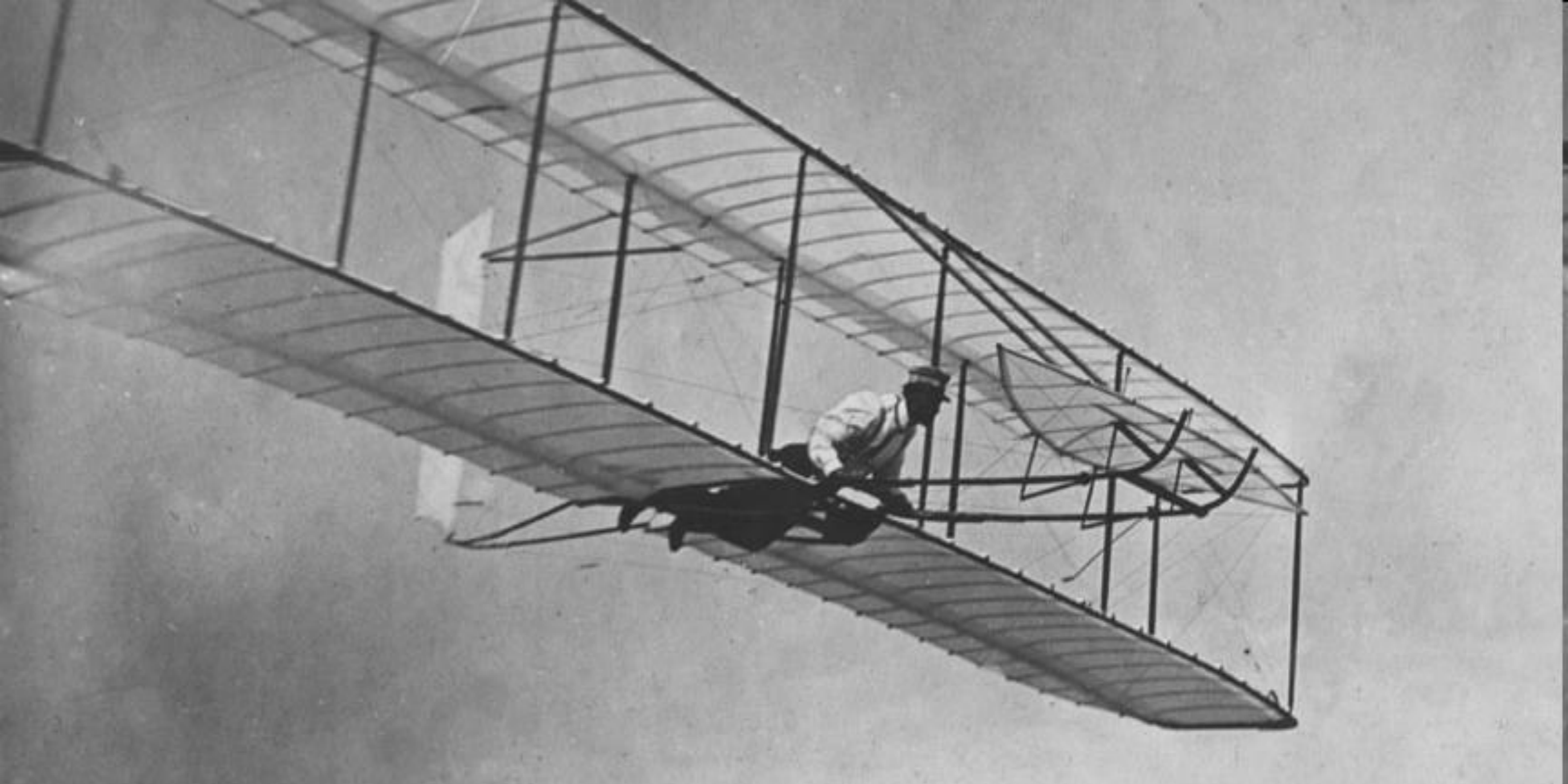
Introduction to Aerospace Engineering

Lecture slides



Introduction to Aerospace Engineering

5 & 6: How aircraft fly

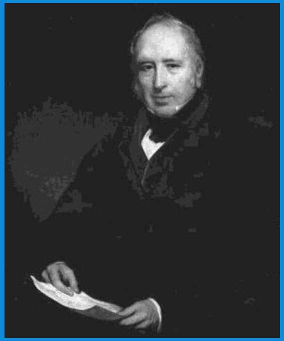
J. Sinke

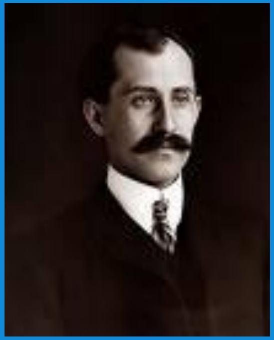
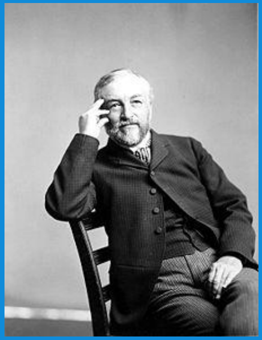
5 & 6.

How aircraft fly

Anderson 1, 2.1-2.6, 4.11- 4.11.1, 5.1-5.5, 5.17, 5.19

george caley; wilbur wright; orville wright; samuel langley, anthony fokker; albert plesman



19^{th} Century - unpowered

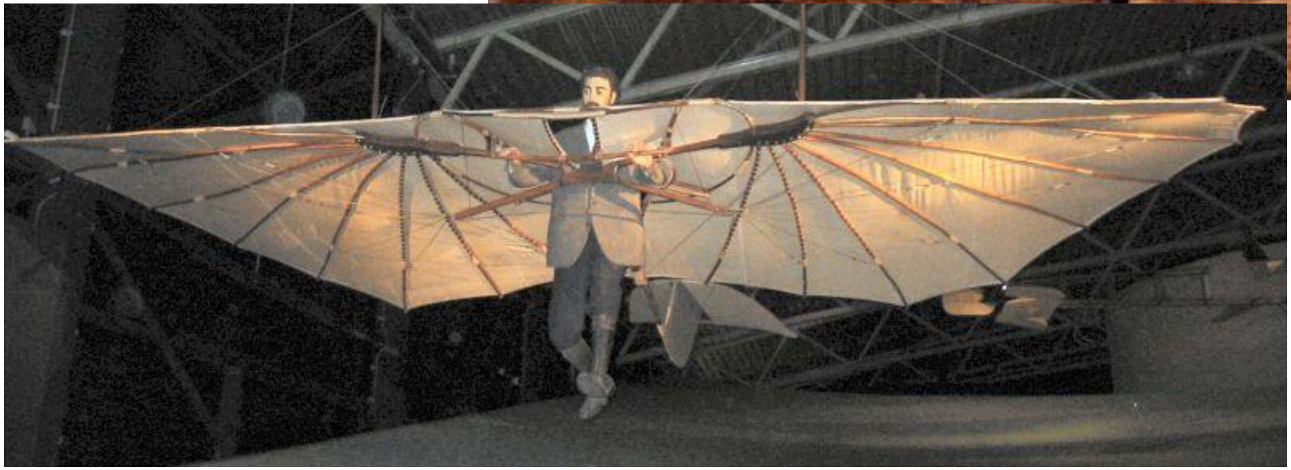
Otto Lilienthal (1848 – 1896)

Was fascinated with the flight of birds (Storks)
Studied at Technical School in Potsdam
Started experiment in 1867
Made more than 2000 flights
Build more than a dozen gliders
Build his own “hill” in Berlin
Largest distance 250 meters
Died after a crash in 1896.

No filmed evidence:
film invented in 1895 (Lumiere)

Otto Lilienthal

Few designs



Hang gliders

Derivatives of Lilienthal's gliders

Glide ratio
E.g., a ratio of 12:1 means
12 m forward : 1 m of altitude.

Typical performances (2006)
Gliders (see picture):
 V= ~30 to >145 km/h
 Glide ratio = ~17:1 *(V_{opt} = 45-60 km/h)*
Rigid wings:
 V = ~ 35 to > 130 km/h
 Glide ratio = ~20:1 *(V_{opt} = 50-60 km/h)*

Question

With Gliders you have to run to generate enough lift – often down hill to make it easier. Is the wind direction of any influence?

Answer

What matters is the Airspeed – Not the ground speed.

$\rightarrow$ The higher the Airspeed – the higher the lift.

So if I run 15 km/h with head wind of 10 km/h, than I create a higher lift (airspeed of 25 km/h) than when I run at the same speed with a tail wind of 10 km/h (airspeed 5 km/h)!!

That's why aircraft:

- Take of with head winds – than they need a shorter runway
- Land with head winds – than the stopping distance is shorter too

Beginning of 20th century: many pioneers

Early Flight
1m12s

Failed Pioneers of Flight
2m53s

1903 – first powered HtA flight

The Wright Brothers

Wright Flyer take-off & demo flight

Wright Brothers lift-off
0m33s

Wright Brs. – the Flyer (1903)

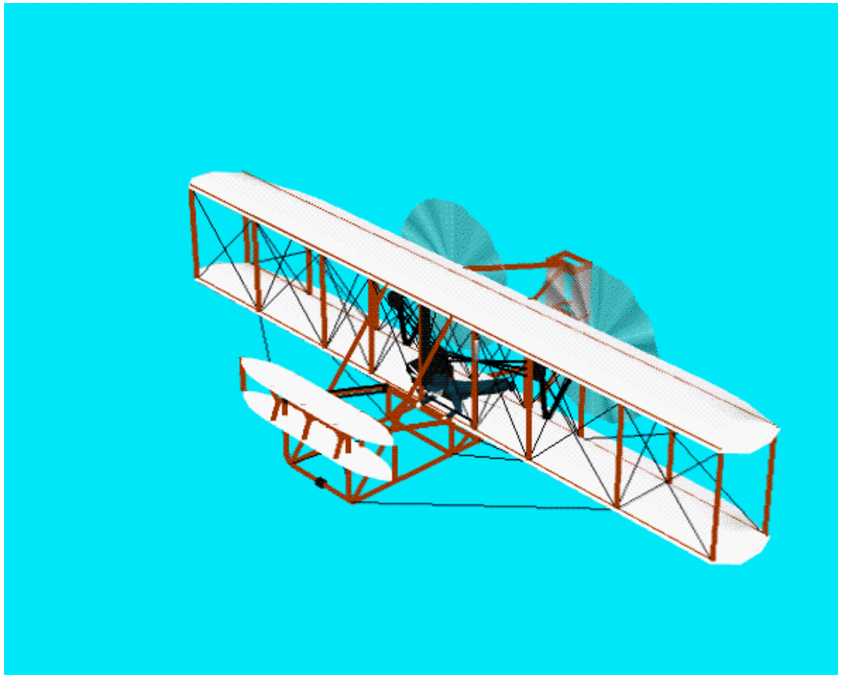
Printing firm & Bicycle shop
Interested in flying
(inspired by Lilienthal' gliders)
Did a lot of investigations:
- Build a wind tunnel to test planes

Timing (readiness of technology)
Pressure of Samuel Pierpont Langley

- The engine 12 Horse Power

- The propeller (2 counter rotating push propellers)
  - *Perfected in wind tunnel!*

Wright's Flyer 1903

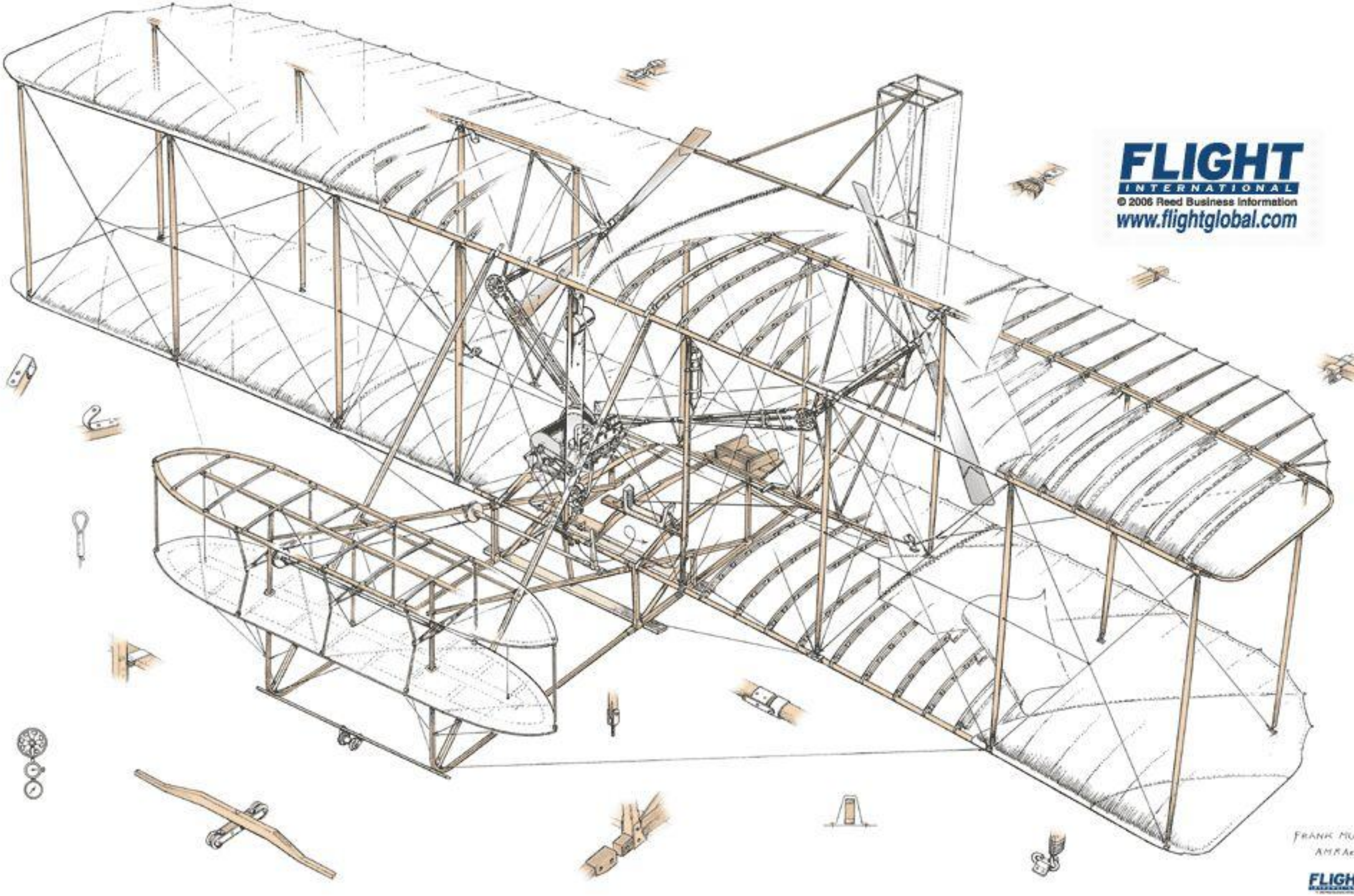


Some features/dimensions:

- Aircraft: weight of 275 kg
  - 344 kg (incl. engine)
- Length 6.4 m;
- Wingspan: 12.2 m;
  (efficient wing due to wind tunnel)
- Wing area 48 m^2

Longest distance (first flight): 260 meters
Flying time was 59 sec. (*average speed??)*

Flyer had later models (larger engines; improved wing surfaces)


FLIGHT
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Influence of Wright's Flyer

- The Flyer series of aircraft were the first to achieve **powered & controlled** heavier-than-air flight
- The Flyer design depended on **wing warping** and a **forward horizontal stabilizer**, features which *would not scale* and produced a *hard-to-control* aircraft; Later: **ailerons** by Curtiss and Farman
- Highly efficient wings and propellers, which resulted from the Wrights' exacting **wind tunnel** tests

> 100 years later

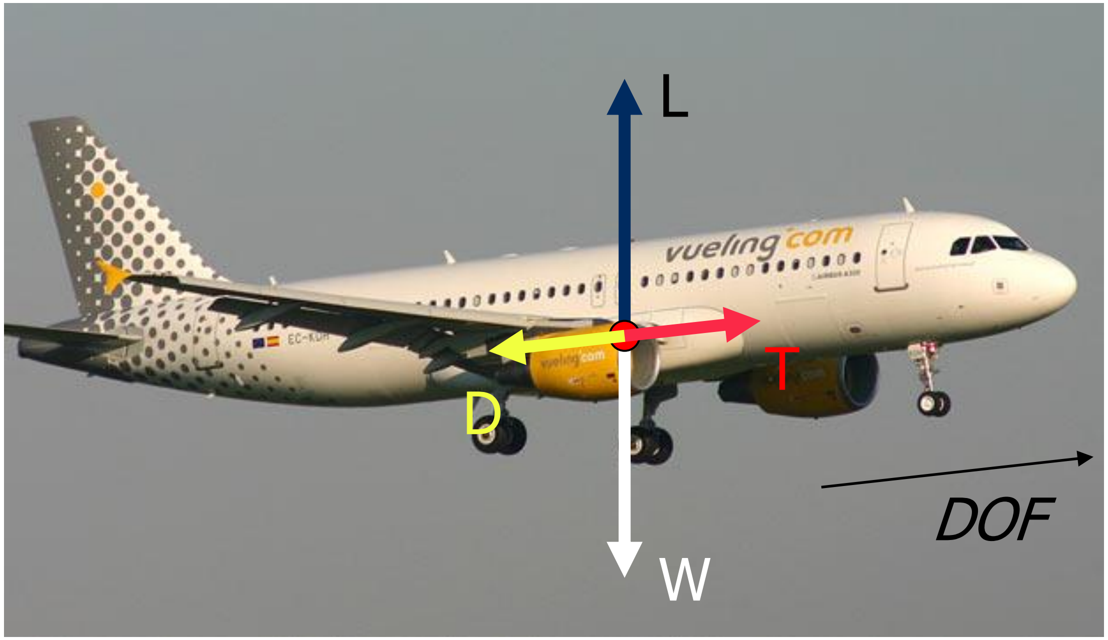
End of introduction

Questions?

Straight, horizontal, steady flight

Four forces:

- Weight (W)
- Lift (L)
- Drag (D)
- Thrust (T)



For V & alt. = constant

Force Equilibrium:

$L = W$

$D = T$

DOF= Direction Of Flight

Forces

- **Lift**: mainly generated by the **wing** (small contributions of e.g. tail surfaces)
- **Weight** is composed of three main components: **aircraft empty** weight, **fuel**, **payload** *(passengers + luggage, freight)*
- **Drag** is caused by **fuselage**, **wings**, **tail surfaces**, etc.
- **Thrust** is provided by the **engines**

Question: *One of the main rules in aerospace design is to create **LIGHTWEIGHT** aircraft. WHY??*

Answer

An aircraft consists of 3 main weights:

- empty weight (structure, systems, etc.)
- fuel
- payload

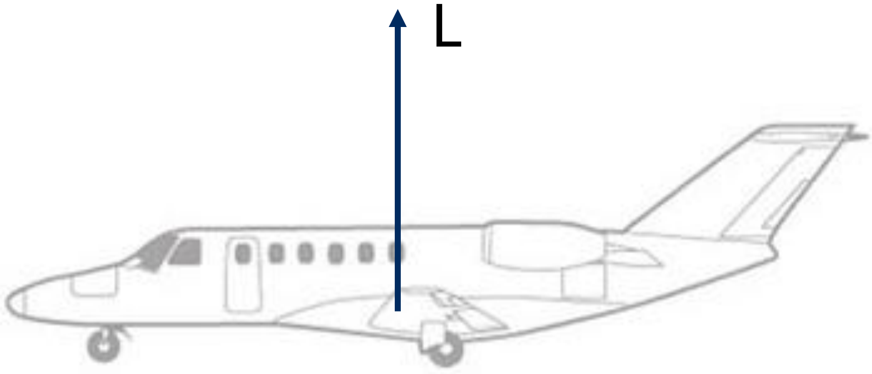
(Costs vs revenues)

If we reduce the empty weight (MTOW = constant), we can

- transport more payload (higher revenue)
- take more fuel on board (fly longer distance)

General: Improve the PERFORMANCE of the aircraft

Lift



The formula for the LIFT is:

$$L = C_L \times (\tfrac{1}{2}\rho V^2) \times S$$

C_L = Lift coefficient
ρ = Density of the air [kg/m^3]
V = Air speed [m/s]
S = Wing area [m^2]

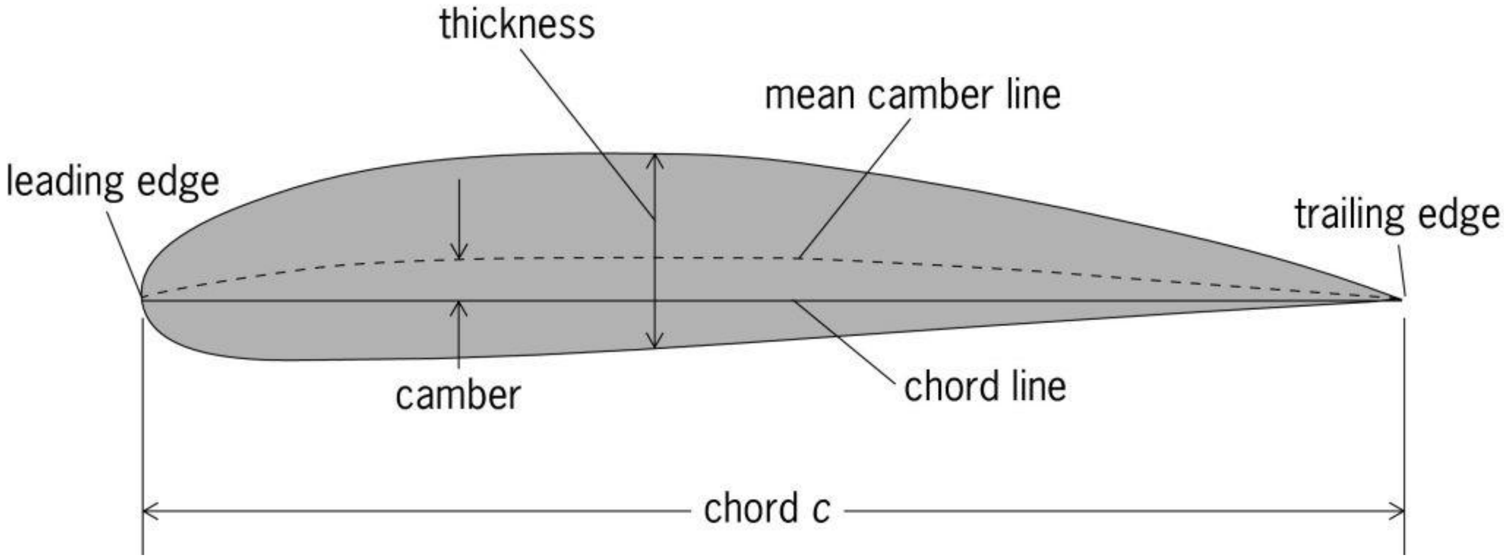
Question: *What is the dimension of C_L ?*

Answer: N = [?][kg/m^3][m/s]^2[m^2] = [?][kg/m^3][m^4/s^2] = [?]kg.m/s^2
= [?]N; so [?] =[-]

Lift-parameters

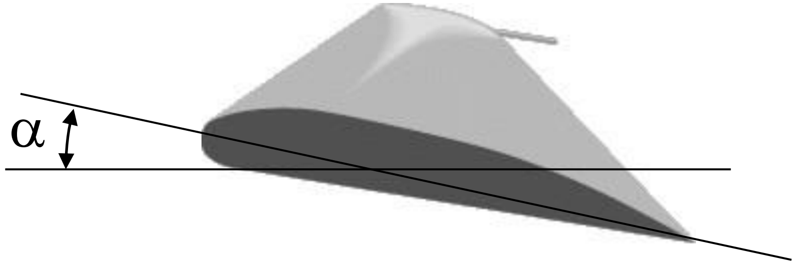
C_L (Lift coefficient) depends on

- airfoil or wing profile



C_L represents "quality of airfoil" (ability to generate Lift)

Lift-parameters



- C_L (Lift coefficient) depends also on
  - *angle of attack (α)*
- ρ (air density) depends on:
  - altitude & temperature (atmosphere)
- V (air speed) and S (wing area) are design parameters

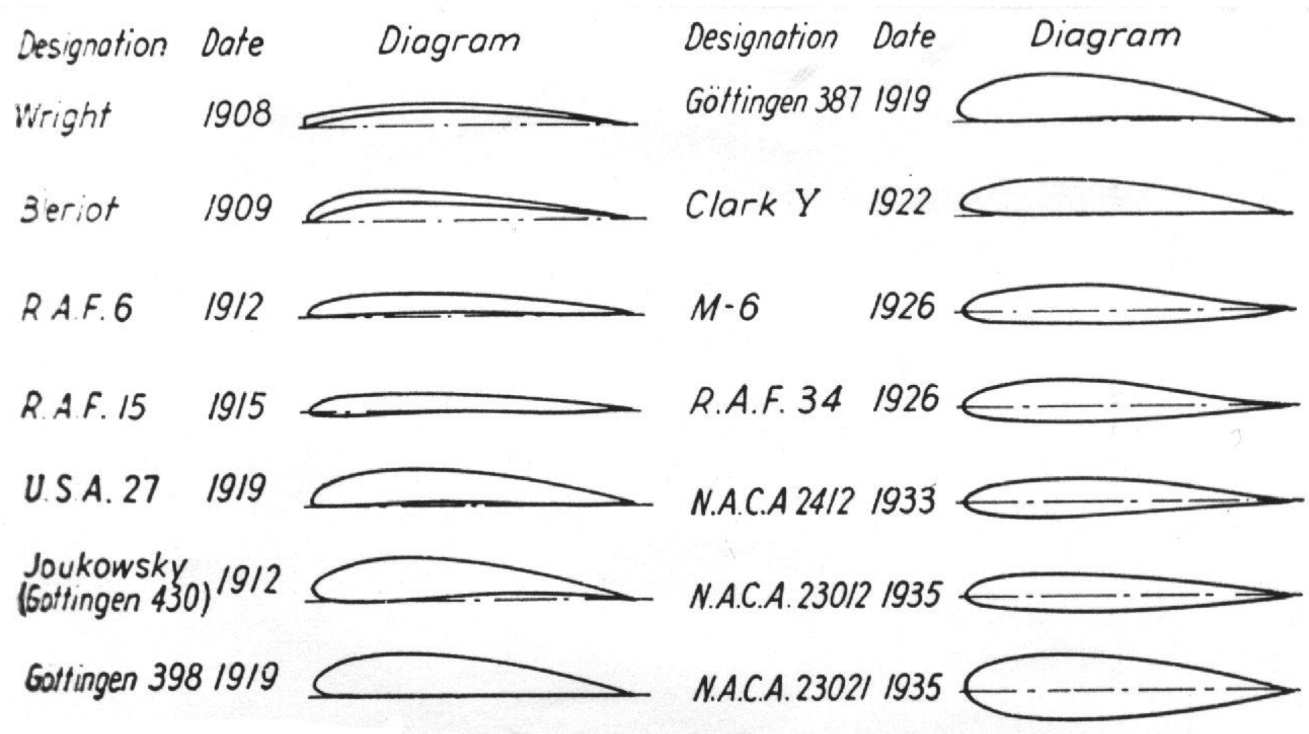
Lift Parameters

Question: Why do we use these cambered profiles; why not simple symmetrical ones?

Answer: For horizontal flight (cruise) an inclined symmetrical wing profile generates more drag = fuel inefficient

History of wing profiles

Early years: many different airfoil descriptions



History of wing profiles

National Advisory Committee for Aeronautics (NACA) – 1915

supported research & development (at Langley)

a.o. retractable landing gear; engine nacelles, propellors, etc.

aerodynamics (first open windtunnels)

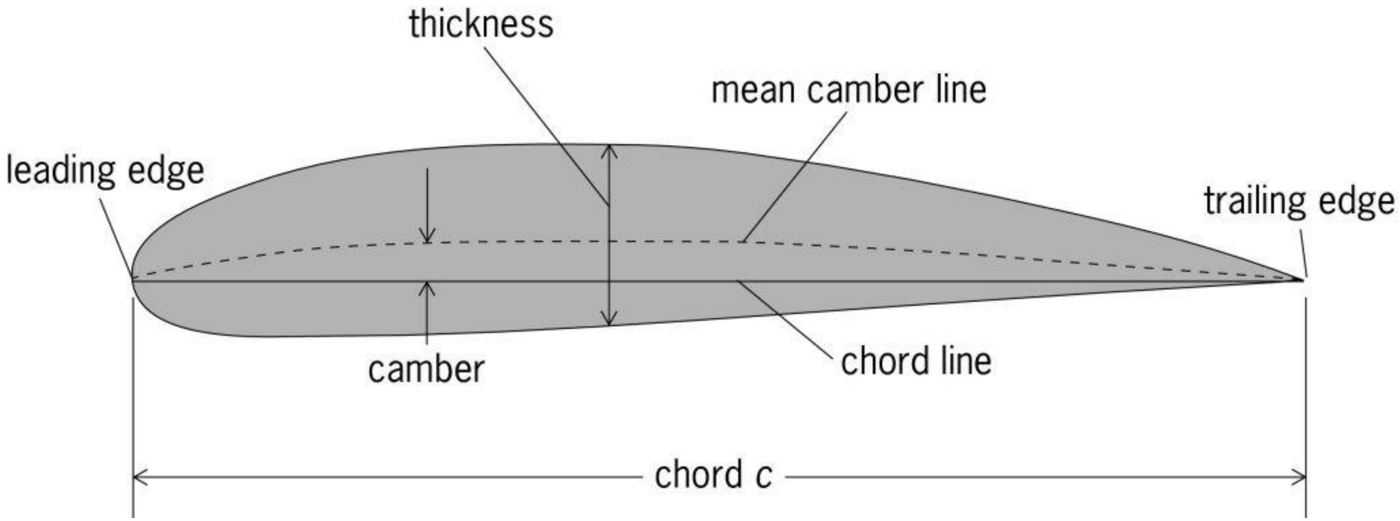
Also airfoils (large overview in 1933)

specific (4-numbered) nomenclature to describe:

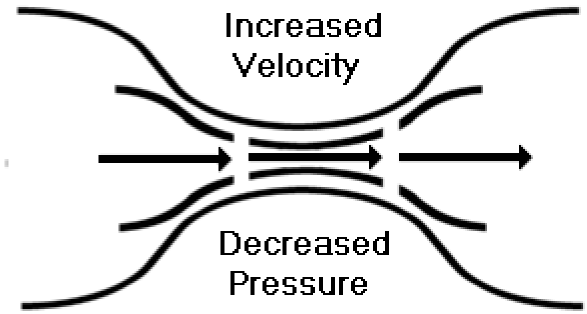
History of wing profiles

2412 means:

2% camber (of *chord length*) at
0.**4** of the chord (from LE); and
12% thickness/chord ratio (or 0.12)



Generation of Lift - Bernoulli

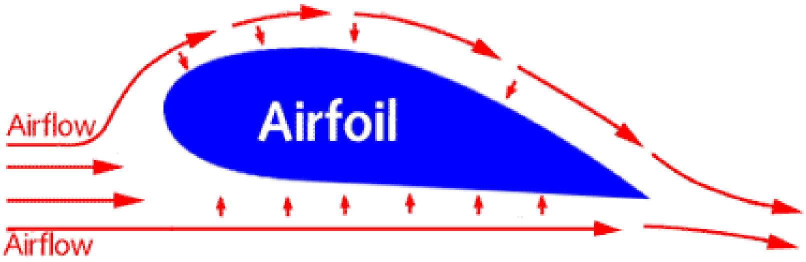


Sum of **static** and **dynamic pressure** remains constant

$$p_1 + \tfrac{1}{2}\rho V_1^2 = p_2 + \tfrac{1}{2}\rho V_2^2$$

or $\boldsymbol{p + \tfrac{1}{2}\rho V^2 = constant}$ *(along a streamline)*

Consequence:
higher velocity = lower local pressure!!
So - Lift by pressure difference



Airfoils:
Curvature of upper surface larger than for lower surfaces
And:
Angle of attack improves lift

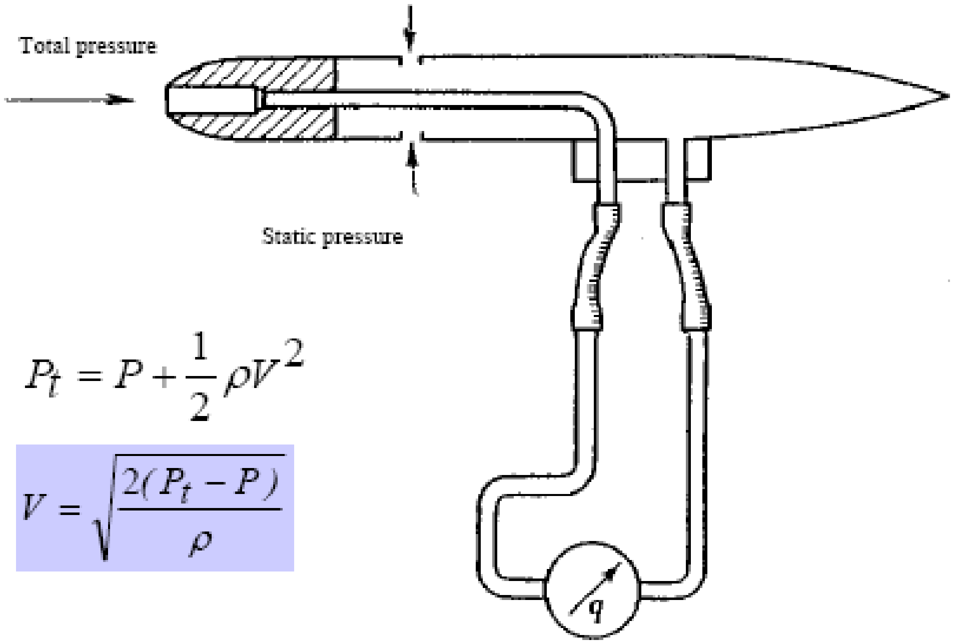
Question

How can you use the Bernoulli-law ($p + \frac{1}{2}\rho V^2 = constant$) to measure the speed/velocity?

Do we measure the Air speed or the ground speed?

Answers

1. Pitot Static tube



$$P_t = P + \frac{1}{2}\rho V^2$$

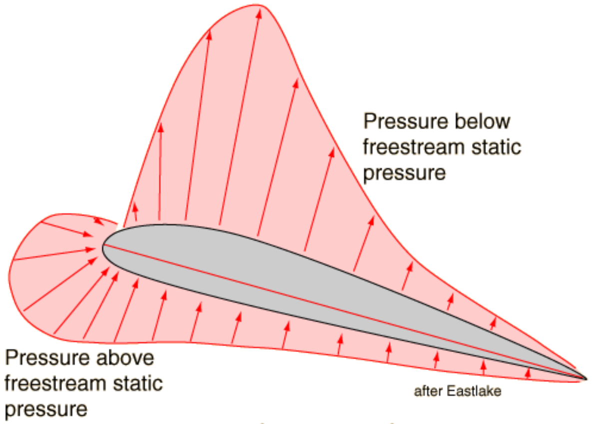
$$\boxed{V = \sqrt{\frac{2(P_t - P)}{\rho}}}$$

2. Air speed! *(how to measure ground speed?)*

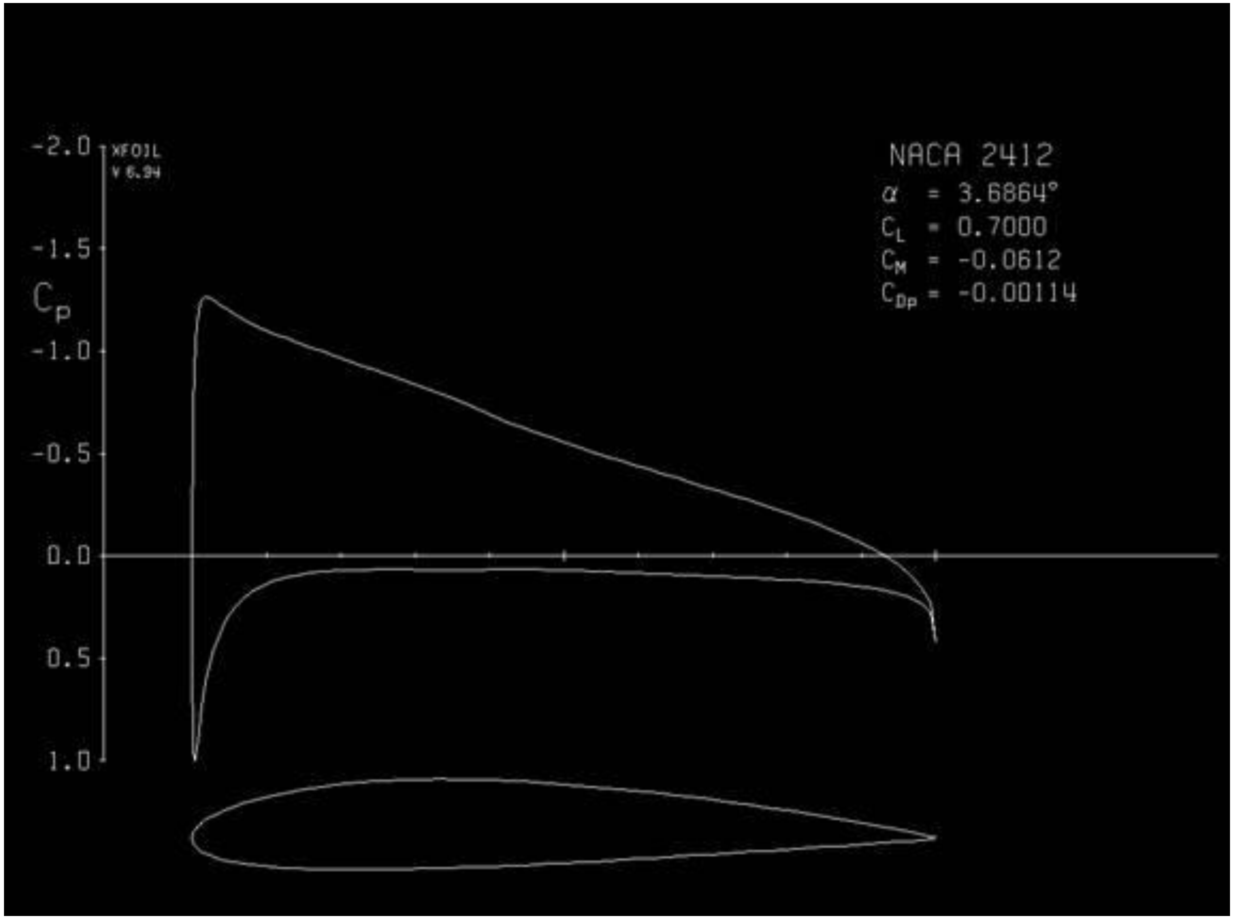
Lift – by Pressure distribution

Lift due to **pressure differences** over the airfoil – Bernoulli

Example



Pressure profile around airfoil

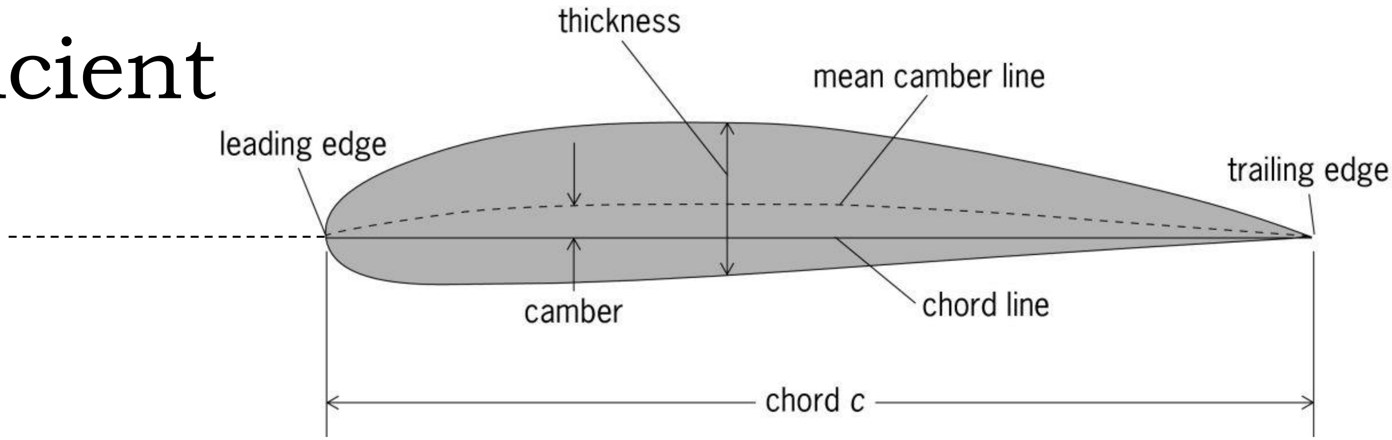


Lift - Pressure distribution

http://www.grc.nasa.gov/WWW/K-12/airplane/foil2.html

Upper and lower pressure

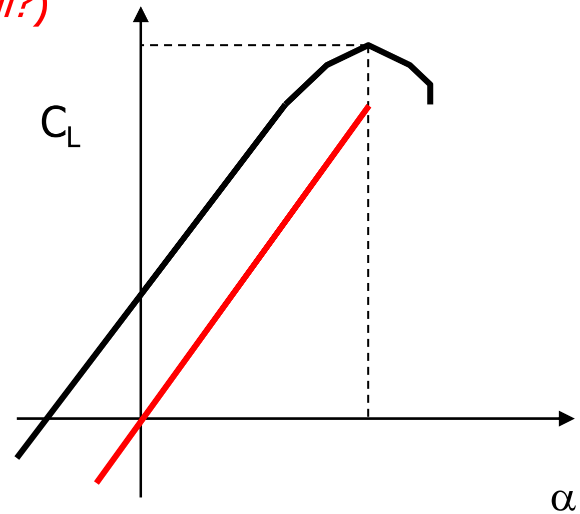
Lift coefficient



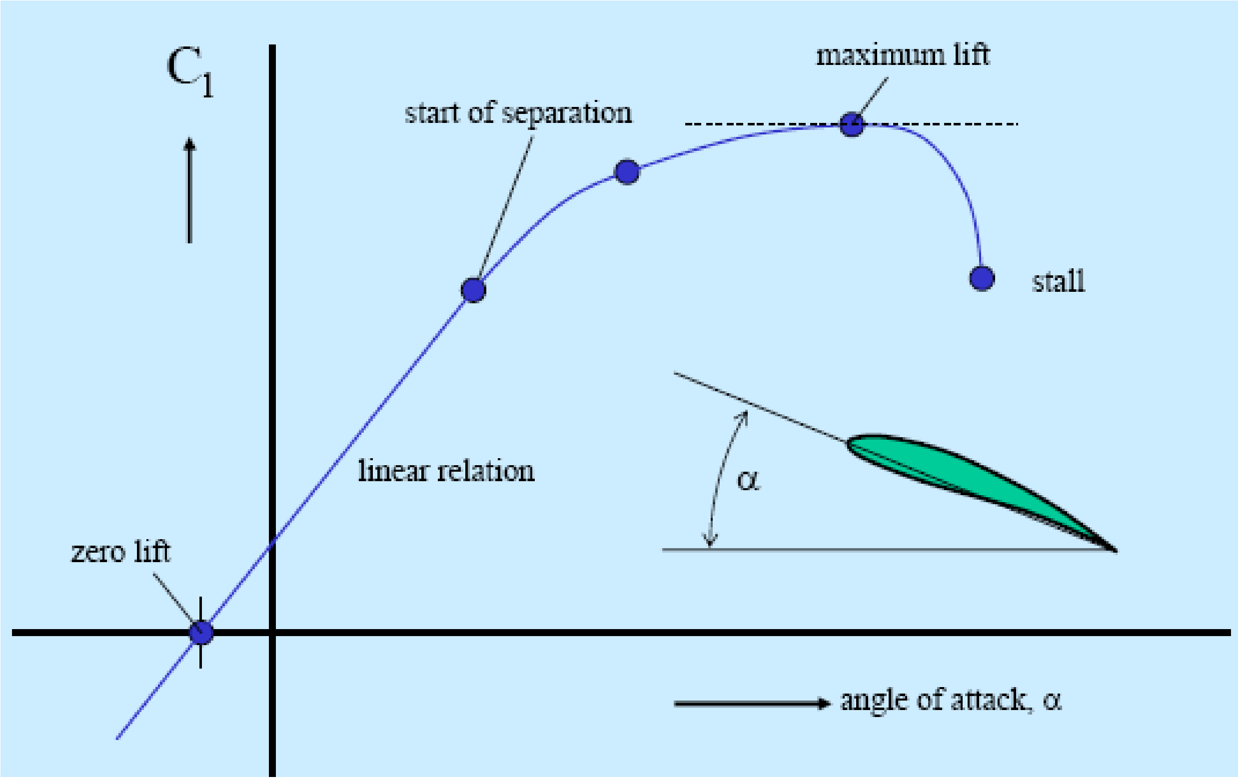
Lift coefficient depends on:

- **<u>Airfoil</u>** - NACA description ABCC – e.g. NACA 0012 and NACA 2412
- **<u>Angle of attack</u>** (*which curve for symmetrical airfoil?*)
- **<u>Wing features</u>**: size, width, angles, etc.

Coefficient has a maximum (separation of air flow)



Lift - C_L-α curve

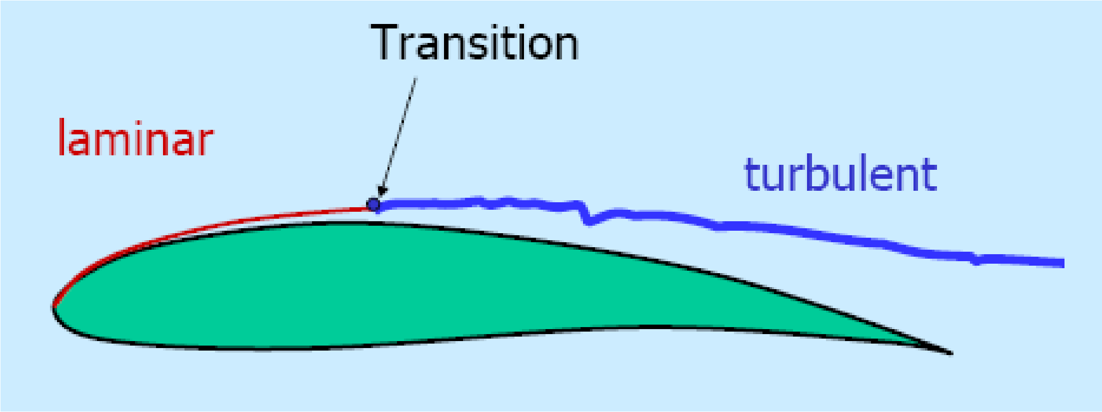


Lift - Airflow

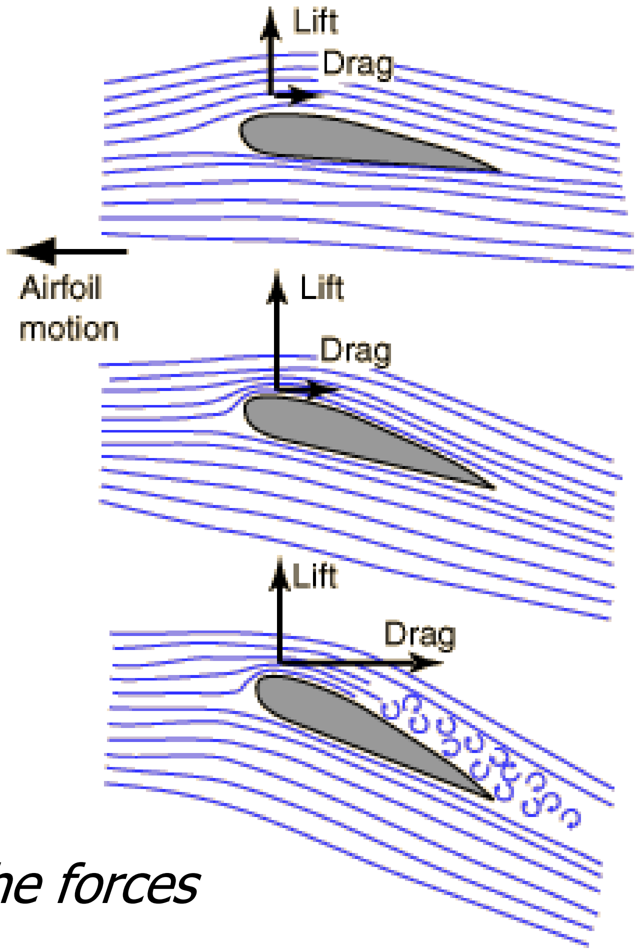
Laminar Boundary layer: thin, low friction

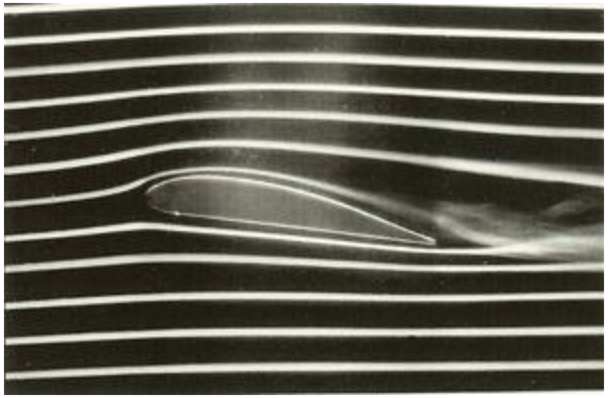
Turbulent Boundary layer: thick, high friction

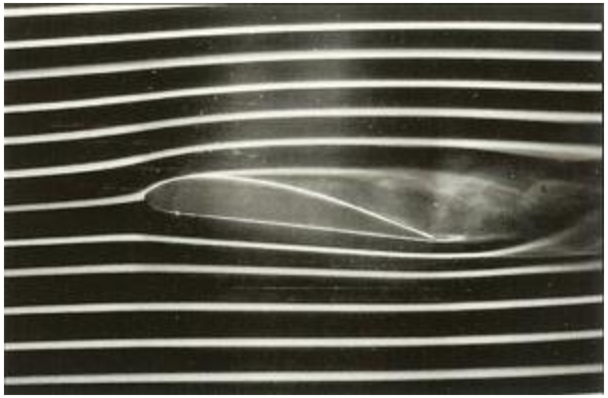
Stall: high friction but no lift.



Lift - Airflow







Note the forces

Lift

What to do if we would like to fly at low air speeds (take-off and landing)? Tip: think about the formula for the lift.

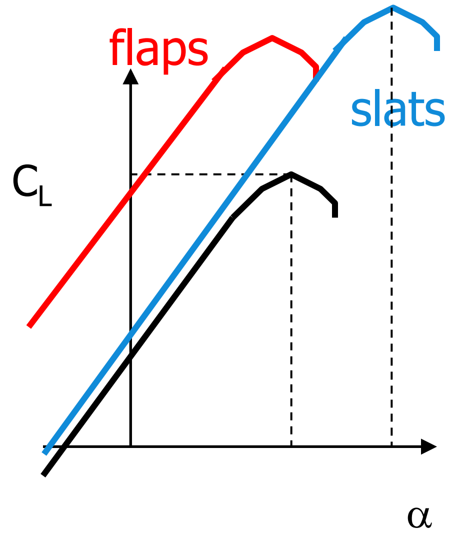
The weight of the aircraft W does not change
And remember $L = W = C_L \times (\frac{1}{2}\rho V^2) \times S$

If V decreases; to maintain the same L,
- *S and C_L should increase*
- *devices to increase both (flaps and slats)*

Lift increasing devices

Purpose:

Able to fly at low airspeeds

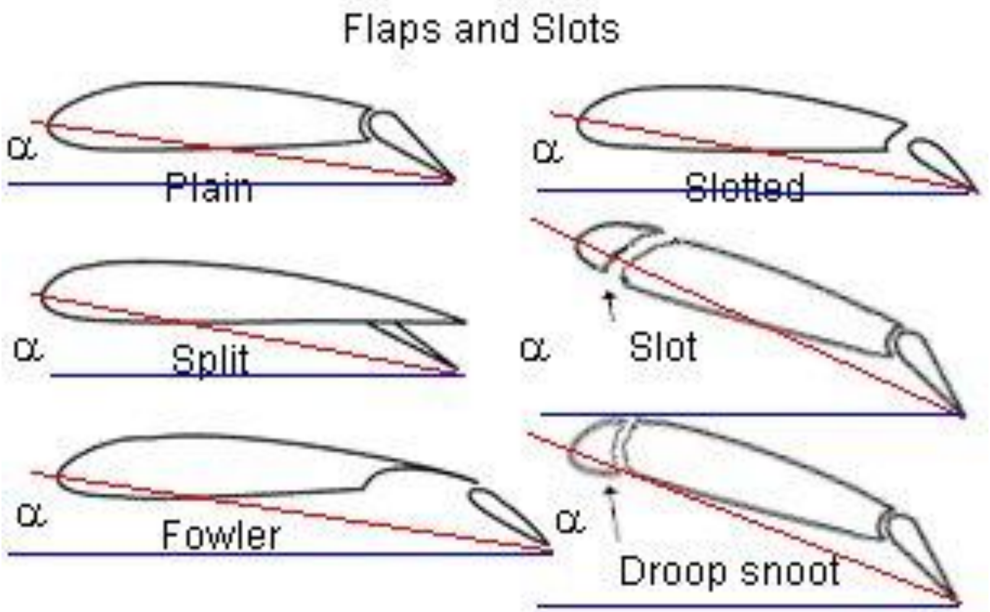


By:

Increasing critical α

Increasing maximum $C_{\mathbf{Lmax}}$

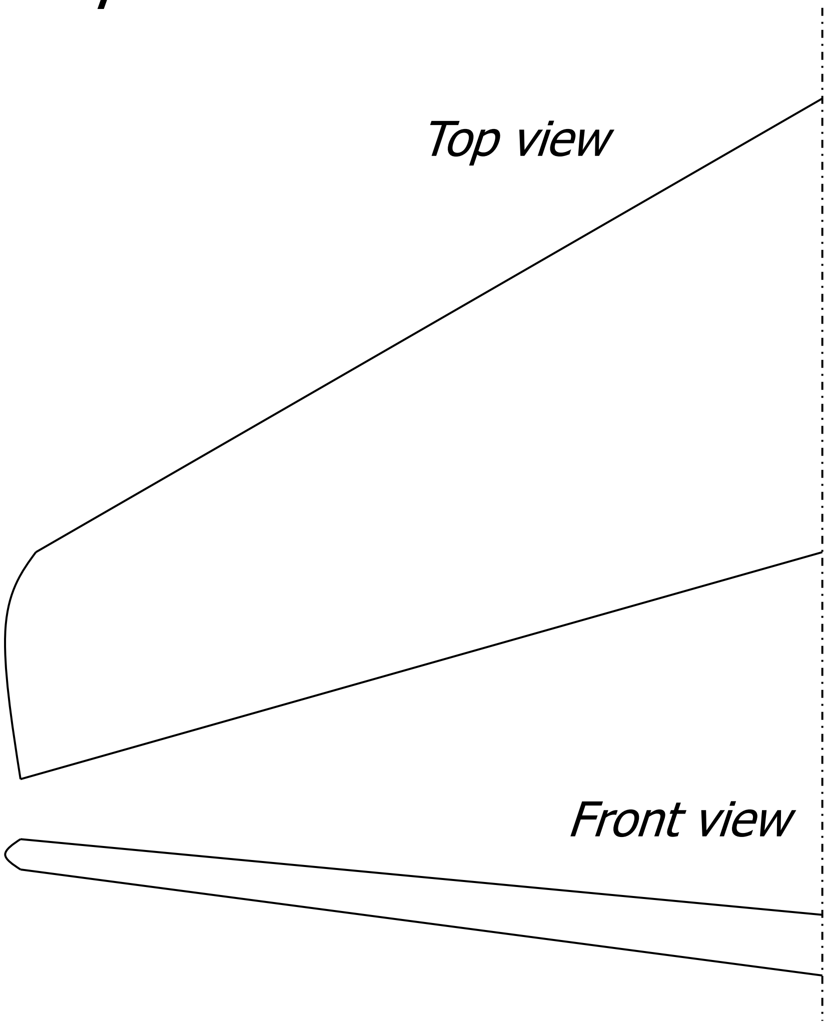
Increasing wing Area S



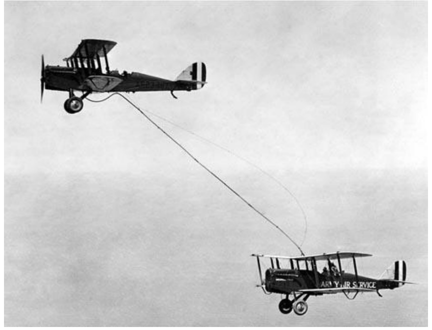
Lift - Wing surfaces/areas

Many different wings possible:

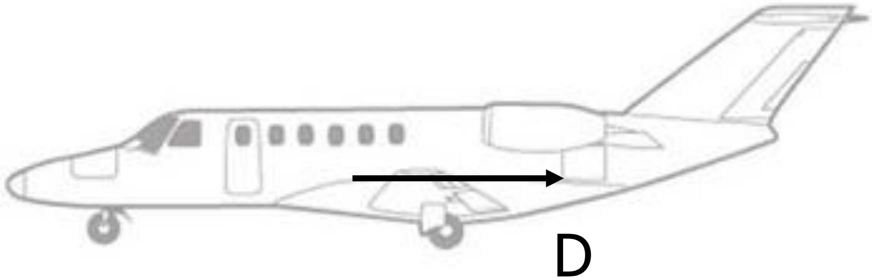
- Wing span
- Wing surface
- Taper
- Sweep angle
- Dihedral
- Chord (root & tip)
- Winglet



Lift - Wings - examples



Drag



$D = C_D \times (\frac{1}{2}\rho V^2) \times S$

C_D (Drag coefficient) consists of:

- profile drag (result of pressure & friction forces)
- parasitic drag

ρ (air density) depends on:

- altitude (see previous lecture on atmosphere)

V (air speed) and S (wing area) are design parameters

Drag origins

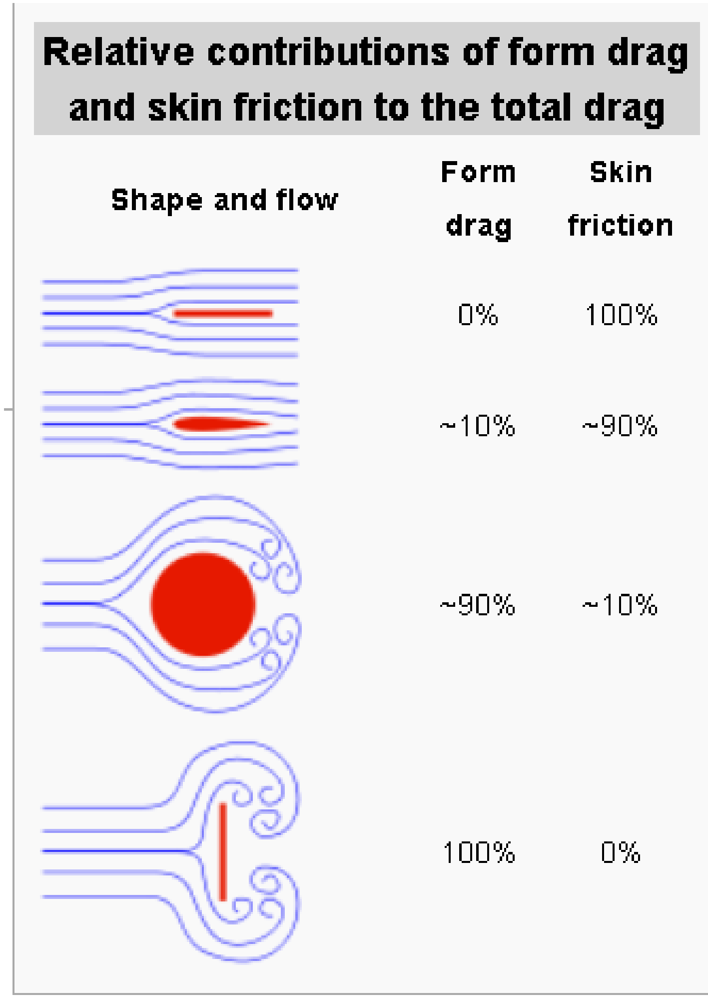
- Skin friction drag
- Pressure drag
- Wave drag (at transonic & supersonic speeds)
- Parasitic drag (no-lift devices like fuselage, engines, etc.)

Drag: $$C_D = C_{D_0} + C_{D_i}$$ *i → Induced drag*

$$C_D = C_{D_0} + \frac{{C_L}^2}{\pi e A R}$$

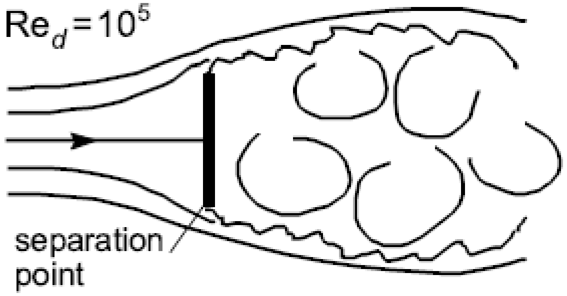
2D drag

- Low speeds: two types of drag
  - friction drag and
  - pressure (form) drag
- Drag coefficent (per 1 meter span)
  c_d

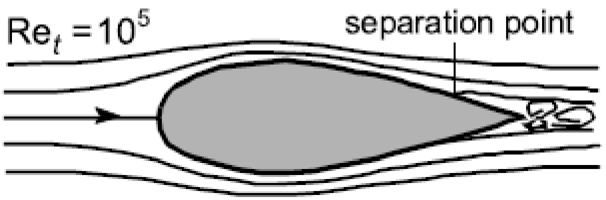


Two dimensional shape & drag:

Note: Now c_d relative to frontal surface (b x d iso b x c) !



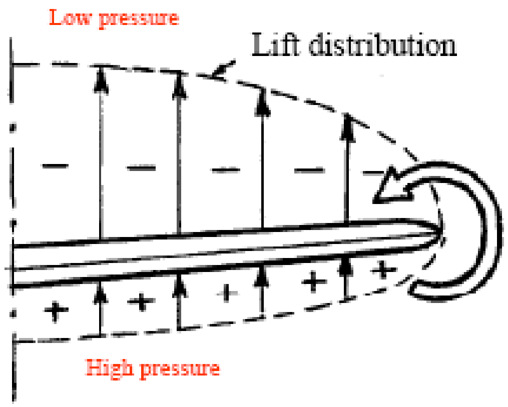
(a) flat plate (height d): $C_D = 2.0$

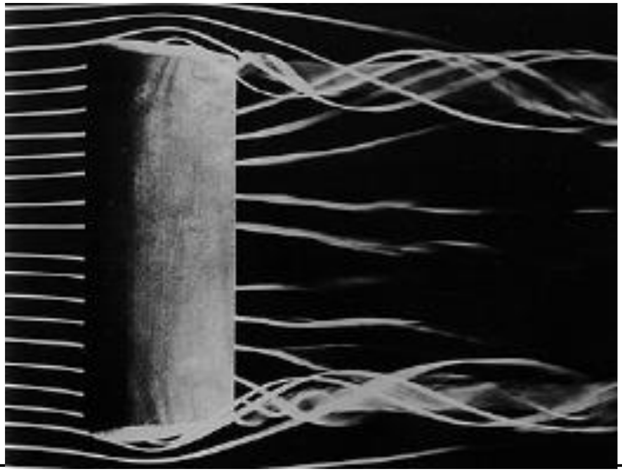


(e) streamline section (thickness t): $C_D = 0.12$

Why 2D & 3D different?
Finite wings

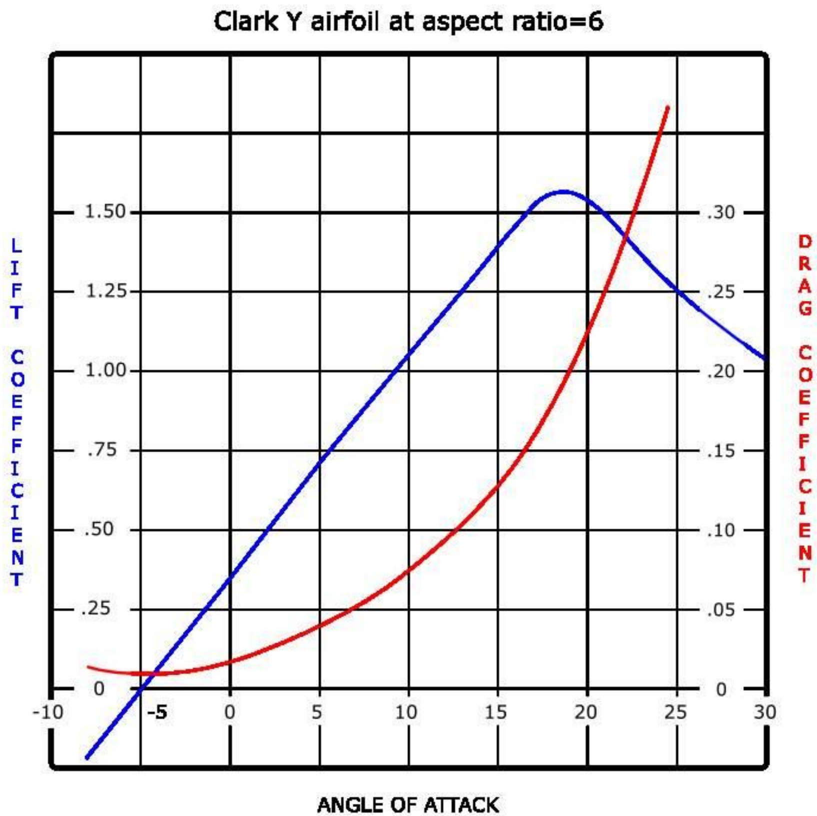
Drag by vortices - Caused by pressure differences over the wing

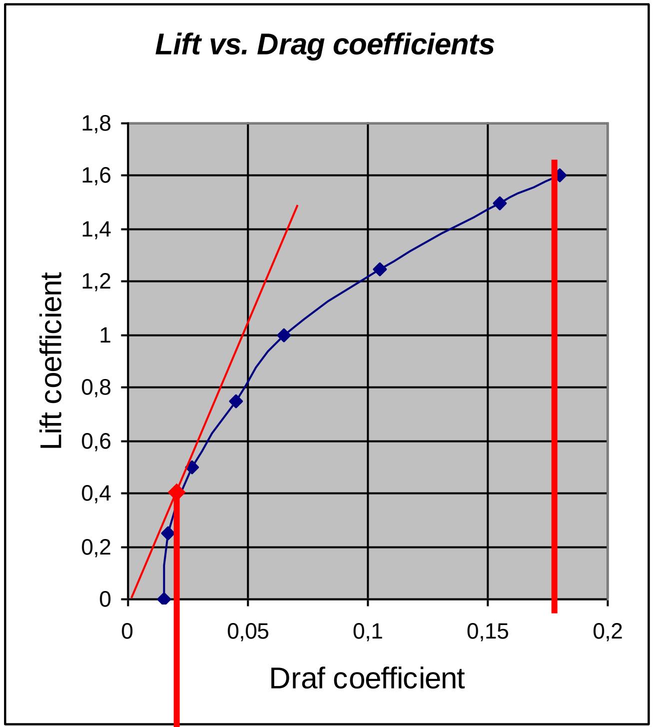




Note: winglets reduce fuel consumption

Drag: Lift-Drag polar





Maximum C_L/C_D - ratio

Look at scales!

Drag: Lift-Drag polar

Why is the maximum C_L/C_D ratio important?

This value indicates the minimum Drag at a specific Lift.
If possible, an aircraft should fly (as much as possible) with this C_L/C_D ratio – low fuel consumption

C_L/C_D ratio is an important design parameter.

Drag – Glide ratio

L/D ratio = C_L/C_D ratio (glide ratio)

Some typical numbers:

Modern sail plane

<u>Lockheed U2</u>

Albatross

B-747

Concorde (cruise)

Cessna

<u>Concorde (take-off)</u>

House sparrow

Space shuttle (hypersonic flight) 1

?

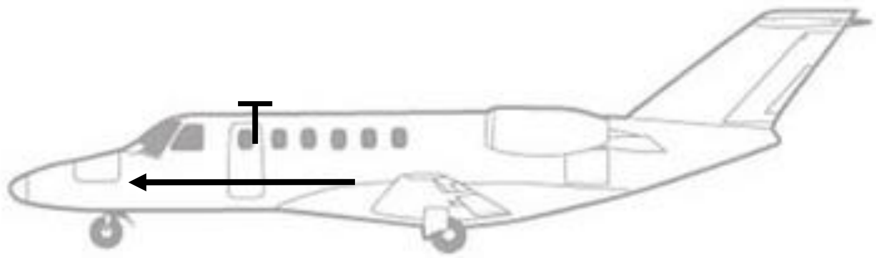
Drag – Glide ratio

L/D ratio = C_L/C_D ratio (glide ratio)

Some typical numbers:

Modern sail plane	± 60
<u>Lockheed U2</u>	28
Albatross	*20*
B-747	17
Concorde (cruise)	7.1
Cessna	7
<u>Concorde (take-off)</u>	4.35
House sparrow	*4*
Space shuttle (hypersonic flight)	1

Thrust

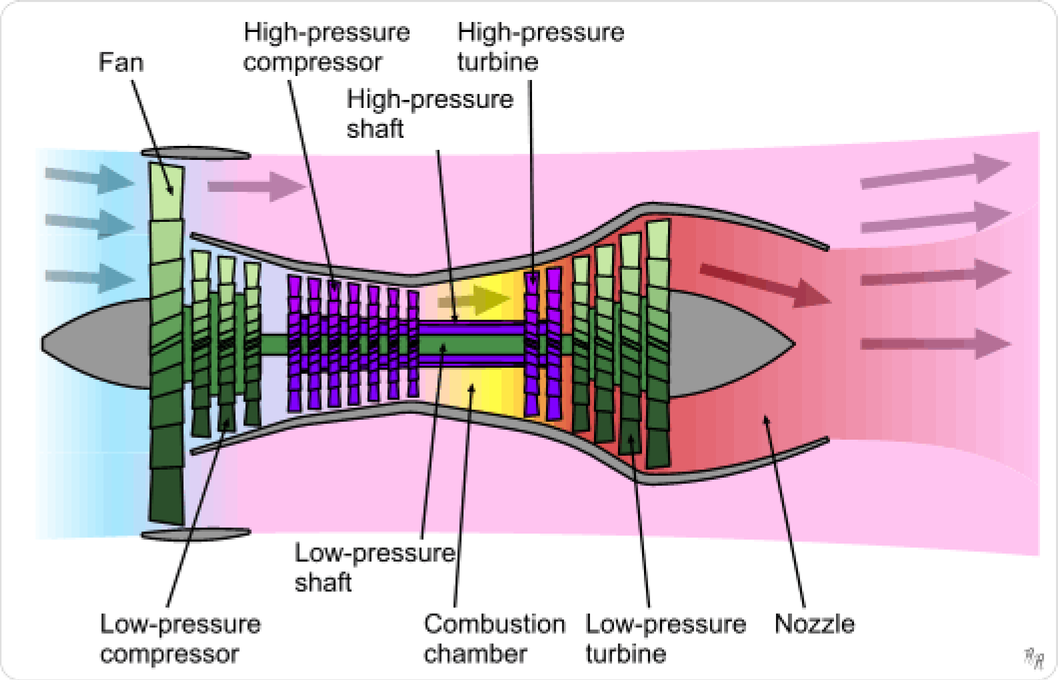


Maintains constant speed

T = D

Engine types:

- Propeller engine
  - Piston engine
  - Turboprop engine
- Jet engine
  - Turbojet
  - ***Turbofan***
  - Ramjet



Trust

For straight, steady, horizontal flight

$$T = D$$

But : *Why do we fly at high altitude?*

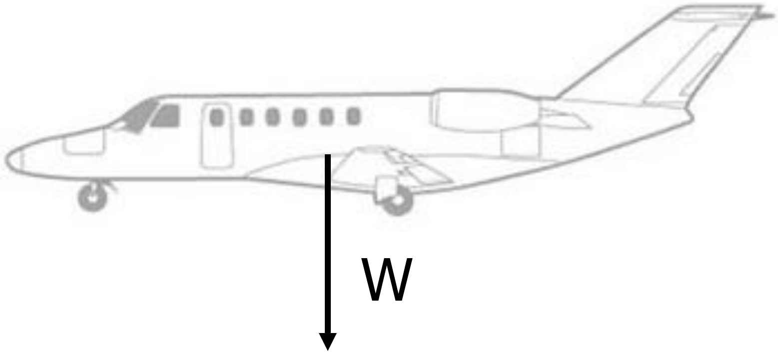
$$D = C_D \times (½\, \rho V^2) \times S$$

Fly at optimum glide ratio – C_D more or less fixed; Wing area (S) is constant

Only variables are density and air speed – 4 options

- *V and ρ are low; not sufficient Lift*
- *V = low; ρ = high; fly at low altitude; low speed (general aviation)*
- *V = high; ρ = low; high speed and high altitude*
- *V= high and ρ= high; high speed at low altitude; very fuel inefficient*

Weight



- Aircraft Empty Weight
  - Structure: Wing - Horizontal Tail - Vertical Tail – Fuselage - Landing Gear - Surface Controls - Propulsion System – APU
  - Systems: Instruments and Navigation - Hydraulics and Pneumatics - Electrical System – Electronics – Furnishings - Air Conditioning and Anti-Ice
  - Crew and Flight Attendants
  - Operating Items
- Payload
- Fuel

→ One should **minimize** the ***weight of aircraft structures & systems***, and ***Fuel***, in order to **maximize** ***Payload***

Weight examples

A320	Passengers	180
	MTOW	73.5 tonnes
	OEW	42.4
	Max. Fuel	19.2
	Payload	± 16
B747-400	Passengers	416-524
	MTOW	397 tonnes
	OEW	178
	Max Fuel	173
	Payload	± 65

Weight

Weight reduction with constant Maximum Take Off Weight

- More fuel – longer distance
- More passengers or cargo – more revenues
- Combination

If we decide not to increase the payload or the amount of fuel, we can create a “snowball-effect” (ultimate weight reduction is (much) larger than the original/starting weight reduction).

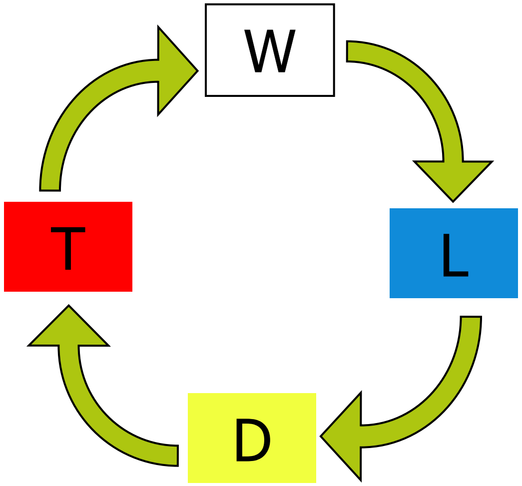
Can you explain the “snowball-effect”?

Answer – “snowball effect”

- Reducing the weight of e.g. structures, systems, etc., result in lower overall weight of the aircraft
  → Which results in less required LIFT
  → Which results in a smaller wing
  → This reduces the DRAG
  → And therefore the THRUST can be reduced (smaller engines)

Both the smaller wing and the smaller engines will result in less weight and the cycle can start again!!

It is assumed that ***<u>the weight for fuel and payload doesn’t change</u>***



Summary

- ✓ Flying in Heavier than Air vehicles is a very young discipline
- ✓ In a steady horizontal flight we can discover 4 forces

  Weight, Lift, Thrust and Drag

- ✓ Lift is generated by the airflow and created by pressure differences over the airfoil
- ✓ The Bernoulli law is important in order to understand How to fly.

  $(p + \frac{1}{2}\rho V^2 = constant)$

- ✓ Lift is $L = C_L . \frac{1}{2}\rho V^2 .S$; Drag $= C_D . \frac{1}{2}\rho V^2 .S$

- ✓ Weight consist of: empty weight + fuel + payload
- ✓ By reducing empty weight, the fuel and/or payload may increase