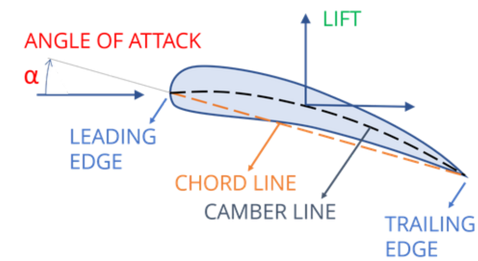
Principles of Flight (Basic Aerodynamics)

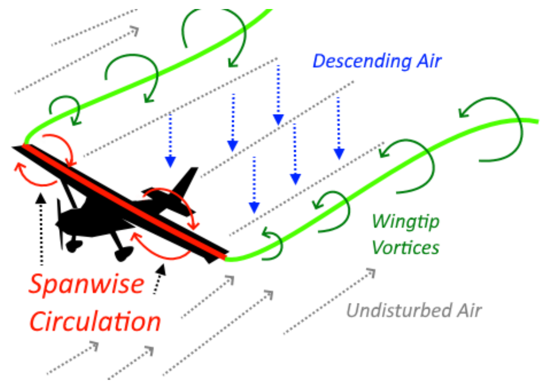
Objective

To ensure the applicant learns the purpose of and can exhibit a clear understanding of basic aerodynamics and the various factors which affect airplane stability and controllability.

Purpose

A basic understanding of aerodynamics and airplane stability and controllability is essential for every pilot. When flying, pilots need to understand the four forces acting on an airplane, why a wing stalls, why right rudder is needed in a climb, and how the center of gravity affects controllability and maneuverability. This lesson in basic aerodynamics will introduce pilots to the four forces, airfoils, lift, stalls, left-turning tendencies, load factors, stability and many other important concepts that are fundamental to other aspects of flying.





Schedule

- **Ground Lesson**: 1 hour
- **Student Q&A**: 15 minutes

Equipment

- Whiteboard / Markers (optional)
- Model Airplane (optional)
- Wind Tunnel App on Tablet (optional)

Student Actions

- Ask any questions, receive study material for the next lesson.
- Watch linked video.
- Review listed references.

Instructor Actions

- Deliver the ground lesson (below).
- Answer student questions.

Completion Standards

- Student can explain:
    - The Four Forces
    - Angle of attack, and how airfoils produce lift
    - Why wings stall
    - The left-turning tendencies
    - Stability and the impact of Center of Gravity
    - Load Factor
    - Wake Turbulence and Wake Turbulence Avoidance

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Editable versions available at binnsflightservices.com/cfibinder

References

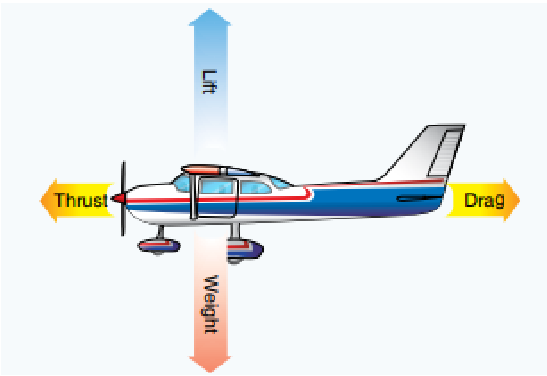
- Federal Aviation Administration - "How Airplanes Fly - 16mm Training Film (1968)"
  - YouTube - https://www.youtube.com/watch?v=CgIDjLhPhcE
- FAA-H-8083-25C (Pilot's Handbook of Aeronautical Knowledge) - Chapter 5, Page 3-5 [Lift], Chapter 5, Page 5 [Lift/Drag Ratio], Chapter 5, Page 6-8 [Drag], Chapter 5, Page 8-10 [Wingtip Vortices], Chapter 5, Page 14-15 [Static and Dynamic Stability], Chapter 5, Page 15-17 [Longitudinal Stability], Chapter 5, Page 17-19 [Lateral Stability], Chapter 5, Page 19-20 [Directional Stability], Chapter 5, Page 25-26 [Stalls], Chapter 5, Page 30-33 [Left Turning Tendencies]
- FAA-S-ACS-25 (CFI ACS) - Area II Task D

Ground Lesson Outline

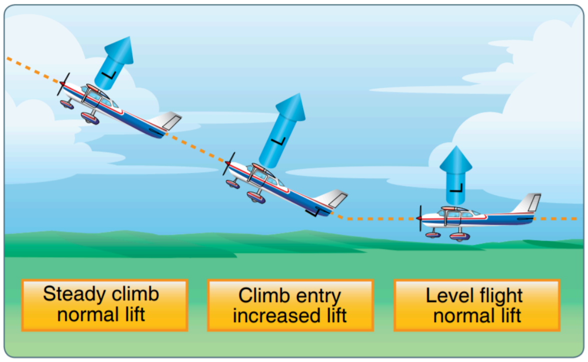
- The Four Forces
  - Weight, Lift, Thrust, Drag
  - How Airplanes Climb
- Airfoils
  - Even a Barn Door Can Fly
    - Creating lift creates drag
    - Any moving object creates drag - Parasite drag: Form drag, interference drag, skin friction drag
  - Airfoil Design Features
    - Leading Edge, Trailing Edge
    - Chord, Camber, Thickness, Span / Aspect Ratio
  - Angle of Attack
    - Only thing that creates lift
- How Airfoils Produce Lift
  - Air is a Fluid
    - Has mass, therefore momentum
    - Has pressure, can transfer momentum to nearby air/objects
  - Basic Facts about Lift Production
    - Angle of Attack, Pressure Differential, Circulation
  - Other Facts
    - Bernoulli's Principle, Equal Transit Time Fallacy, Action at a Distance, Airfoils Can Be Any Shape, Creating Lift Creates Wingtip Vortices
- Stalls
  - Critical angle of attack
  - Flaps affect camber, delay stall
- Static and Dynamic Stability
- Maneuverability and Controllability
- Longitudinal Stability
  - Center of Lift, Center of Mass, Natural Tendency for stall recovery
- Lateral Stability (Roll)
- Directional Stability
- Left Turning Tendencies
  - Torque reaction, Spiraling Slipstream, 'P-Factor', Gyroscopic Precession
- Bank Angle and Load Factor
  - Normal, Utility Category, Limit Load Factor, Ultimate Load Factor
  - Vne
  - Vg Diagram, Flight Envelope
- Wake Turbulence
  - Caused by wingtip vortices, Sinks, expands, moves with wind, Starts, stops with production of lift
  - Avoidance strategies
- Further Reading - Lift and Airfoils (expanded)

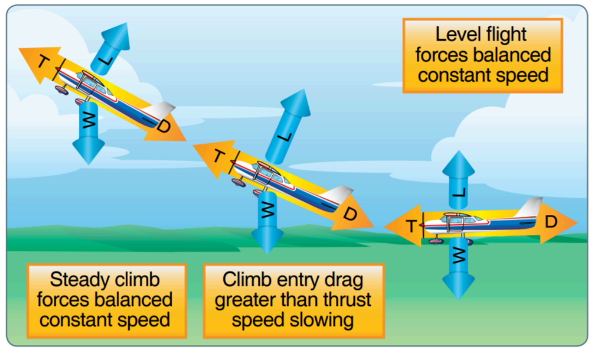
Ground Lesson Content

- **The Four Forces** - Airplanes in straight and level flight are subject to 4 basic forces:
  - **Weight** - *Weight* is the downward force provided by gravity. As an airplane sits stationary on the ground, the only force acting on it is gravity.
  - **Lift** - *Lift* is the upward force provided by the wing. As air flows over and around the wing, it is redirected downward, providing an upward force which during flight balances the downward force of gravity.
  - **Thrust** - *Thrust* is the forward force provided by the engine. Airplanes must move forward to generate lift, and this movement is provided by engine thrust.
  - **Drag** - *Drag* is the rearward force of air resistance, which opposes thrust. Most pilots are already familiar with air resistance… holding a hand out of the window of a moving car is a simple demonstration of drag.



- **How Airplanes Climb** - Aircraft do not necessarily need to have an engine. Gliders are quite popular and work perfectly well without an engine, demonstrating that airplanes can fly for extended periods of time without any engine power at all. However, without an engine, it is very difficult or impossible to *climb*. While gliders can manage this by using the energy of rising air, **conventional powered airplanes are considerably less efficient and can only sustain a climb by using engine power**.
  - **Climbs Require Power** - It is a common misconception that simply 'pulling back' on the flight controls is all that is needed for an airplane to climb. While that will produce a brief climb, **climbs almost always require an increase in engine power as compared to level flight.**
  - Put another way, airplanes can only sustain a climb when the power available is greater than the power required to maintain level flight. If there is more power available (if the throttle can be increased), the airplane can climb.
  - **Forces in Climbs** - During *unaccelerated flight*, such as during straight and level flight, the four forces acting on an airplane are in equilibrium. (If the forces were not equal, the airplane would experience an acceleration in some direction-- up, down, forward, back)
  - **When an airplane initiates a climb, it pitches up, and directs its thrust in a slightly upward direction.** This initially causes an acceleration (upwards), and the airplane begins to ascend. Once the airplane stabilizes in the climb, it is now *moving* upwards (climbing), but it is no longer *accelerating* upwards (it has a stable vertical rate of climb). It has again returned to the forces being in equilibrium.

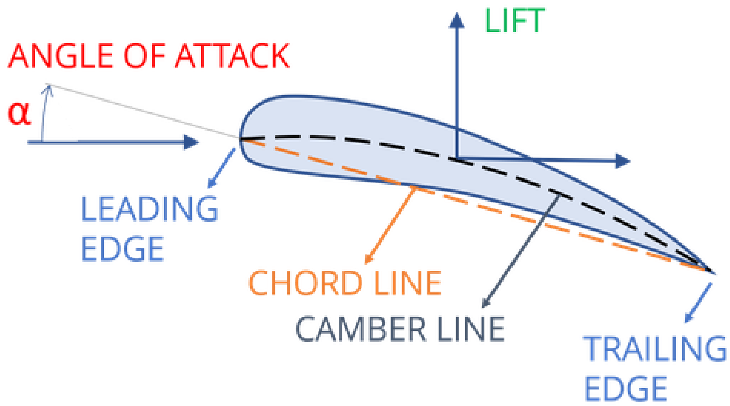




- **Climb Speeds -** Because airplanes climb due to excess power, it is important to realize that the amount of excess power an airplane has is also dependent on the airspeed. Airplane manufacturers calculate the speeds that produce the best rates of climb, and so typically pilots aim to maintain a particular airspeed in a climb. **Generally, the steeper the climb, the lower the airspeed. However, there is a speed below which the climb rate actually slows.** (*See the lesson on Slow Flight*)

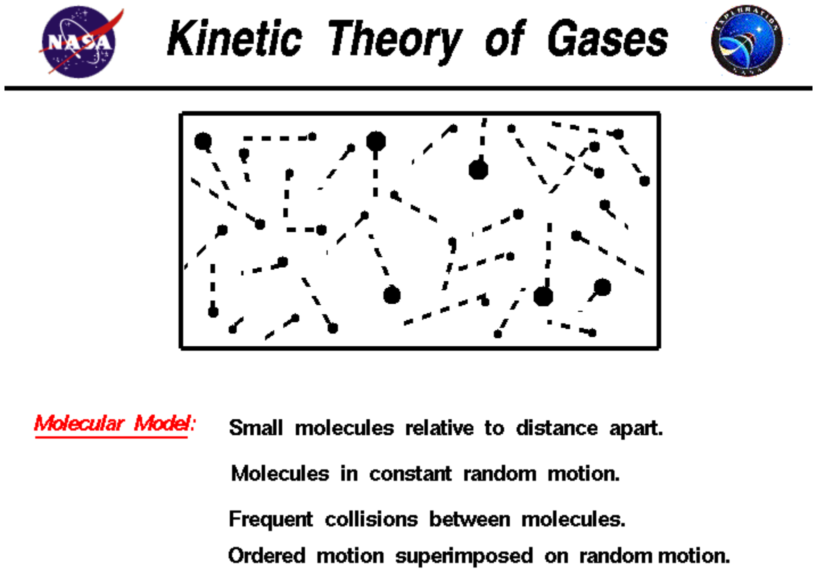
- **Airfoils** - Airfoils are another name for *wings*, but generally refer to any aerodynamic surface which is meant to produce *lift*. Airfoils have a number of design characteristics which contribute to their ability to produce lift, and make them more ideal for lift production than other less-optimized shapes.
  - **Even a Barn Door Can Fly** - Although airfoils are *good* at producing lift, nearly any flat or mostly flat surface when exposed to moving air (the *relative wind*) will produce some lift. The thing that airfoils excel at is that **they can produce relatively large amounts of lift with limited drag**.
    - **Creating Lift Creates Drag** - Lift always acts perpendicular to the chord line, which means that some of the lift points backwards, opposing the airfoil's overall motion. There is no way to create lift without creating drag. This drag is called *induced drag*.
    - **Any Moving Object Creates Drag** - All objects which move through the air create drag, even those that create no lift. The drag that is created unrelated to the production of lift is called *parasite drag*, and is always present. Parasite drag varies with the square of the speed of the object. There are three types of parasite drag:
      - *Form Drag* - Drag created by the shape of the object.
      - *Interference Drag* - Drag created when the disturbed air from two different features interacts with one another, creating more drag.
      - *Skin Friction Drag* - Drag created by friction between the air and the surface of the object.

- ○ **Airfoil Design Features -** Airfoils all generally share the same characteristics, and use those characteristics to varying degrees to achieve their design goals.

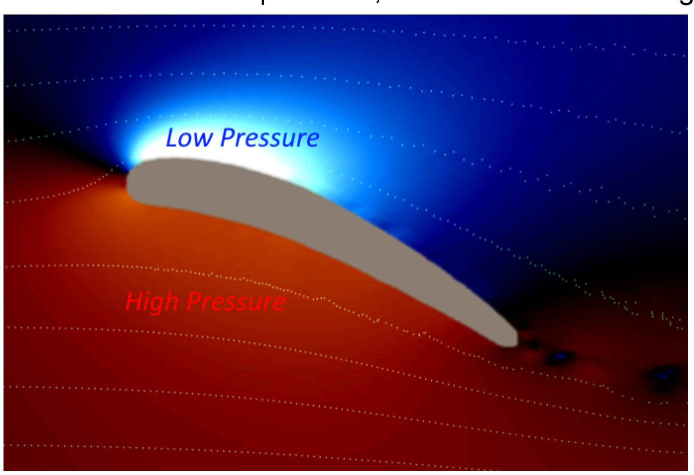


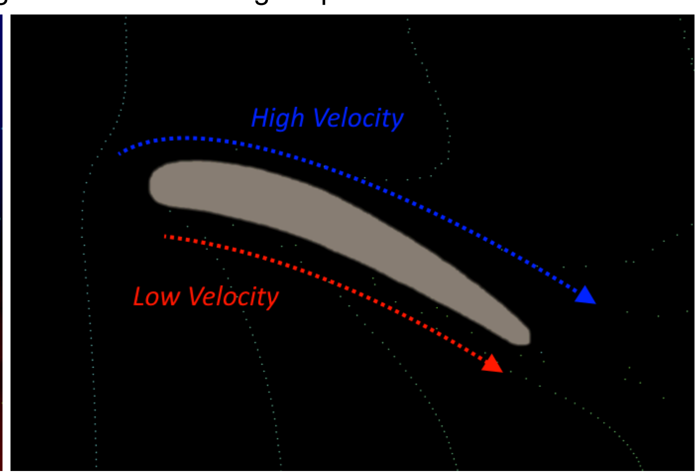
  - ■ **Leading Edge -** Most airfoils have a rounded leading edge which the oncoming air can move smoothly around.
  - ■ **Trailing Edge -** Most airfoils have a very pointed, sharp trailing edge, behind which the two air streams (above and below the wing) can rejoin smoothly.
  - ■ **Chord -** The imaginary line that connects from the leading edge of the wing to the trailing edge, and is usually discussed in terms of *chord length*. Generally, a longer chord length produces more lift.
  - ■ **Camber -** The curvature of the airfoil. Generally, the upper surface of an airfoil is more curved than the lower surface, **however this is not required**. Airfoils with more camber generally stall at higher angles of attack.
  - ■ **Thickness -** The thickness of the airfoil itself. Thick wings have different flight characteristics than thin wings.
  - ■ **Span -** The length of the wings. Longer wingspans produce more lift. The most important value is usually the *aspect ratio*, which is the ratio of the span to the chord.
- ○ **Angle of Attack -** One property all airfoils share is that **they only produce lift when flying at a non-zero angle of attack**. The *angle of attack* is the angle between the chord line and the relative wind. Generally, the greater the angle of attack, the more lift (and drag) is produced, up to a point.

- **How Airfoils Produce Lift -** There are many misconceptions, myths, and incomplete explanations about how airfoils produce lift. The real underlying mechanisms are complicated and generally require an advanced understanding of physics.
  - ○ **Air is a Fluid -** In order to understand how airfoils create lift, it is crucial to understand that *air is a fluid*. Like any other fluid, it has some properties:
    - ■ **Mass -** Air has mass, and therefore **when it is in motion it has *momentum***. Like all moving objects, because of Newton's laws, it will not change direction without being acted on by another force.
    - ■ **Pressure -** Air has *pressure*, which is a fancy way of saying, individual molecules collide against each other constantly, and so **air molecules can transfer momentum to their neighbors or other surroundings**.

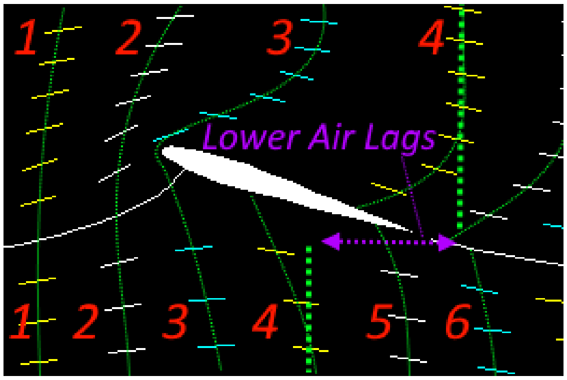


- **Basic Facts About Lift Production** - There are some basic facts about airfoils that can be stated which avoid the incorrect explanations:
  - **Airfoils produce lift by flying at an angle of attack.**
  - **Airfoils produce lift by creating a pressure differential.**
  - **Airfoils produce lift by creating a circulation which redirects air downward, transferring momentum to the air.**
- The above facts are not "a little of A, a little of B, a little of C". These are all part of the same underlying physical mechanism. **One is not more true than the others**.
- A few other basic facts are worth mentioning:
  - **Bernoulli's Principle** - Airfoils *temporarily* accelerate air above them and decelerate air below them. *Bernoulli's Principle* states that air which is moving faster will have lower pressure, and air which is moving slower will have higher pressure.

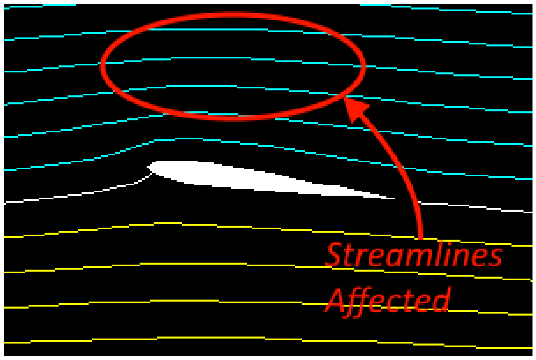


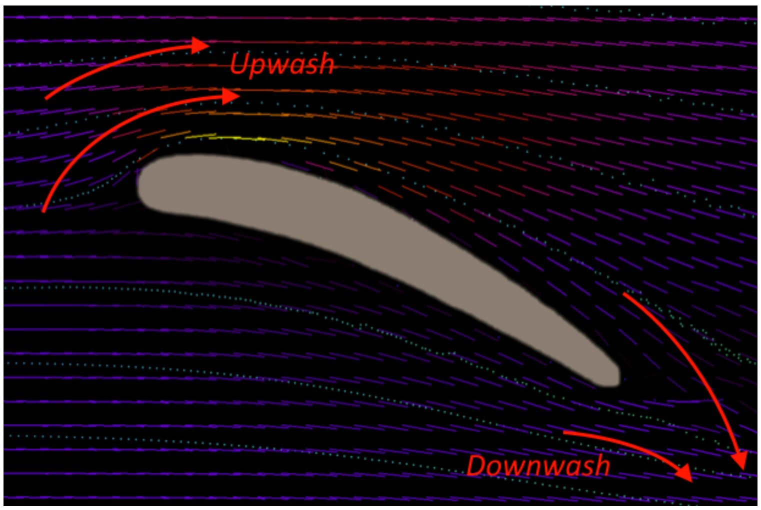


  - **Equal Transit Time Fallacy** - There is a common myth regarding lift that the air over the upper surface of an airfoil (the *upper air parcel*) must meet the air traveling underneath the airfoil (the *lower air parcel*) at the same time at the trailing edge. **This is false. In fact, this is only true of airfoils flying at 0 angle of attack, which are producing no lift!** All lift-producing surfaces actually accelerate the upper air such that it arrives at the trailing edge *well before* the lower air. In reality, the momentum has been transferred to the airfoil, meaning that the upper and lower air parcels will never meet again! (*The lower air parcel will never catch up to the upper air parcel*)

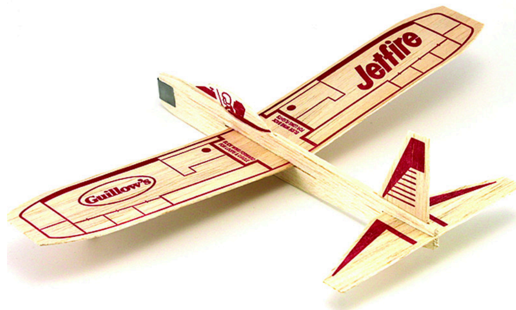


- **Action at a Distance** - Wings affect air that is not even directly in contact with them, generally **up to one wingspan away**. The circulation created by an airfoil creates significant *upwash* in front of the airfoil and significant *downwash* behind the airfoil.

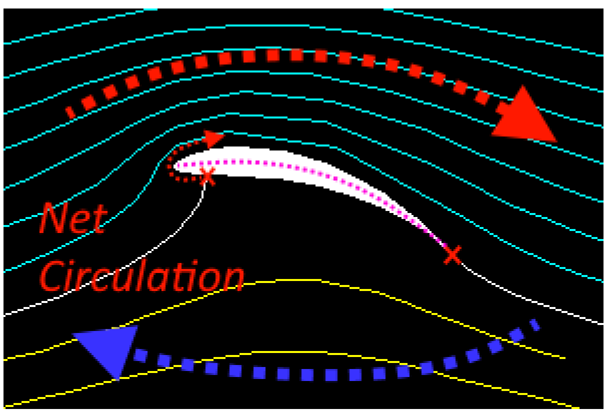


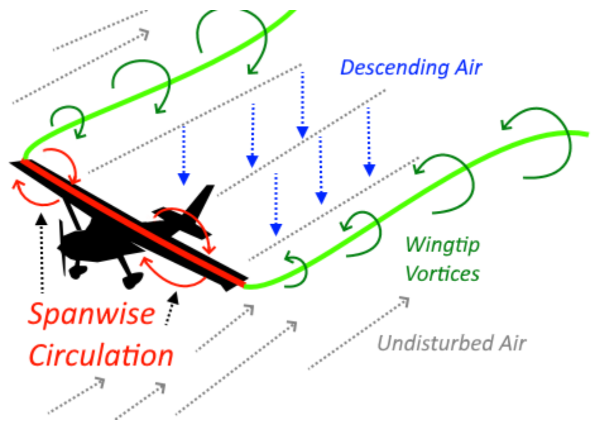


- **Airfoils Can Be Any Shape** - As stated before, even a barn door or flat plate will create lift (at the expense of a significant amount of drag). Consider a balsa wood airplane glides fairly well for having wings which are basically flat plates.

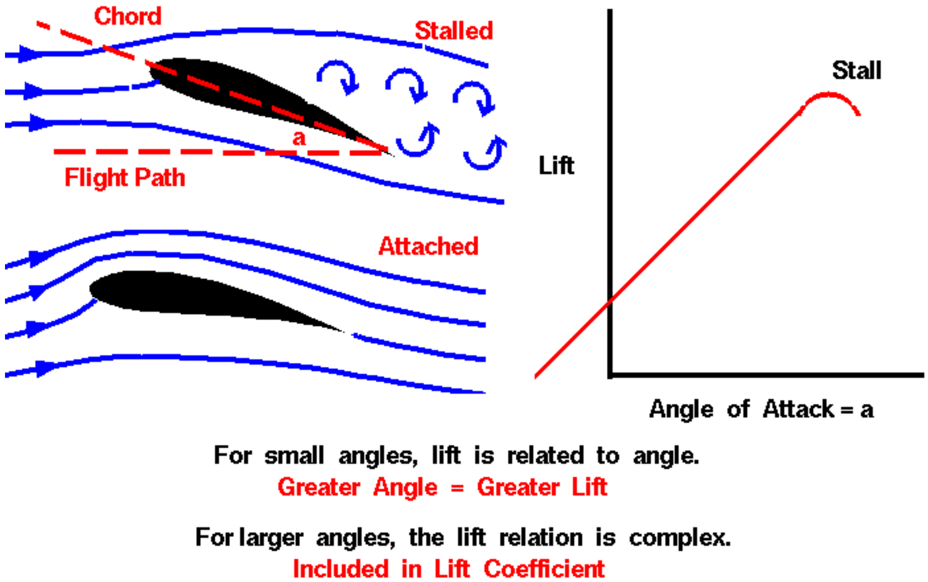


- **Producing Lift Creates Wingtip Vortices** - When airfoils create lift by inducing circulation, there is a *vortex* (area of spiral movement) that rotates around the airfoil, along the span (around the airfoil as seen from the side, also called *spanwise* circulation). Because airfoils cannot have an infinite span, eventually the vortex meets the edge of the wing, and spills over into the undisturbed air around the airfoil. The overall motion of the air in the wake of the airfoil is downwards, relative to the surrounding air. **This causes a pair of vortexes to trail behind the airfoil, from the tips.** These vortexes rotate opposite to each other, and generally move slowly outwards and downwards.

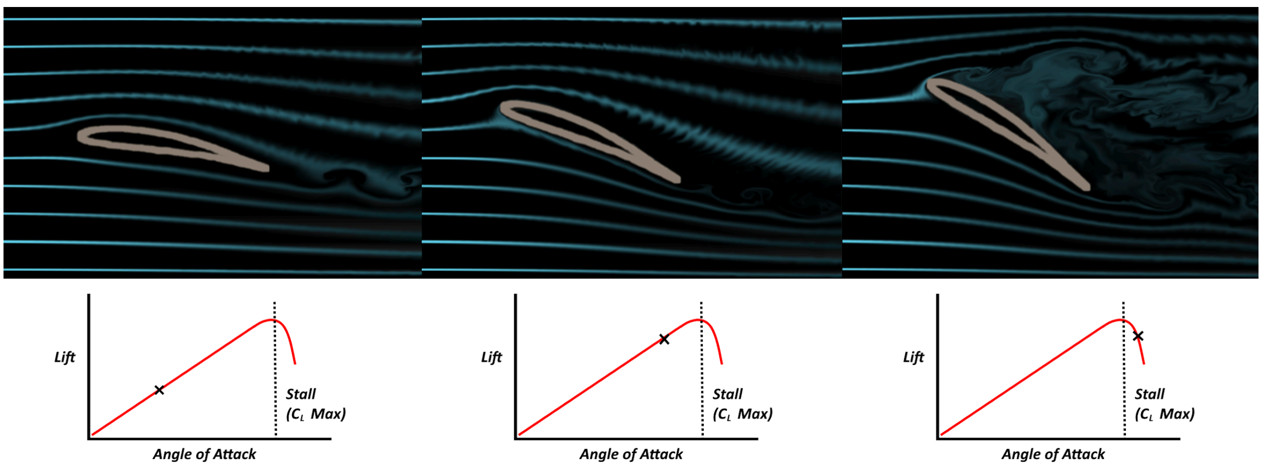




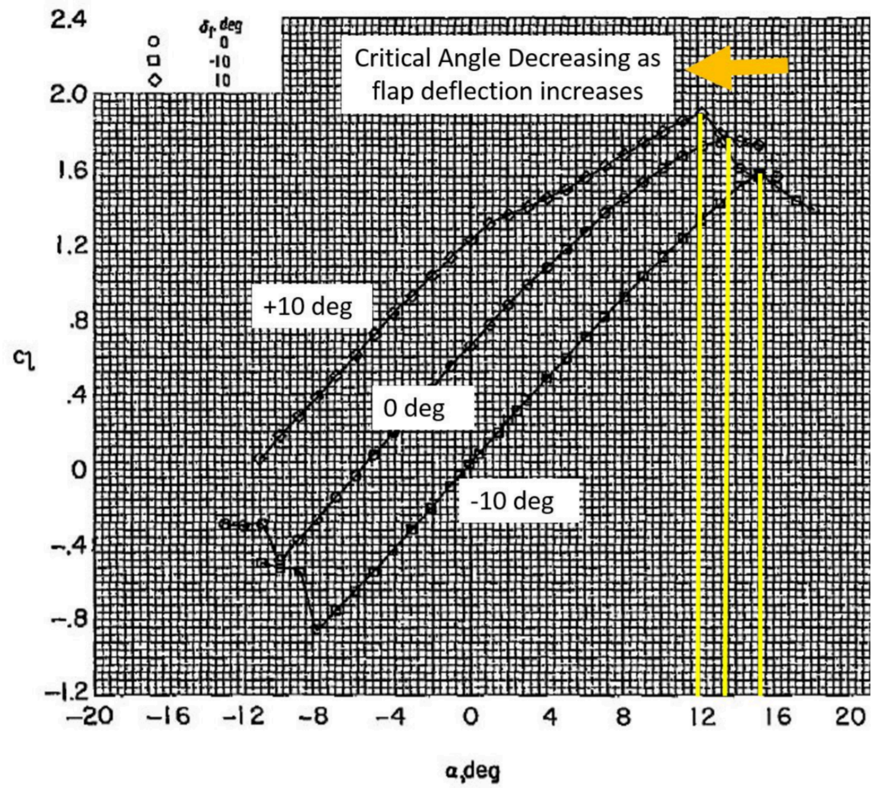
- **Stalls** - An aerodynamic *stall* is what happens when a wing 'stops flying'. Recall that wings only produce lift when they are flying at an angle of attack. As the angle of attack increases, wings produce increasing amounts of lift. As the wing moves at a low angle of attack, the air moving over its upward surface moves as a smooth flow, which is *attached* (tends to follow the contours of the wing). Airflow at low angles of attack generates relatively little drag. As the angle of attack increases, the flow becomes more turbulent, and at some point, the air flowing over the wing's upper surface cannot remain attached, and becomes very turbulent. At this point, the lift produced by the wing drops dramatically, with a corresponding dramatic increase in drag. The angle at which the lift is at maximum, before decreasing rapidly, is called the *critical angle of attack*. Once a wing exceeds the critical angle of attack, it is said to be *stalled*. (It 'stops flying') **An important property of wings is that they always stall at the same critical angle of attack, regardless of airspeed!**



- Below is an airfoil in the normal (low angle of attack), high lift (high angle of attack), and stalled condition, along with the corresponding angle of attack vs lift graph:

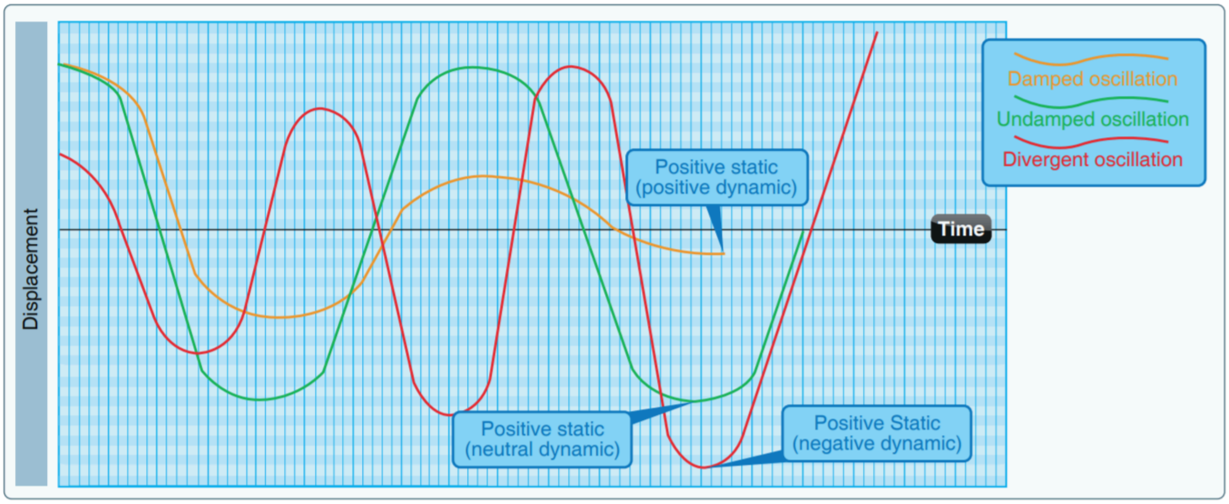


- Although a given wing always stalls at the same angle of attack, most airplanes have wings that can actually change their design to some extent. The addition of *flaps* changes the aerodynamics of a wing by lengthening the chord line and changing the overall curvature of the wing (called *camber*). In most cases, flaps add more lift, but significantly more drag. Because of the increased camber, flaps allow airplanes to produce more lift for a given angle of attack. However, **flaps generally *decrease* the critical angle of attack at which the wing stalls.**



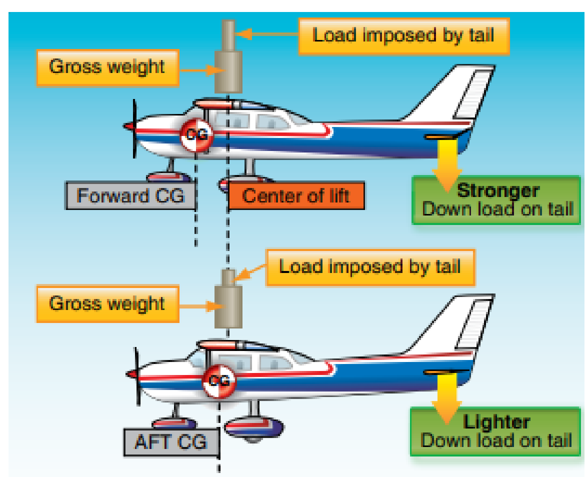
- A wing which is stalled is now producing very little lift relative to the drag it is producing. It has 'stopped flying'. **The only way to recover from the stall and to get the wing flying again is to reduce the angle of attack!**

- **Static and Dynamic Stability** - An airplane's flight characteristics can be described in terms of *static stability* and *dynamic stability*.
  - **Static stability** refers to the tendency of an airplane to return to its original flight attitude when it is disturbed. An airplane that has *positive static stability* tends to return to its original attitude. An airplane which has *neutral static stability* tends to stay in the new attitude, and an airplane with *negative static stability* tends to move further away from the original attitude.
  - **Dynamic stability** refers to the tendency of an airplane, *over time*, to oscillate. Nearly all airplanes undergo *oscillations*, where the airplane may gently change attitude in a repeated, cyclical fashion. If these oscillations tend to become greater over time (called a *divergent* oscillation), the airplane is said to have *negative dynamic stability*. If the oscillations become lesser over time (called a *damped* oscillation), the airplane has *positive dynamic stability*.

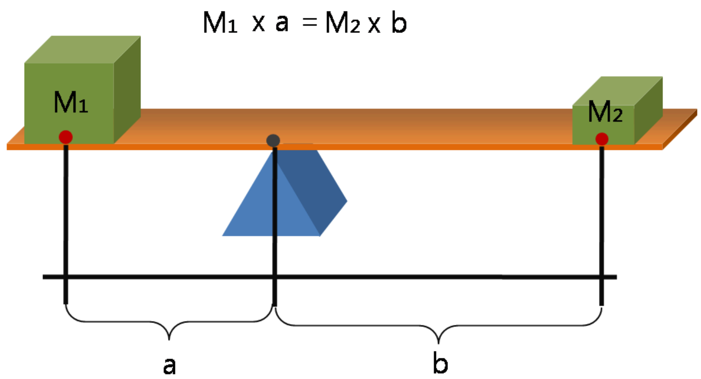


- **Maneuverability and Controllability** - Airplanes have two properties which are primarily affected by stability: *maneuverability* and *controllability*.
  - **Maneuverability** is the ability for the airplane to easily perform the maneuvers commanded by the pilot, and to withstand the stresses of the maneuvers. **Airplanes which are more stable tend to be less maneuverable**. (They may require more effort to maneuver and respond more slowly)
  - Controllability is the ability of an airplane to remain under control and respond correctly to pilot inputs. **Airplanes which have positive stability tend to be highly controllable**, and airplanes with negative stability may be uncontrollable in many situations. Divergent oscillations may lead to rapid loss of control.

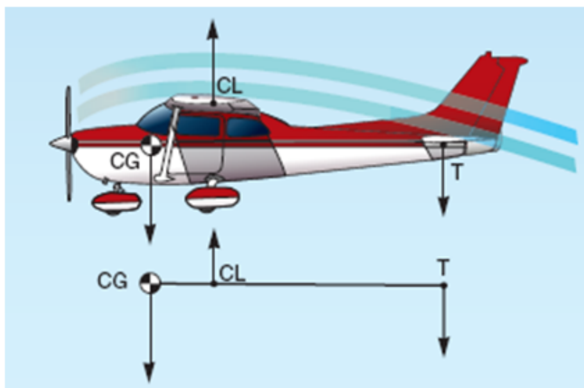
- **Longitudinal Stability and Stall Recovery** - *Longitudinal stability* refers to an airplane's **stability in pitch**. Most airplanes are stable in pitch, and have a gentle up-down pitch oscillation over time. The most important factor in longitudinal stability is the location of the center of gravity relative to the center of lift.
  - **Center of Gravity and Center of Lift** - When conventionally designed airplanes fly, the center of gravity is always *in front of* the center of lift. You can think of the center of lift as a sort of pivot point in a seesaw. Because the horizontal stabilizer is far behind the center of lift, it produces *downward* force (essentially lift, but downward) to keep the nose of the airplane level. This downward force opposes the upward force of the main wing, requiring it to produce slightly more lift to compensate. Also, because any airfoil that produces lift also produces drag, the amount of drag caused by the horizontal stabilizer depends on the force it must produce.



- When the center of gravity is further forward, the horizontal stabilizer must produce more downward force to raise the nose, which adds to the loads placed on the Center of Lift pivot point (the main wing).

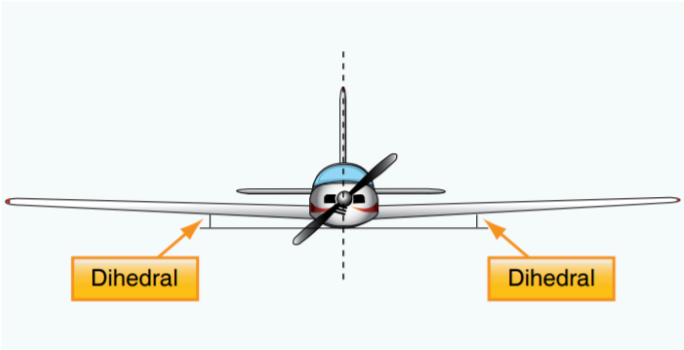


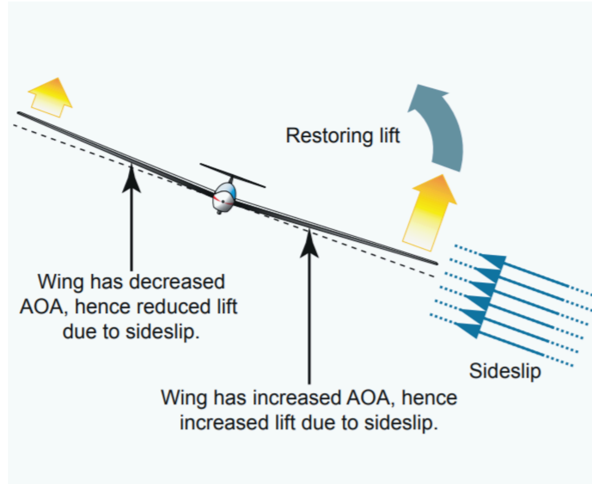
- Airplanes are designed so that they have a natural tendency to recover from a stall. **A well-designed airplane's Center of Gravity is always forward of the Center of Lift.**



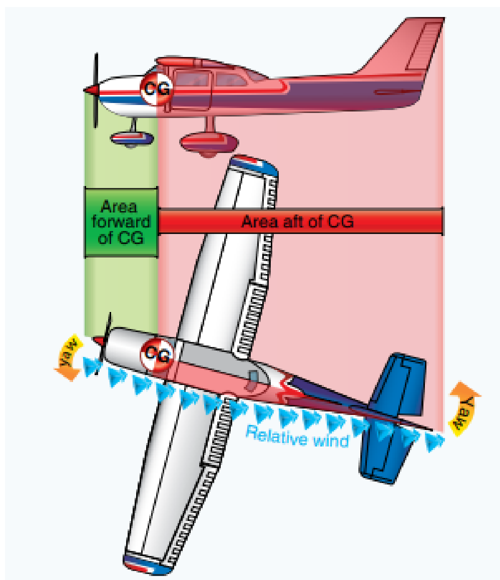
- This design causes a natural tendency for the airplane to nose down, reducing the angle of attack. To counteract this, the horizontal stabilizer and elevator surfaces of an airplane are designed to produce a *downward* force, which 'holds up' the heavier nose area by pivoting the airplane around the Center of Lift. **When an airplane stalls, if the elevator pressure is relaxed, the Center of Gravity will fall naturally.**
- As the Center of Gravity moves closer to the Center of Lift, the natural nose-down stall-recovery tendency is weakened, and it requires less downward force by the tail to move the nose up or down. **In this configuration, relatively small movements of the elevator can cause large, rapid changes in pitch.** When an airplane Center of Gravity is too close to the Center of Lift, or even behind it, a very dangerous situation exists where there is no natural tendency to recover from a stall. **In fact, if the Center of Gravity is too far rearward (aft), the airplane may be uncontrollable in pitch and a stall may be unrecoverable!** This situation is called *longitudinal instability*.

- **Lateral Stability -** *Lateral stability* is stability in roll. Most airplanes have fairly good lateral stability because they are designed with *dihedral*, which means the wings are inclined slightly with respect to each other. During turns, as the airplane begins to sideslip, the lower wing will experience a slightly higher angle of attack, which will tend to roll it back towards straight and level flight.

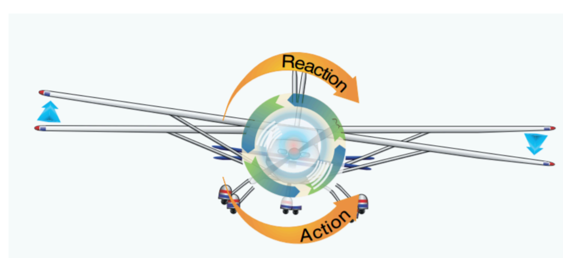




- **Directional Stability** - *Directional stability* is stability in yaw. Airplane yaw is largely controlled by the vertical tail surface, and to a lesser extent, the fuselage itself. Due to the large distance from the center of gravity, the tail surface is very effective at maintaining directional stability. **When the CG moves rearwards, towards the tail, the tail surface is less effective and directional stability is reduced.**

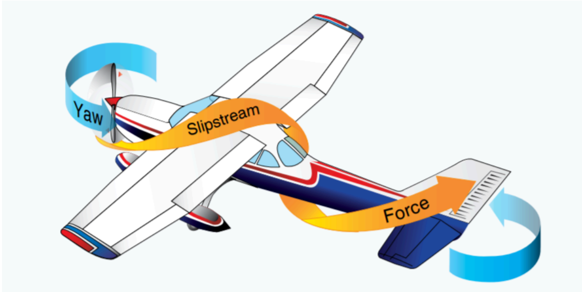


- **Left-Turning Tendencies** - Airplanes with conventional *clockwise rotating propellers* during flight are subject to a few physical phenomenon that result in a natural tendency for the airplane to turn left:
    - **Torque Reaction** - As the engine turns the propeller to move the air, Newton's laws of motion require an equal and opposite reaction. In particular, as the propeller turns clockwise (from the pilot's point of view), **the airplane wants to rotate (bank) opposite the propeller rotation, to the left**. In order to counteract this, airplanes are generally designed so that the left wing makes slightly more lift than the right wing (which also



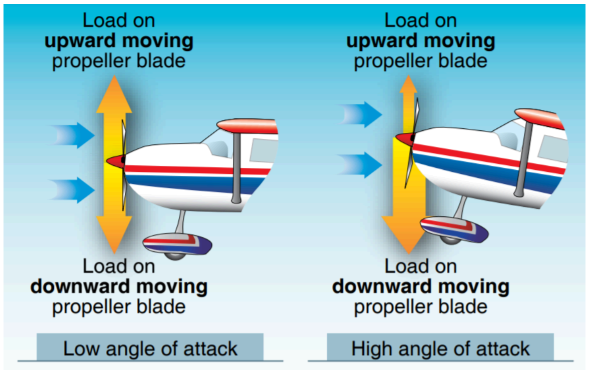
produces slightly more drag), but these design features are tuned for cruising flight. At higher power settings, this will produce a noticeable left-turning tendency.

- **Spiraling Slipstream** - As the airflow moves through the propeller and around the fuselage, wings, and control surfaces, it is spinning. The spinning propeller imparts a considerable spiraling motion to the slipstream, and **because the vertical tail surface extends only above, and not below, the spiraling slipstream pushes the tail slightly right, leading to left yaw.**

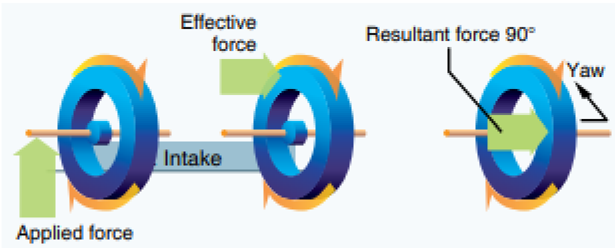


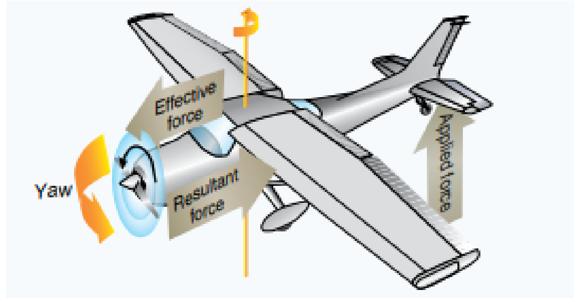
  - *Note:* The spiraling slipstream also induces a *slight right rolling force*, however this is negligible because it is applied very close to the center of gravity. The vertical tail is much further from the center of gravity and so the same force on it produces a much more pronounced effect.

- **P-Factor** - As the airplane bites into the oncoming air, it is important to realize that it is just a rotating wing, and it has an angle of attack just as any other wing. However, because the engine is mounted in a fixed orientation relative to the airplane, when the airplane itself is flying at a high angle of attack, the angle of attack of the descending blade is considerably different (higher) than the ascending blade. **This produces more thrust on the right side of the propeller disc, and pushes the nose to the left.**

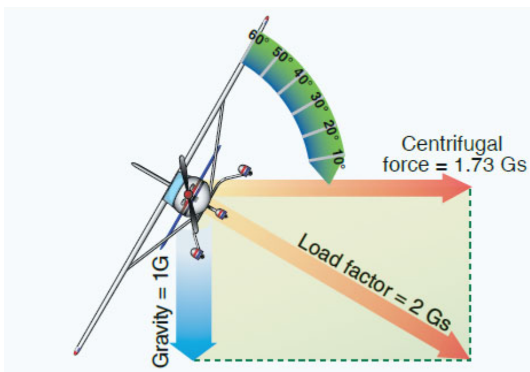


- **Gyroscopic Precession** - An airplane's spinning propeller has a significant amount of mass, and due to this behaves like a gyroscope. Gyroscopes have a rather unusual property, called *gyroscopic precession*, that when a force is applied to them, the force is actually felt as if it were applied *90 degrees ahead in the direction of rotation*. Because conventional airplane propellers spin clockwise (from the pilot's perspective), **a downward pitching motion causes a left yaw, and an upward pitching motion causes a right yaw.**



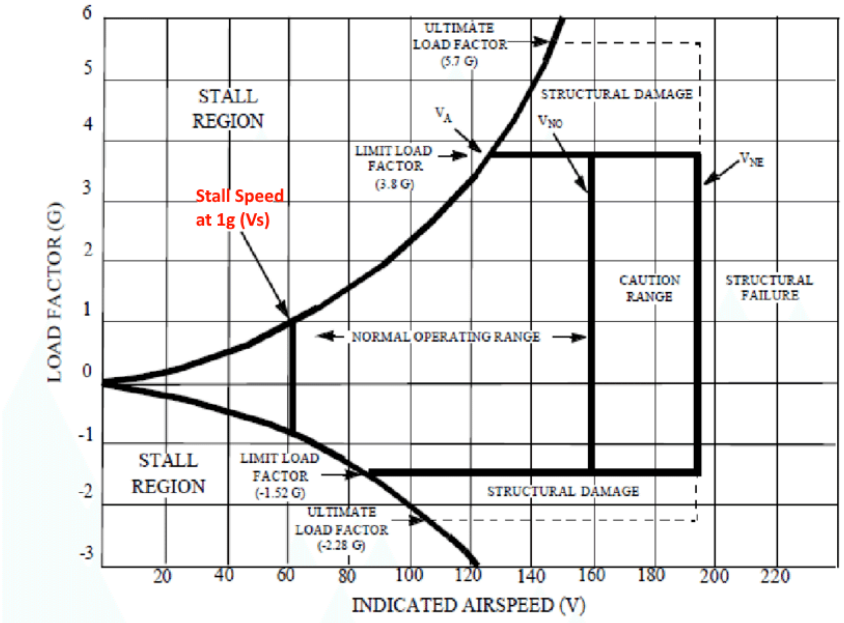


- **Bank Angle and Load Factor -** As an airplane turns, its weight remains the same, and therefore the upward component of lift must remain equal to its weight. During a turn, some of the lift must be directed towards the center of the turn, reducing the upward component of lift. If no pilot corrections were applied, the airplane would not produce any more than the normal 1g of lift, and the airplane would begin to descend. In order to correct for the loss of vertical lift, and maintain a level altitude, the wing must produce more lift, which requires increased *back elevator pressure*. This increased back elevator pressure will cause the wing to fly at a ***higher angle of attack***, producing the increased lift that is required. This can be felt by the pilot as a higher than normal G-force.
  - In order to maintain 1g of vertical lift, while also turning, the wing must produce more than 1g of total lift. The amount of total lift is called the ***load factor***.



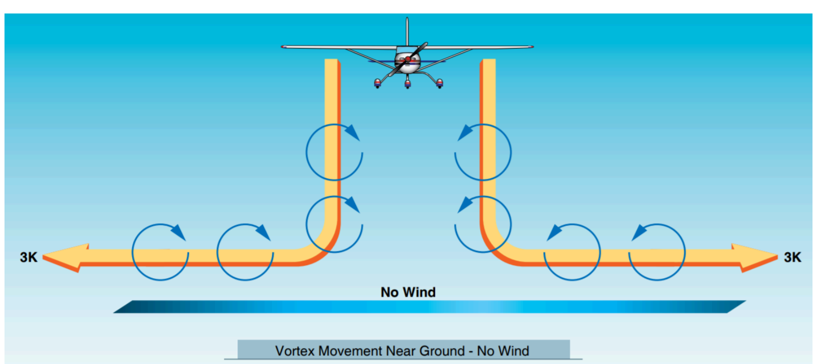
  - To meet the demands of turning flight and normal maneuvering, **airplanes must be designed such that they can withstand load factors of considerably higher than 1g**. In airplane design, there are two *categories*, which dictate the maximum positive and negative load factors that an airplane can withstand, which cover most non-aerobatic airplanes:
    - **Normal Category -** *+3.8 G to -1.52 G*
    - **Utility Category -** *+4.4 G to -1.76 G*
  - These maximum load factors are **called the *limit load factor*, and represent the maximum certified load that the airplane can handle during normal use without causing structural damage**. There is another, higher load factor, called the *ultimate load factor*, which is the load factor at which the airplane can be expected to suffer a structural failure.
  - **Maximum Speed** - Every airplane also has a maximum speed, called the *never exceed speed*, or **Vne** for short above which the airplane may suffer structural damage.
  - **Vg Diagram and the Flight Envelope** - The *Vg diagram* graphically illustrates the relationship between airspeed and load factor, shown below. The Stall Speed we normally see for our aircraft, Vs or Vs_0, applies only to 'unaccelerated' flight--that is, flight at 1g load factor. Observe from the Vg diagram that as the load factor increases, the stall speed also increases. **Note that the wing can stall at any airspeed!** If the load factor is high enough, the wing will either stall,

or suffer structural failure. The normal operating area within the load limits is called the *flight envelope*.

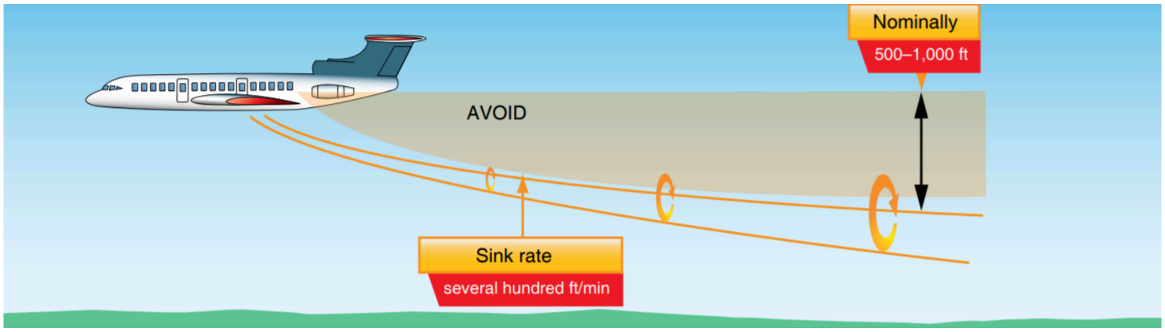


- **Dangers of Wake Turbulence -** As discussed previously, when wings produce lift, they produce wingtip vortices. This is also called *wake turbulence*. The strength of these vortices strongly depends on how much lift is being produced, which means that larger airplanes produce very large wingtip vortices. **A small airplane which encounters these invisible vortexes can roll violently and without warning.**

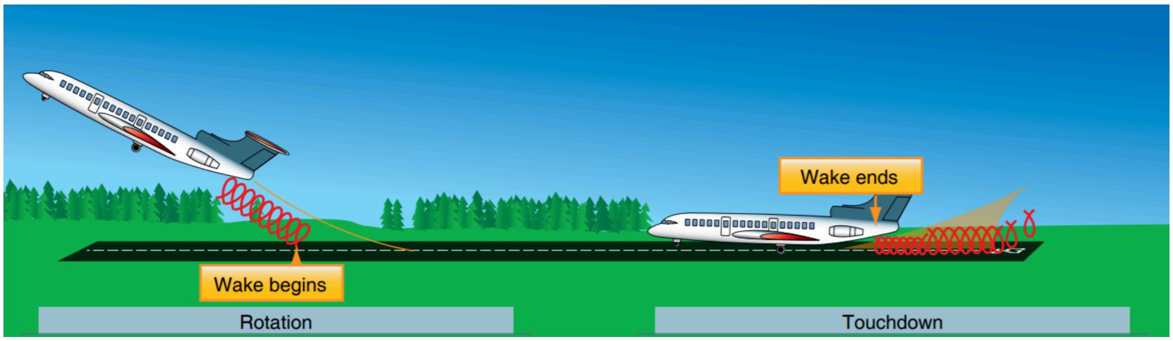
- There are two properties which pilots can use to avoid them, however, the behavior of the vortices is predictable:
  - **Wingtip Vortices Move Slowly Outward -** They move out and away from the wingtips over time.



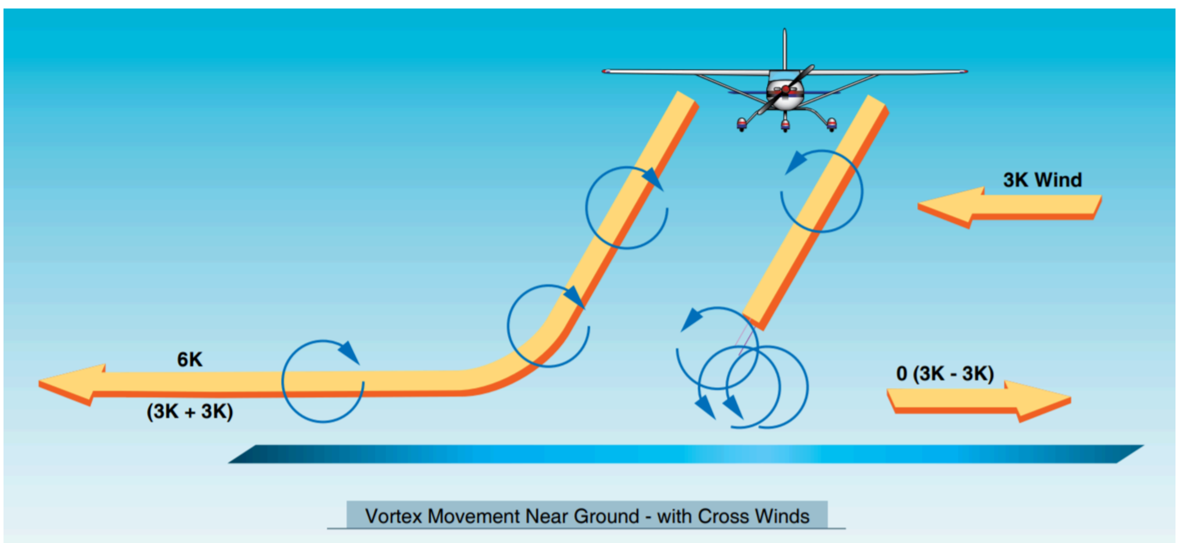
  - **Wingtip Vortices Move Slowly Downward -** They move slowly downward over time, with the overall downward moving air in the wake of an airplane.



- Wingtip Vortices Stop When Lift Stops - Before an airplane rotates on takeoff and after an airplane lands, the wings produce relatively little lift, and therefore very little wake turbulence.

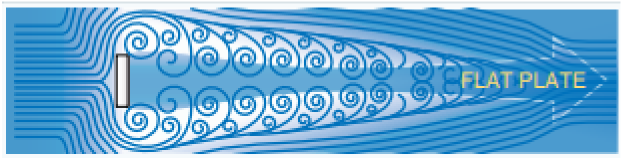


- **Wingtip Vortices Are Affected By Wind** - In a mild crosswind situation, the downwind vortex moves rapidly away from the runway, but the movement of the upwind vortex is slowed, or stalled, and it may linger over the runway.

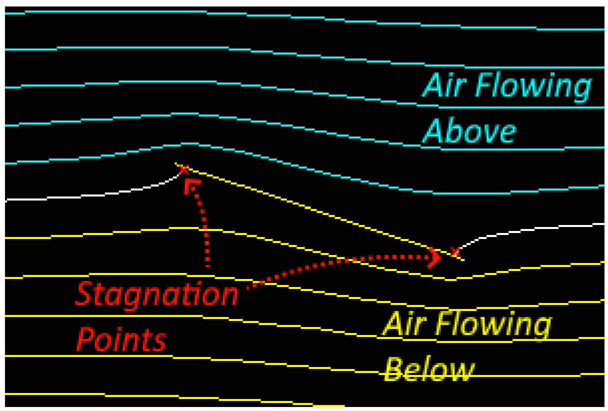


Further Reading - Lift and Airfoils (Expanded)

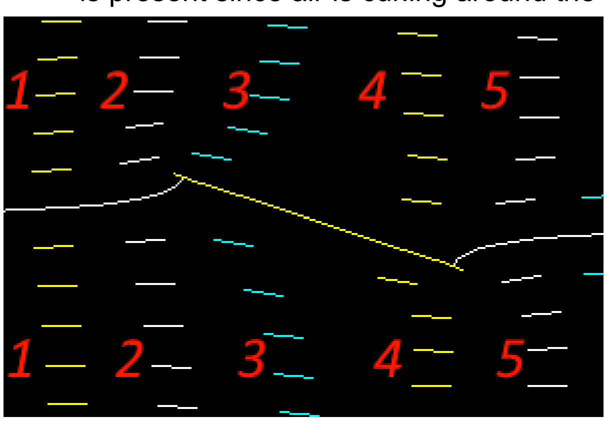
- **Lift Is All About Circulation** - Putting aside conventional airfoil shapes, consider the airflow around a flat plate. A flat plate will produce lift when it flies at an angle of attack because it can create *circulation*.
  - Consider how air would flow around a flat plate which was perpendicular to the air. Air would split and flow around both edges, curling back upon itself, like the following:

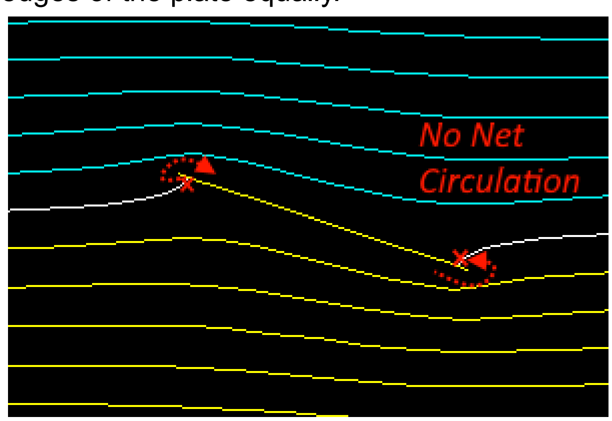


- Obviously a flat plate does not produce any lift, and produces a large amount of drag. Note that there is a point at which all the air above flows around the top of the plate, and all the air below follows around the bottom of the plate. This is called a *stagnation point*, and the air there is completely still, and there is one directly in the middle of the plate. There would also be a stagnation point directly behind the plate, where the air from the top and the bottom reunites.
- Now, consider how air would flow past an *inclined* flat plate. Air will strike the plate, and just as before, spill around the edges. Similar to the perpendicular flat plate, there is a stagnation point near the leading edge, where all the air to one side will flow around the edge of the plate to the top side, and all the air to the other side will flow below and along the plate. There will be another stagnation point near the trailing edge, where air from below will spill around to the back of the plate. This looks like the following:



- If this particular airflow pattern were present, the plate would not create any lift, because there would be no circulation induced in the air. Because air is flowing around both the leading and the trailing edges of the plate, there is no net circulation, and so the air in the wake of the plate is not moved relative to its former position. In the below image, it is possible to see that **the air over the top and bottom of the plate catches up to each other in the wake of the plate**. We can also look at how air flows around the two stagnation points to see that no net circulation is present since air is curling around the edges of the plate equally.

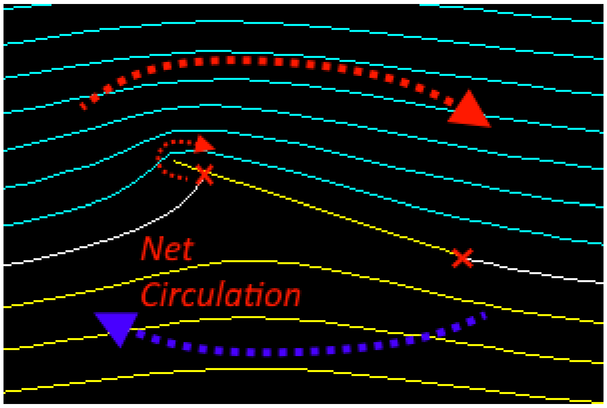




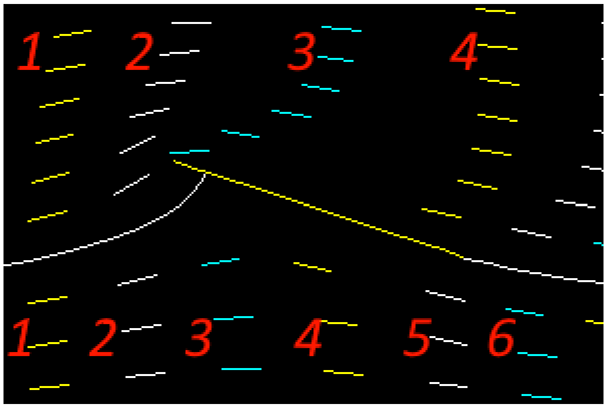
- While this is one possible way air can physically flow around a flat plate, it turns out, however, that **this particular configuration of airflow is unnatural**. Air does not readily tend to turn sharp corners *at the trailing edge of an obstruction*. **Air tends to naturally assume an airflow pattern where the air flows cleanly off the trailing edge**. As the plate moves through the air, the air is unable to turn the corner at the trailing edge rapidly enough, and so the rear stagnation point eventually moves to the trailing edge. This is called the *Kutta Condition*:

- See: https://en.wikipedia.org/wiki/Kutta_condition

- When the Kutta Condition has developed around a flat plate, we can now see that a net circulation has developed, where air is moving more around the upper surface than the lower surface:



- It is also possible to see now that, because of this circulation, the air moving over the upper surface is temporarily accelerated compared to air along the lower surface, as well as redirected slightly downwards. In fact, the air traveling beneath the surface will never catch the air traveling above the surface. **Because of this downward turning and acceleration of the airflow, downward momentum has been permanently transferred to the air.**



- As a general statement, it is perhaps simpler to say, creating lift *requires* creating circulation, and when circulation is present, the airflow above will always be accelerated relative to the airflow below. **If the airflow above is not accelerated relative to the airflow below, no circulation exists and no lift is being produced.**

- Incorrect Theories
  - Equal Transit Time - https://www.grc.nasa.gov/www/k-12/airplane/wrong1.html
  - Skipping Stone/Bullets Theory - https://www.grc.nasa.gov/www/k-12/airplane/wrong2.html
  - Venturi Theory - https://www.grc.nasa.gov/www/k-12/airplane/wrong3.html
- Airfoils and Airflow (Technical Discussion) - https://www.av8n.com/how/htm/airfoils.html
- "Bernoulli vs. Newton" - https://www.grc.nasa.gov/WWW/K-12/airplane/bernnew.html