Lift and drag

1. Wing lift
2. Drag
3. Wing shape
4. Reduce drag
5. L/D ratio

2A: Lift and Drag theory supplement

Lecture Presented By: Kevin Kochersberger

In this lecture you will learn:

- How wings generate lift
- What are the equations of lift and drag?

First, some useful information on units and conversions

- We will be working primarily in SI units:

$$Mass = kilogram = kg$$

$$Force = Newton = N = 1\ \frac{kg\,m}{s^2}$$

$$Velocity = V = \frac{m}{s}$$

$$Acceleration = a = \frac{m}{s^2}$$

$$Power = \frac{J}{s} = \frac{Nm}{s} = Watt = W$$

- 1 kg in Earth's gravity = 9.81N
    - *We may use kg or N to describe a weight*

How does a wing generate lift?

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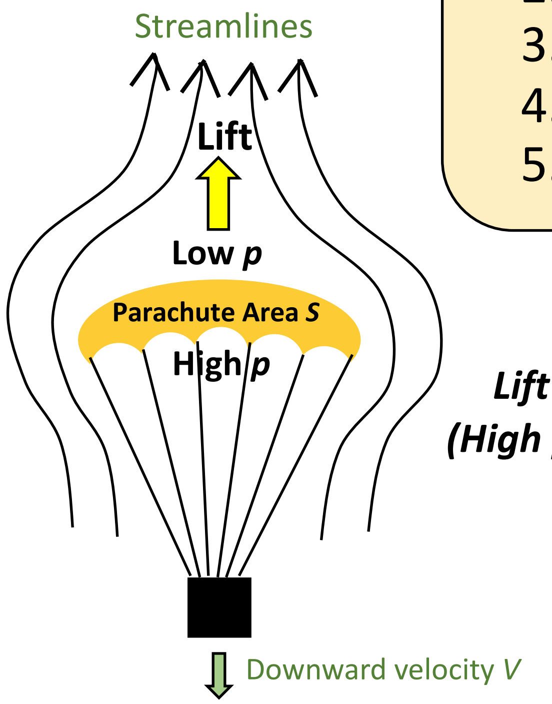
Air is a *fluid* that has *properties* which we can use to create a lifting force

$$\text{Density } \rho = {}^{Mass}/_{Volume}$$

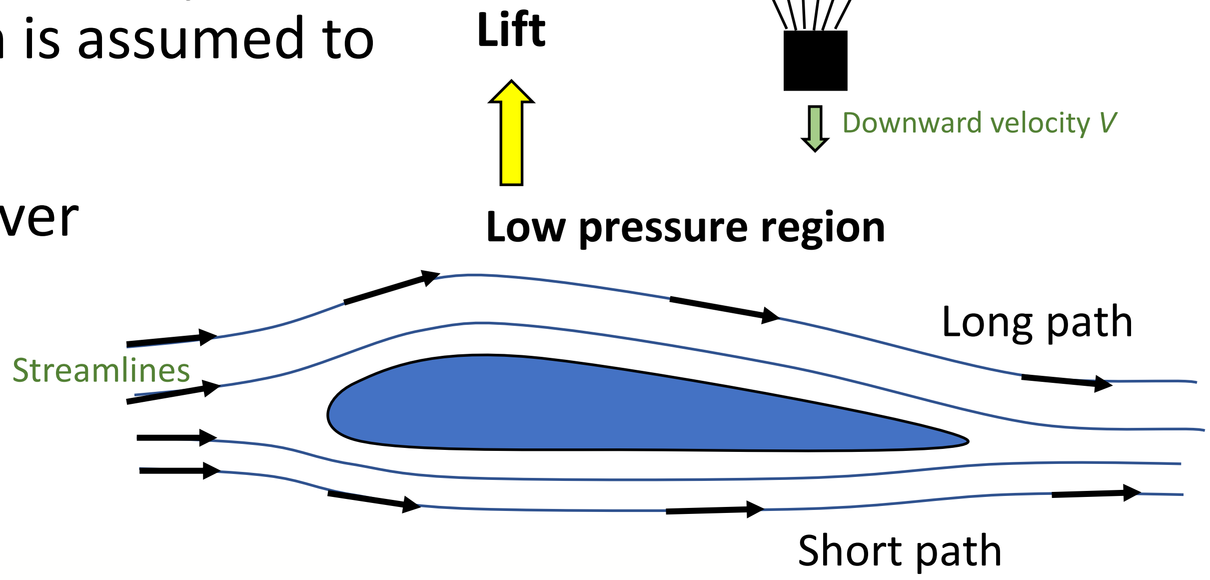
$$\text{Pressure } p = {}^{Force}/_{Area}$$



Lift force = (High p – Low p) S

An **airfoil** is a special kind of wing that is only described by its 2D shape - it's length is assumed to be infinite

- Lift is generated when air flowing over the top of the airfoil must travel further than air flowing over the bottom, resulting in a reduction in pressure on the top surface



How does a wing generate lift?

- For an inviscid (not turbulent) and incompressible fluid, we typically refer to Bernoulli's principle to describe the physics of wing lift:

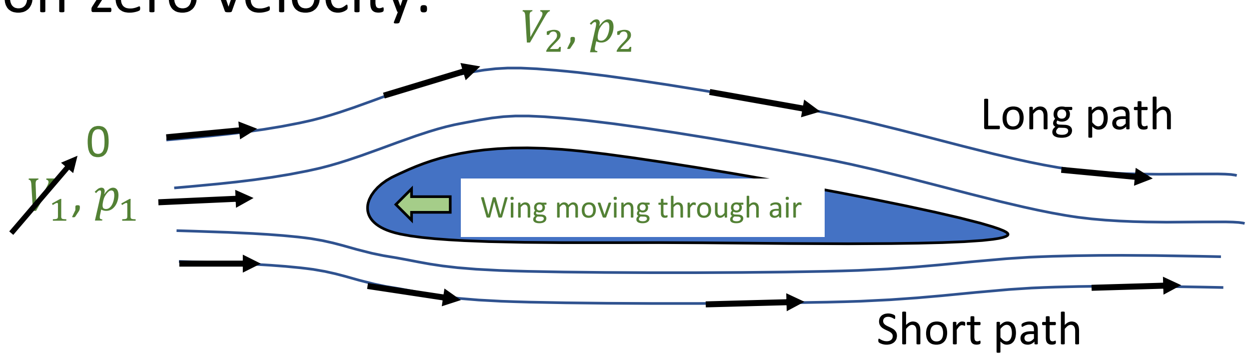
$$\frac{V^2}{2} + gz + \frac{p}{\rho} = constant$$

- For constant height above ground (*z* does not change), this equation becomes:

$$\frac{V^2}{2} + \frac{p}{\rho} = constant$$

- An airfoil moving through the air will cause the air flowing over the top of the wing to accelerate to a non-zero velocity:

$$\frac{V_1^2}{2} + \frac{p_1}{\rho} = \frac{V_2^2}{2} + \frac{p_2}{\rho}$$



$$p_1 - p_2 = \frac{1}{2}\rho(V_2^2 - \cancelto{0}{V_1^2})$$

$$p_1 - p_2 = \frac{1}{2}\rho V_2^2$$

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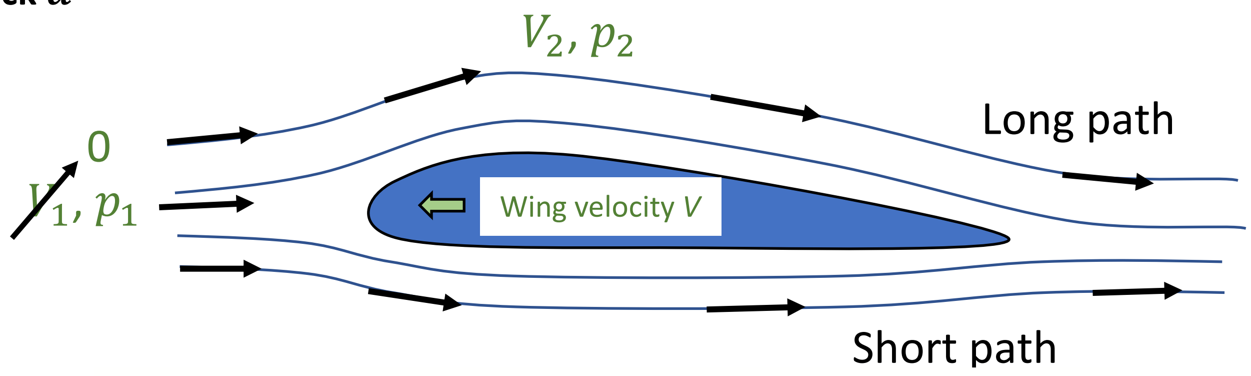
How does a wing generate lift?

- It would be possible to measure the velocity passing over the top of the wing to compute the change in pressure, but to simplify the calculation of lift, we can assume that this induced velocity is proportional to the ***velocity*** of the aircraft and the ***wing angle of attack***
  - An ***increase*** in **angle of attack** will ***increase* the distance** the air travels over the top of the wing**, increasing its velocity**
  - The increase in velocity over the top of the wing is proportional to the (velocity)^2 of the wing through the air:

$$V_2^2 = C_L V^2$$

  - This equation introduces the **lift coefficient *C_L*** as a non-dimensional scaling term that indicates how much the velocity increases over the top of the wing
    - **C_L is a function of** the **a.) wing shape, b.) wing thickness, c.) wing aspect ratio, and most importantly, d.) the angle of attack α**



How does a wing generate lift?

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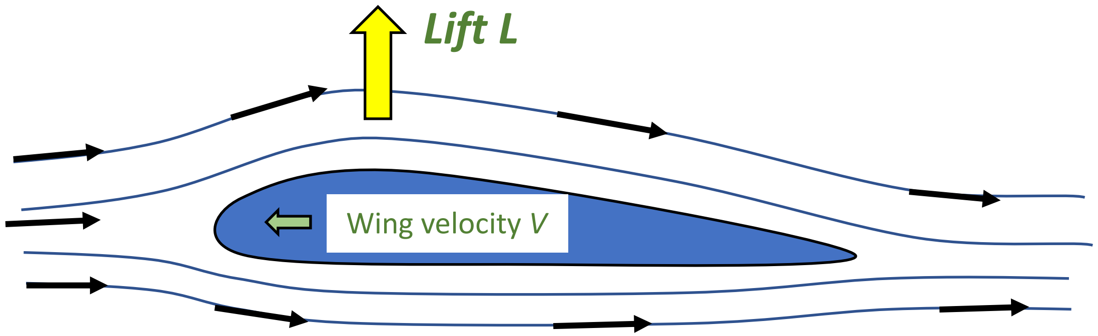
- The change in pressure from atmospheric to the reduced pressure on the top of the wing is described by Bernoulli's equation with C_L and wing velocity *V* substituted into the equation:

$$p_1 - p_2 = \frac{1}{2}\rho V_2^2 = \frac{1}{2}\rho V^2 C_L$$

- The *lift force L* that is generated by the wing is the difference in pressure multiplied by the wing area:

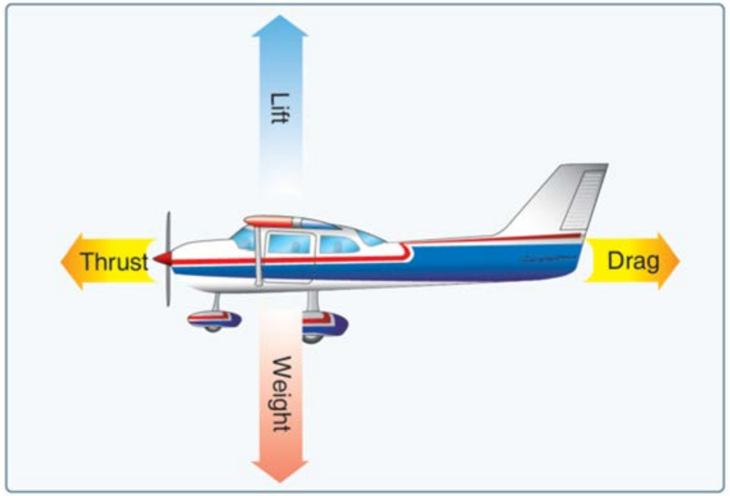
$$\boldsymbol{L = S(p_1 - p_2) = \frac{1}{2}\rho V^2 S C_L}$$

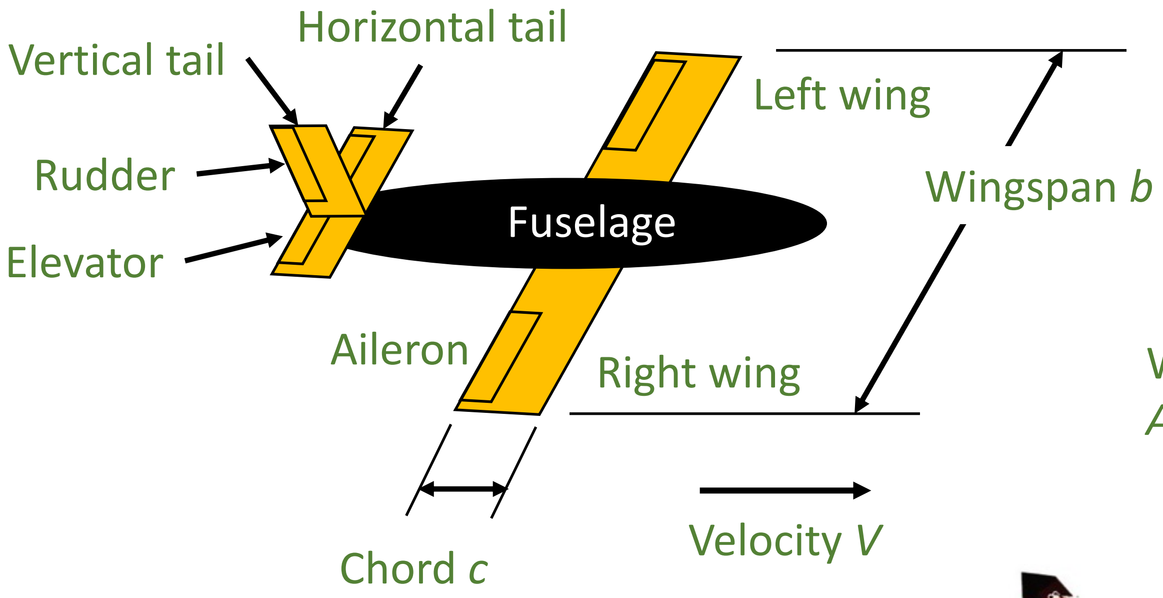
This is the standard equation describing the lift generated by a wing



The lift coefficient, C_L, is a non-dimensional coefficient used to characterize the lift generated by an airfoil

Some useful aircraft definitions





Wing area $S = bc$
Aspect ratio $= b/c$

In the case of a flying wing that does not have a tail, the ailerons also function as the elevator through a mixing of the controls. In this case the surfaces are called *elevons*

From the course material, what can you conclude about lift generation?

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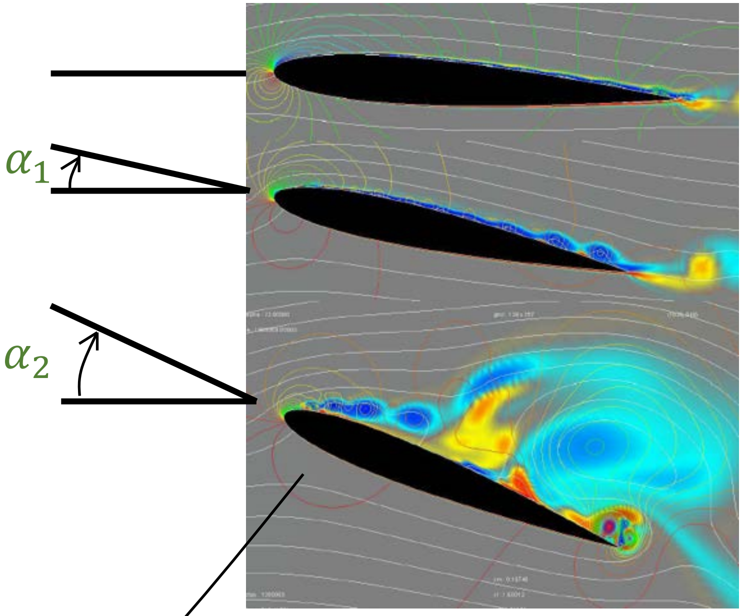
- When you change the angle of attack, what happens?
  - More **lift** is generated as the angle of attack increases
  - The ***lift coefficient*** **increases** as the **angle of attack increases**

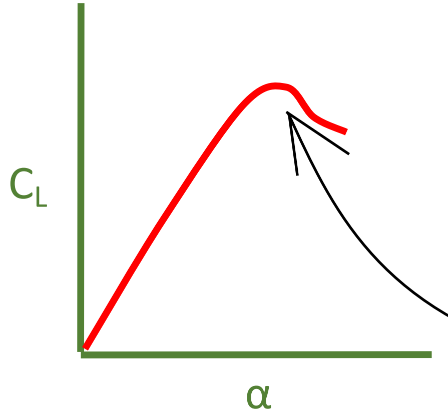


Lift L increases when the lift coefficient C_L increases

$$L = \frac{1}{2}\rho V^2 S C_L$$

ρ = air density
V = aircraft velocity
S = wing area

However, a stall angle of attack causes the airflow to separate from the airfoil and results in a loss of lift



From the course material, what can you conclude about lift generation?

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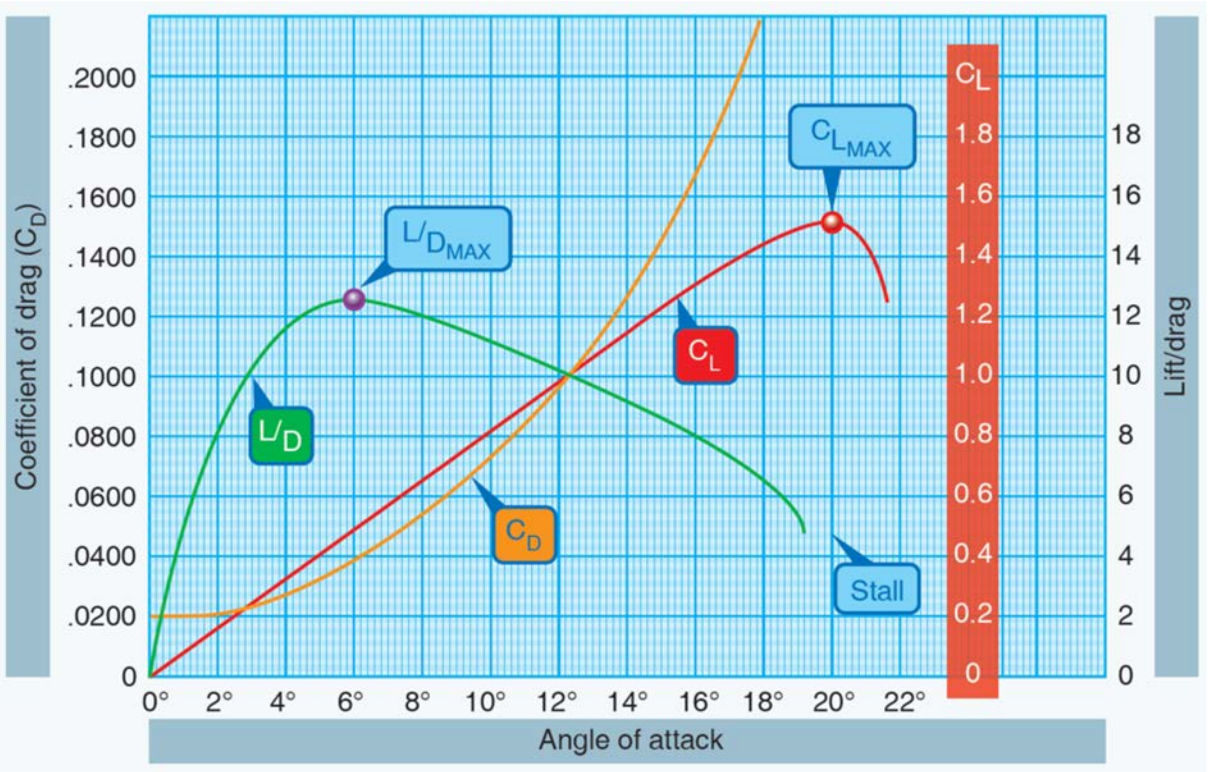
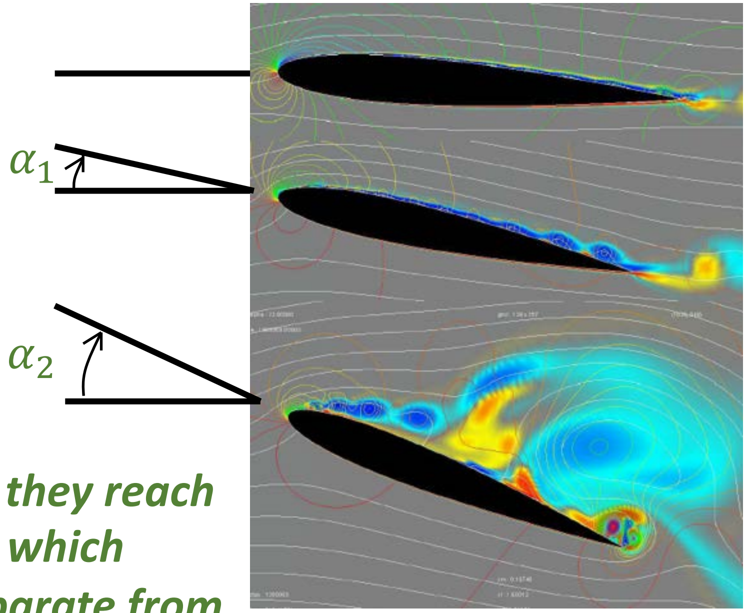
- The lift coefficient is a function of angle of attack:



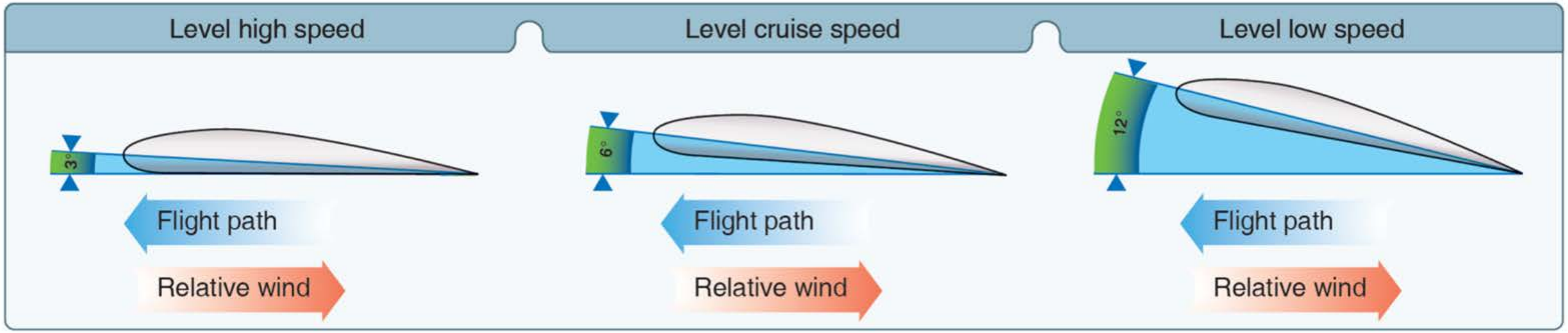
$$C_L = \frac{\Delta C_L}{\Delta \alpha}\alpha$$



All airfoils lose lift when they reach a critical angle of attack which causes the airflow to separate from the top of the wing. The separated flow causes the lift to suddenly decrease, resulting in a stall

The angle of attack that an aircraft flies at depends on its speed

- A **fast** airplane will fly at a lower angle of attack because *V* is high and that requires C_L to be lower to maintain the same *Lift* (see equation slide 3)
- A **slow** airplane will fly at a higher angle of attack because *V* is low and that requires C_L to be higher to maintain the same *Lift* (see equation slide 3)



The stall speed (maximum lift coefficient) should normally be avoided to prevent an uncontrolled descent of the airplane

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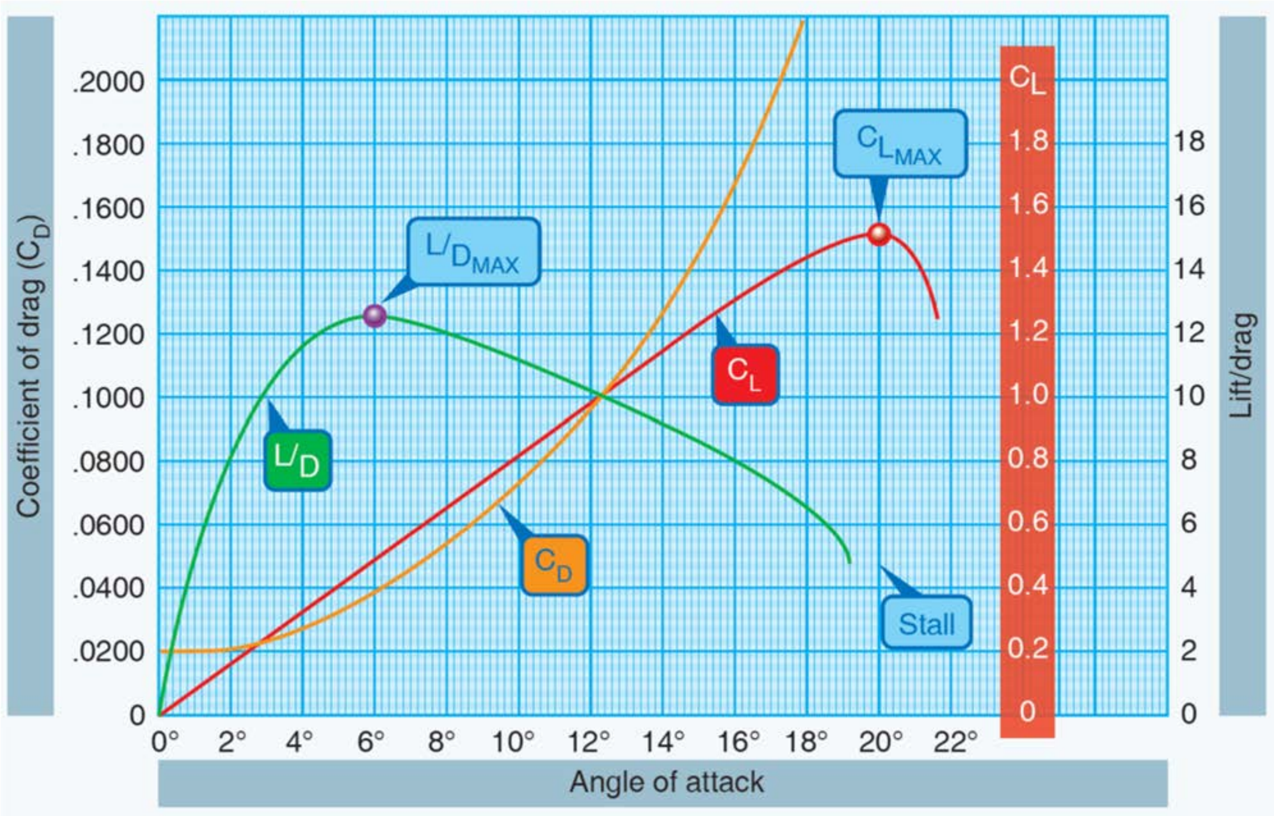
- Airplanes will fly in a lift coefficient range of 0.4 – 1.2
    - What range of angles of attack does this equate to for the given plot (for a given airfoil?)
- This range provides a enough margin away from stall speed that safe flight is possible



The stall speed (maximum lift coefficient) should normally be avoided to prevent an uncontrolled descent of the airplane

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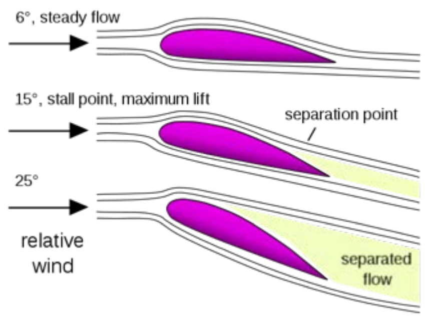
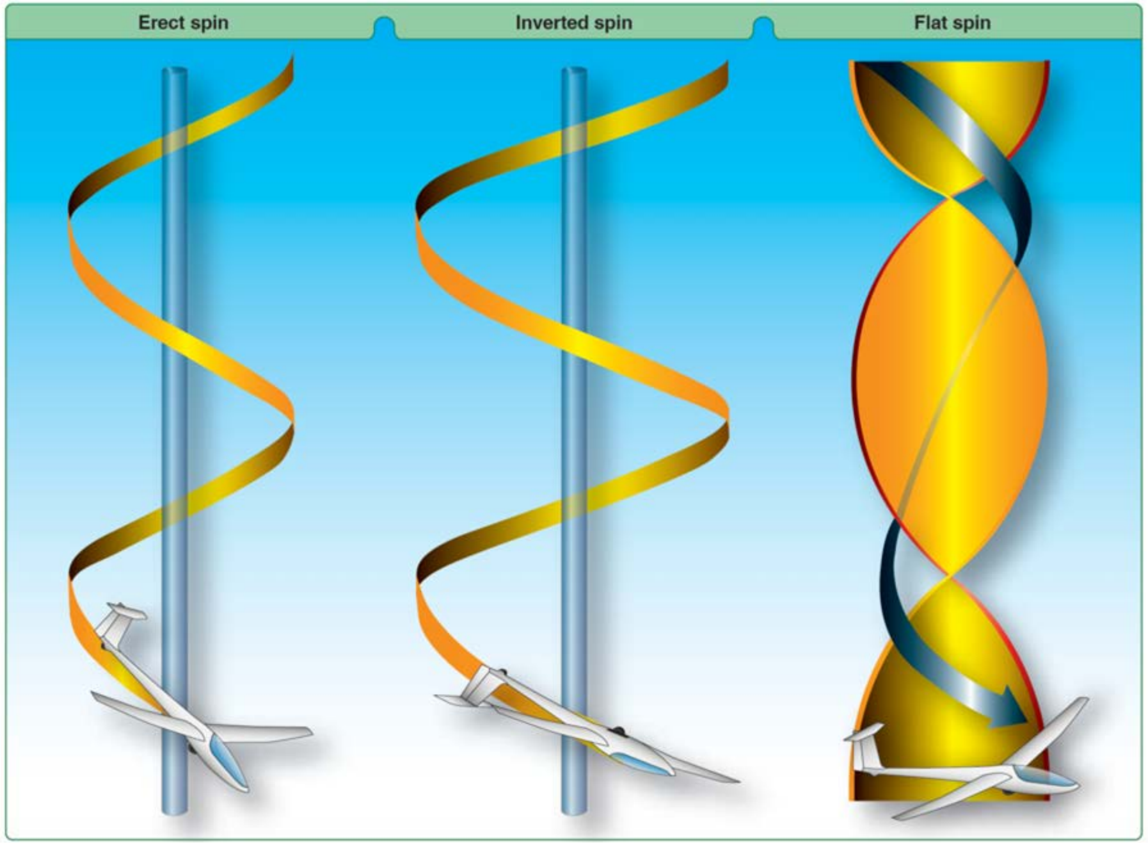
- Airplanes that stall will experience an uncontrolled descent since the control surfaces were not designed to operate in a stalled condition
- The nose of the airplane may drop, or a wing may drop, or the airplane may enter a spin





If one wing stalls slightly before the other wing, the aircraft will enter a spin because the lift force is no longer balanced to each wing

VTOL aircraft can also exhibit the same lift behavior that we see with fixed wing aircraft

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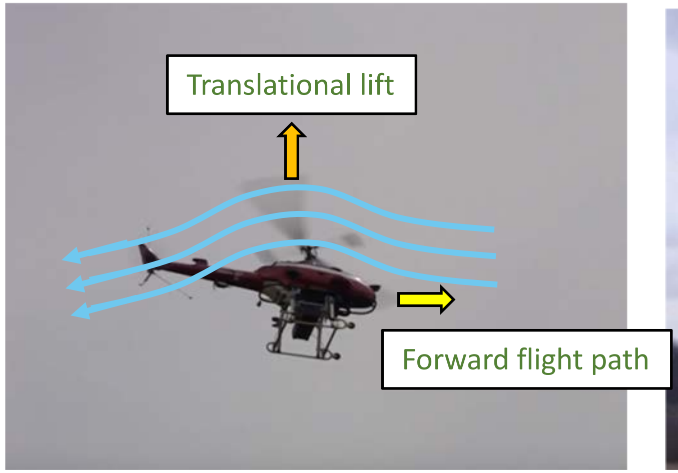
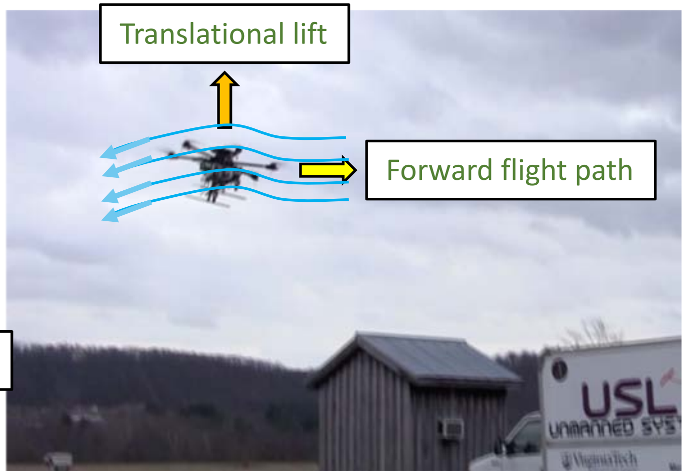
- This is called “translational lift”
- Translational lift is **additional lift** that a VTOL aircraft produces when it **flies forward**
- The downwash created by the rotor(s) act similar to wing with camber that turns the relative air downward



RMAX helicopter



Hexacopter

Lift counteracts the **weight** of the aircraft in level flight while **thrust** is the force that counteracts **drag**

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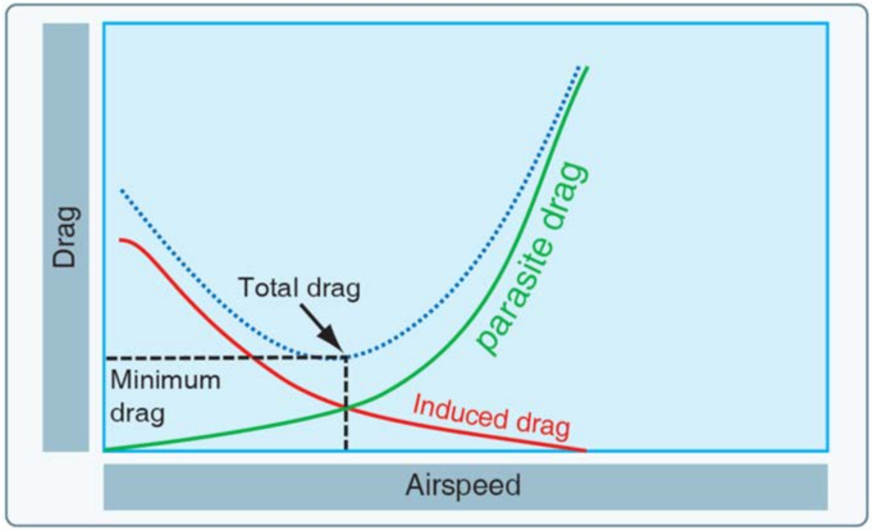
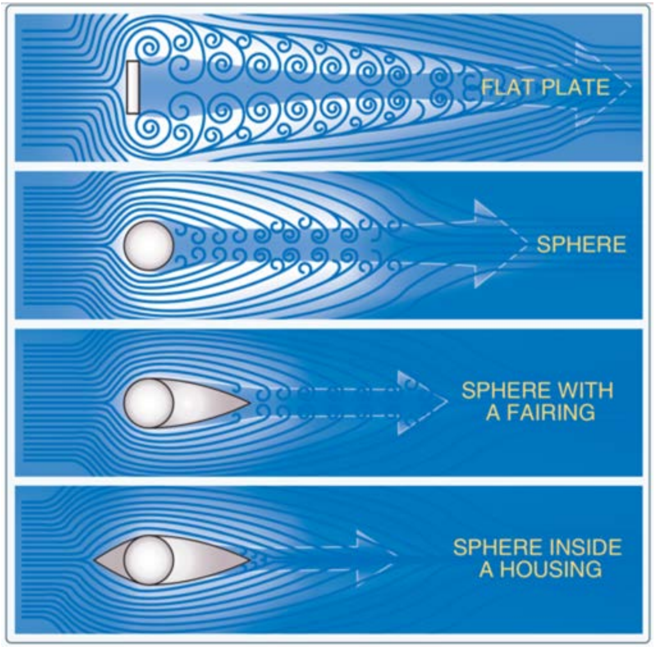
- Drag force is created by the aircraft as it flies through the air
  - The two kinds of drag are *parasite* drag and *induced* drag
    - Parasite drag is caused by the friction the aircraft experiences in flight with the atmosphere
    - Induced drag is drag due to lift generated by the wing



This plot shows that the total drag is minimized when the parasite and induced drag terms are equal



Find a piece of cardboard and move it through the air at different angles, like a wing

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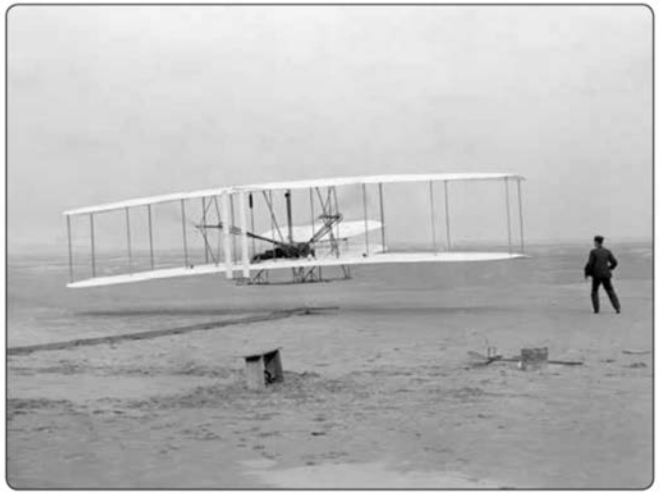
- When you increase the angle of attack of the cardboard sheet, you will feel an increase in the upward lift force, but drag will also increase
  - Is this an increase in ***parasite*** drag or ***induced*** drag?
- *We will talk about propellers soon, but the same principles of lift and drag apply to propellers as well*
- Drag causes the airplane to lose efficiency and require more power to operate, so we always want to minimize drag

Which airplane do you think has higher drag?



The drag force is calculated just like lift force, only it is applied in the direction of aircraft travel

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- The drag coefficient C_D is a non-dimensional coefficient that relates induced drag and parasite drag to the overall drag force on the aircraft
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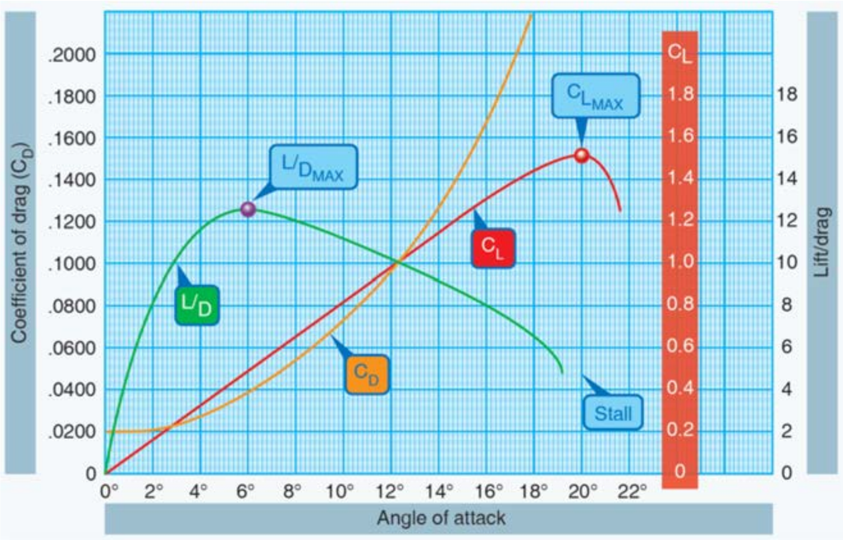
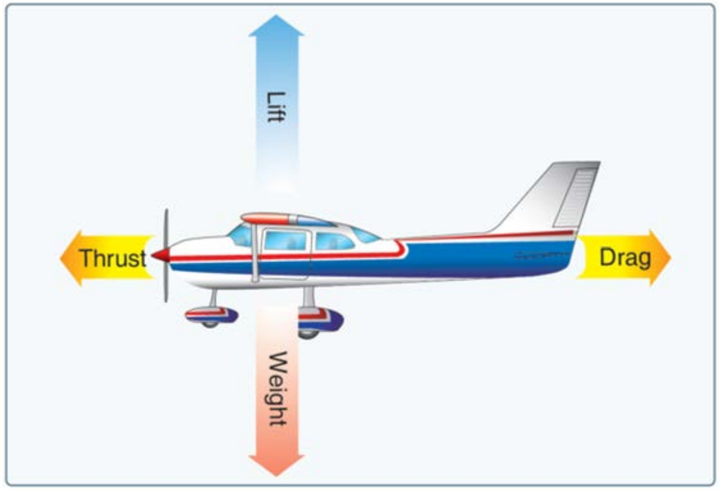
$$D = \frac{1}{2}\rho V^2 S C_D$$

We use wing area S as a reference, but drag is generated by the aircraft fuselage also





Besides wing area *S*, there are other factors that affect the ability of a wing to generate lift

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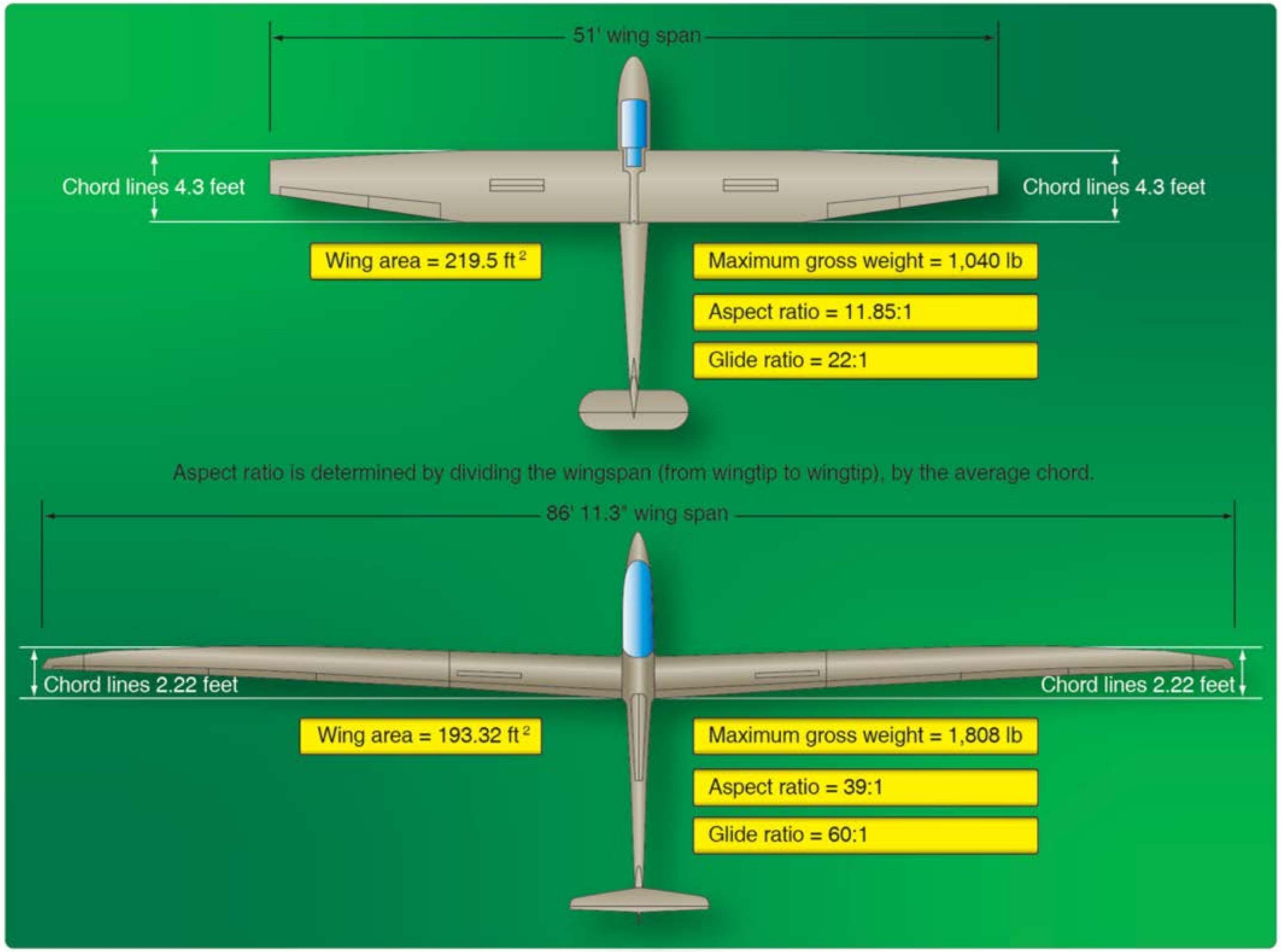

- **Aspect ratio (AR)** is the **ratio** of **wingspan** to **chord length**
- Airplanes with a large AR have less induced drag
  - They are more efficient
  - Sailplanes have a large AR
- Powered aircraft that fly fast at lower C_L have a smaller AR
  - The induced drag is less at low C_L and so the benefit of a high AR is not as great
- Could you tell in the lab experiments that the wing with the higher AR produced more lift and less drag?

Lift and drag

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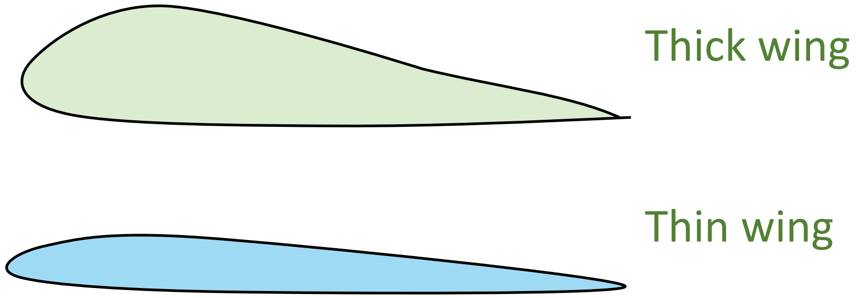
Wing thickness also affects performance

- Wing thickness is just what it sounds like – the thickness of the wing
- The thickness is determined partly due to aerodynamic considerations but also to structural considerations



Aerodynamic considerations

- The absolute speed of the aircraft and its range of speeds will impact wing thickness
- The **maneuverability** of the aircraft is **better** with a **thick wing**
- **Low speed aircraft have less drag with a thick wing**

Structural considerations

- It is easier to make a strong wing when the thickness is large enough to enclose the beam structure

Question: why do you think a butterfly wing is thin?

The butterfly question brings up another topic: **Reynolds Number**

Lift and drag

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- The performance of an airfoil is also dependent on a non-dimensional number called the Reynolds Number - for airfoils it is expressed as:

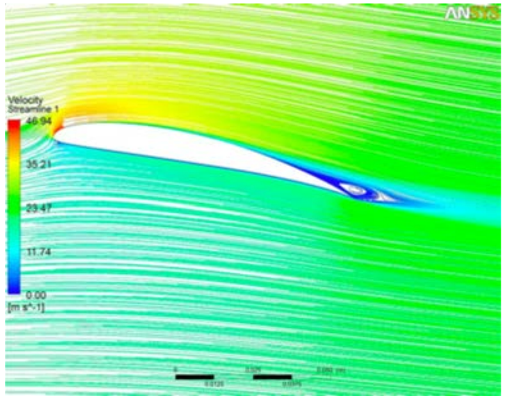
$$Re = \frac{\rho V c}{\mu}$$

$\rho = air\ density$
$V = velocity$
$c = chord\ length\ of\ wing$
$\mu = viscosity\ coefficient$

- It turns out that the Reynolds number represents a scaling that must be considered in wing design

The butterfly operates at very low *Re* and as a result, the optimized airfoil is very thin (like a sheet of paper)

Drones fly at around *Re* = 100,000, which requires a special class of airfoil



Ahmed, M. Rafiuddin & Narayan, Sumesh & Zullah, Asid & Lee, Young-Ho. (2011). Experimental and Numerical Studies on a Low Reynolds Number Airfoil for Wind Turbine Blades*. Journal of Fluid Science and Technology. 6. 357-371. 10.1299/jfst.6.357.

Wing camber also affects the lift and drag of a wing

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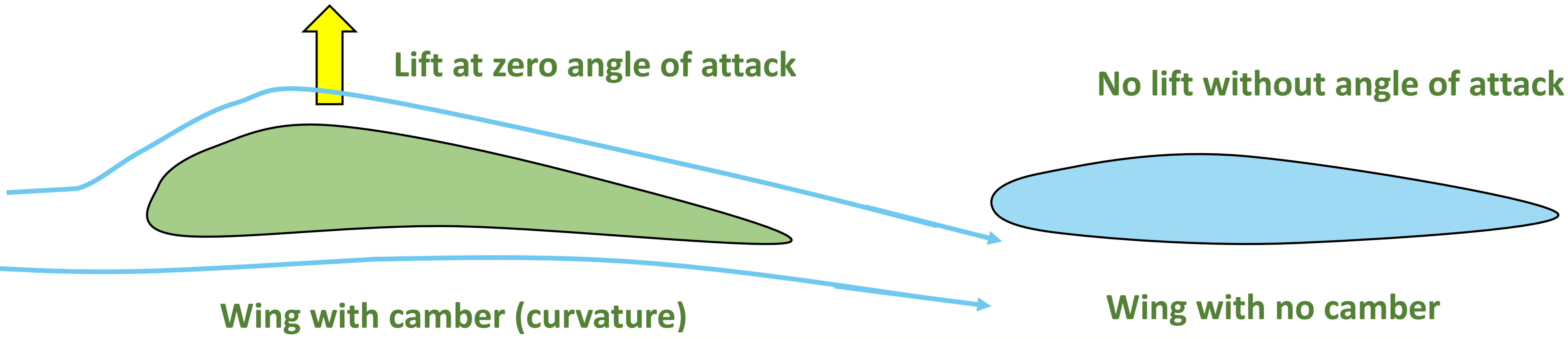
- Wing camber is the shape of a wing – the curvature of the airfoil surface
- A cambered wing will generate **lift** at **zero angle of attack** while a wing with no camber will not generate lift
  - Anytime lift is generated, induced drag will also occur



Wings with camber are generally considered high lift and operate at lower airspeeds because they tend to have high drag

Drag reduction and aerodynamic improvements can improve overall aircraft efficiency

Lift and drag
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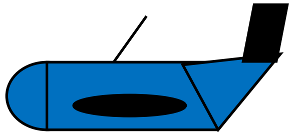
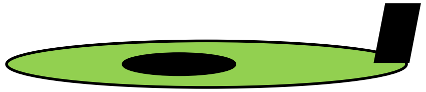
3. Wing shape
4. **Reduce drag**
5. L/D ratio

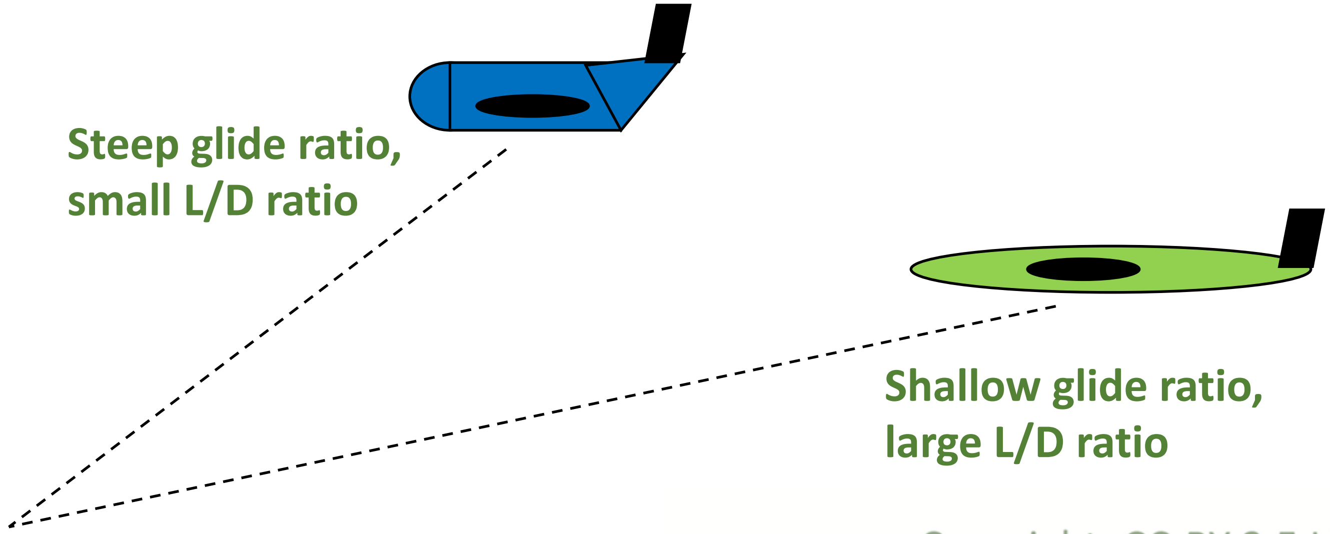
- Fuselage drag cleanup
  - Reduce sharp angles that cause flow separation
  - Enclose antennas inside the fuselage
  - Use fairings that are teardrop shaped
- Wing drag cleanup
  - Make sure control surfaces and hinges do not protrude into the airstream
  - Make sure wing is a smooth, contoured surface

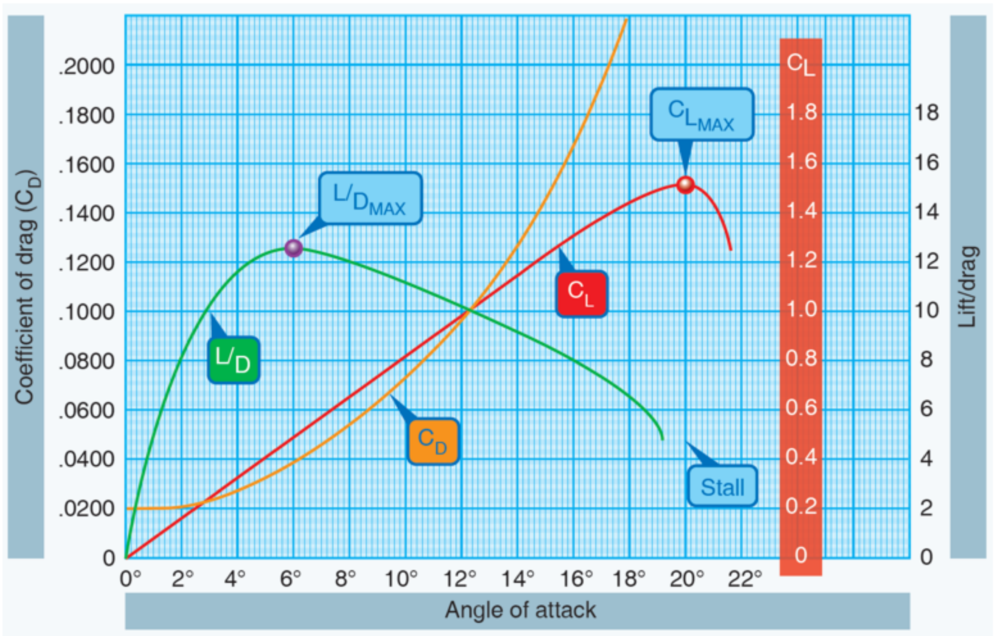




L/D ratio

- The L/D ratio is an important parameter in aircraft performance
  - It is the *Lift/Drag* ratio, which translates to an efficiency number
  - It effectively describes how far an aircraft would translate forward from a given altitude





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Putting it all together

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- In the design of an efficient fixed wing aircraft, we can now collect the previous information into a set of rules that will result in a good aircraft design:
  - For long endurance, what should the wing shape look like?
  - For high speed, what factors should you be concerned about?
  - Highly cambered wings are also high lift, so if lifting capacity is needed you may select a highly cambered wing
    - One downside of a highly cambered wing is its affect on aircraft stability – we will talk about that soon