPU to prevent the computer from overheating.

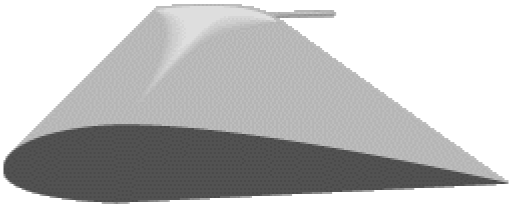
Interesting Things about Wings

There are several interesting facts about wings that are useful in developing a more detailed understanding of how they work. Wing shape, the angle of attack, flaps, slats, rotating surfaces and blown surfaces are all important elements to consider.

Let's start with wing shape.

Wing Shape

The "standard" airfoil shape that we examined above is not the only shape for a wing. For example, both stunt planes (the kind that fly upside down for extended periods of time at air shows) and supersonic aircraft have wing profiles that are somewhat different than you would expect:



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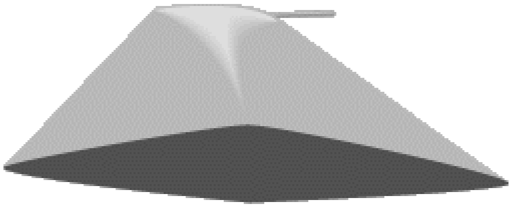

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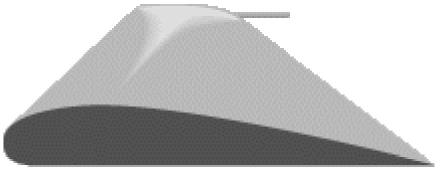
The upper airfoil is typical for a stunt plane, and the lower airfoil is typical for supersonic fighters. Note that both are **symmetric** on the top and bottom. Stunt planes and supersonic jets get their lift totally from the angle of attack of the wing.

Angle of Attack

The angle of attack is the angle that the wing presents to oncoming air, and it controls the thickness of the slice of air the wing is cutting off. Because it controls the slice, the angle of attack also controls the amount of lift that the wing generates (although it is not the only factor).



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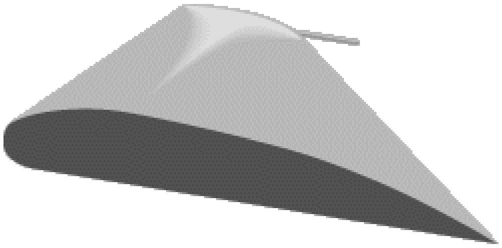
Zero angle of attack



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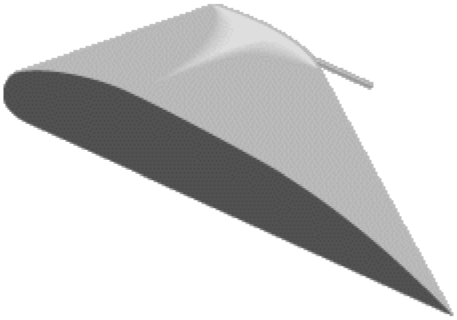
Shallow angle of attack



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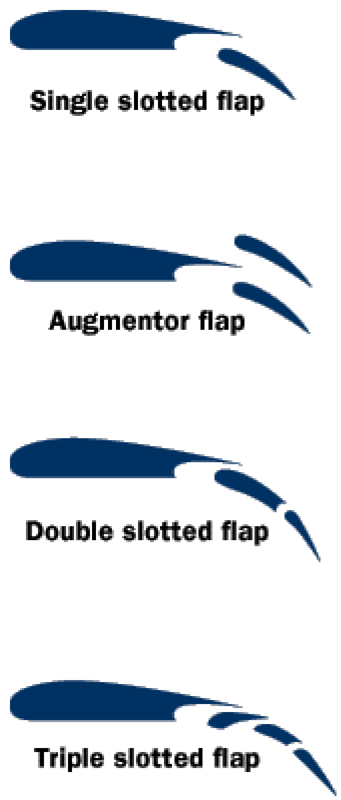
Steep angle of attack

Flaps

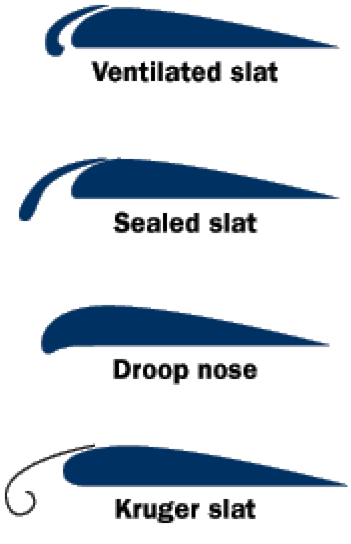
In general, the wings on most planes are designed to provide an appropriate amount of lift (along with minimal drag) while the plane is operating in its cruising mode (about 560 miles per hour, or 901 km per hour, for the Boeing 747-400). However, when these airplanes are taking off or landing, their speeds can be reduced to less than 200 miles per hour (322 kph). This dramatic change in the wing's working conditions means that a different airfoil shape would probably better serve the aircraft.

To accommodate both flight regimes (fast and high as well as slow and low), airplane wings have moveable sections called **flaps**. During takeoff and landing, the flaps are extended rearward and downward from the trailing edge of the wings. This effectively alters the shape of the wing, allowing the wing to turn more air, and thus create more lift. The downside of this alteration is that the drag on the wings also increases, so the flaps are put away for the rest of the flight.



Slats

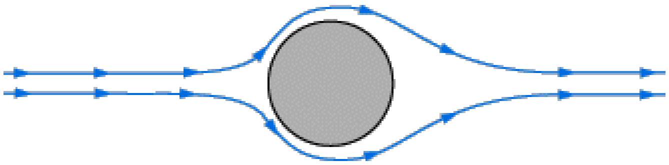
Slats perform the same function as flaps (that is, they temporarily alter the shape of the wing to increase lift), but they are attached to the front of the wing instead of the rear. They are also deployed on takeoff and landing.

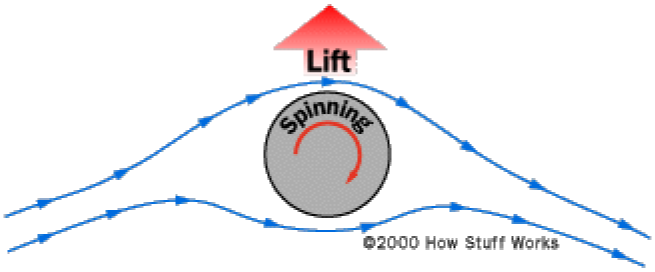


Rotating Surfaces

Given what we know so far about wings and lift, it seems logical that a simple cylinder would not produce any lift when immersed in a moving fluid (imagine a plane with wings shaped like cardboard paper-towel tubes). In a simplified world, the air would just flow around the cylinder evenly on both sides, and keep right on going. In reality, the downstream air would be a little turbulent and chaotic, but there still would be no lift created.

However, if we were to begin rotating the cylinder, as in the figure below, the surface of the cylinder would actually drag the surrounding layer of air around with it. The net result would be a pressure difference between the top and bottom surfaces, which deflects the airflow downward. Newton's Third Law states that if the air is being redirected downward, the cylinder must be deflected upward (sounds like lift to me!). This is an example of the **Magnus Effect** (also known as the **Robbins Effect**), which holds true for rotating spheres as well as cylinders (see any similarities to curveballs here?)





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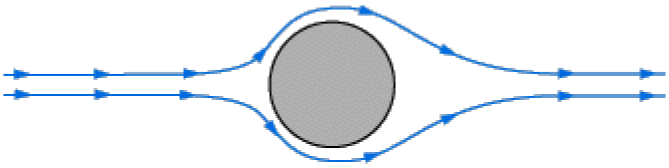
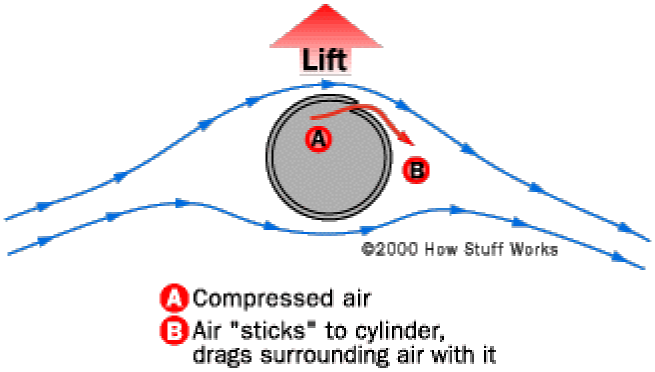
Lift created by a spinning cylinder

Believe it or not, in 1926, Anton Flettner built a ship named the Bruckau that used huge spinning cylinders instead of sails to power itself across the ocean. Click here to learn about Flettner's Rotorship.

Blown Surfaces

Let's take our cylindrical wing from the above examples and find another way to create lift with it. If you've ever held the back of your hand vertically under the faucet, you may have noticed that the water did not simply run down to the bottom of your hand and then drip off. Instead, the water actually runs back up and around the side of your hand (for a few millimeters) before falling into the sink. This is known as the **Coanda Effect** (after Henri Coanda), which states that **a fluid will tend to follow the contour of a curved surface that it contacts**.





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In our cylinder example, if air is forced out of a long slot just behind the top of the cylinder, it will wrap around the backside and pull some surrounding air with it. This is a very similar situation to the Magnus Effect, except that the cylinder doesn't have to spin.

The Coanda Effect is used in specialized applications to increase the amount of additional lift provided by the flaps. Instead of just altering the shape of the wing, compressed air can be forced through long slots on the top of the wing or the flaps to produce extra lift.

Believe it or not, in 1990, McDonnell Douglas Helicopter Co. (now known as MD Helicopters, Inc.) removed the tail rotors from some of its helicopters and replaced them with cylinders! Instead of using a conventional tail rotor to steer the aircraft, the tail boom is pressurized and air is blown out through long slots exactly like the figure above.

More Airplane Parts

The wing is obviously the most important part of an airplane -- it's what gets the airplane in the air. But airplanes have a lot of other characteristic parts designed to control the plane or get it moving. Let's examine the parts you find in a typical airplane by looking at a **Cessna 152**.

The **landing gear** is essential during take-off and landing.

Front landing gear

Rear landing gear

The Cessna 152 has fixed landing gear, but most planes have retractable landing gear to reduce drag while in flight.

Now, let's check out the propeller.

The Propeller

Probably the most important parts of an airplane, after the wing, are the **propeller** and **engine**. The propeller (or, on jet aircraft, the jets) provides the **thrust** that moves the plane forward. (Check out How Gas Turbine Engines Work to learn about jet engines.)

A propeller is really just a special, spinning wing. If you looked at the cross section of a propeller, you'd find that a propeller has an airfoil shape and an angle of attack. Just by looking at the propeller pictured above, you can see that the angle of attack changes along the length of the propeller -- the angle is greater toward the center because the speed of the propeller through the air is slower close to the hub. Many larger propeller aircraft have more elaborate three-blade or four-blade props with **adjustable pitch** mechanisms. These mechanisms let the pilot adjust the propeller's angle of attack depending on air speed and altitude.

Horizontal and Vertical Stabilizers

The tail of the airplane has two small wings, called the horizontal and vertical **stabilizers**, that the pilot uses to control the direction of the plane. Both are symmetrical airfoils, and both have large flaps on them that the pilot controls with the control stick to change their lift characteristics.

Horizontal tail wing

Vertical tail wing

With the **horizontal tail wing**, the pilot can change the plane's angle of attack, and therefore control whether the plane goes up or down. With the **vertical tail wing**, the pilot can turn the plane left or right.

Controlling the Direction

The Main Wing and Flaps

The plane's main wing is 40 feet (~ 12 m) long from end to end, and about 4 feet (~ 1.2 m) wide. On the inner portion of the wing, there are flaps used during takeoff, landing and other low-speed situations. On the outer ends, there are **ailerons** used to turn the plane and keep it level.

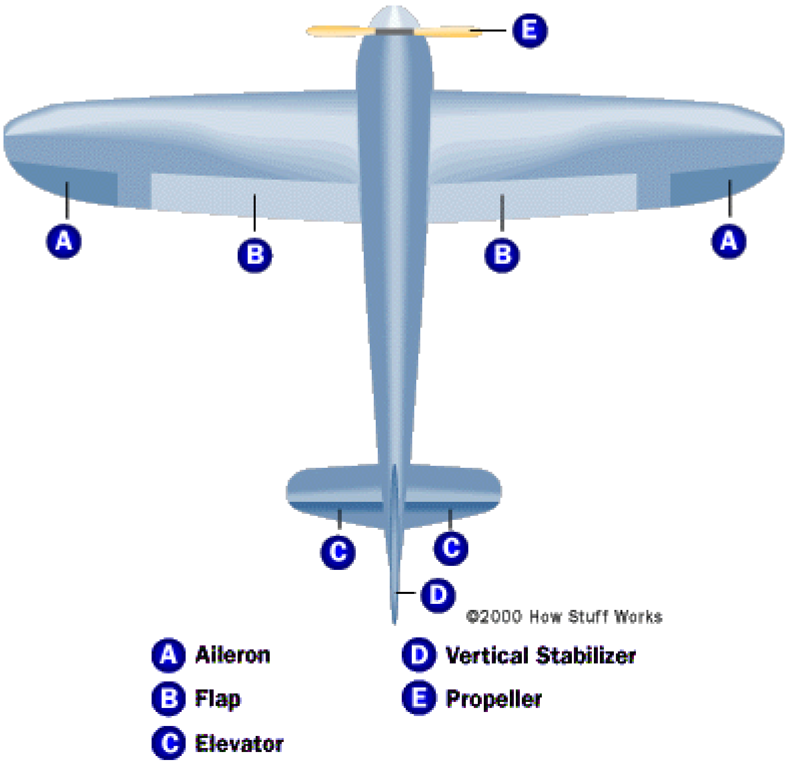
Main wing

Flaps

The flaps are actuated by electric motors in the wing. Also enclosed in the wings are two fuel tanks, each of which holds about 20 gallons of gas.

Airplane Sensors

From this description you can see that a plane has four different moveable control surfaces, as shown here:



The plane also has two different sensors mounted on the wing:

The L-shaped tube is called a **pitot tube**. Air that rams into this tube during flight creates pressure, and that pressure moves the needle on the air-speed indicator in the cockpit. The small opening on the right is a whistle that sounds as the wing nears a stall. The larger opening visible near the cockpit is used for ventilation.

For more information on airplanes, flight dynamics and other related topics, check out the links on the next page.

Lots More Information

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