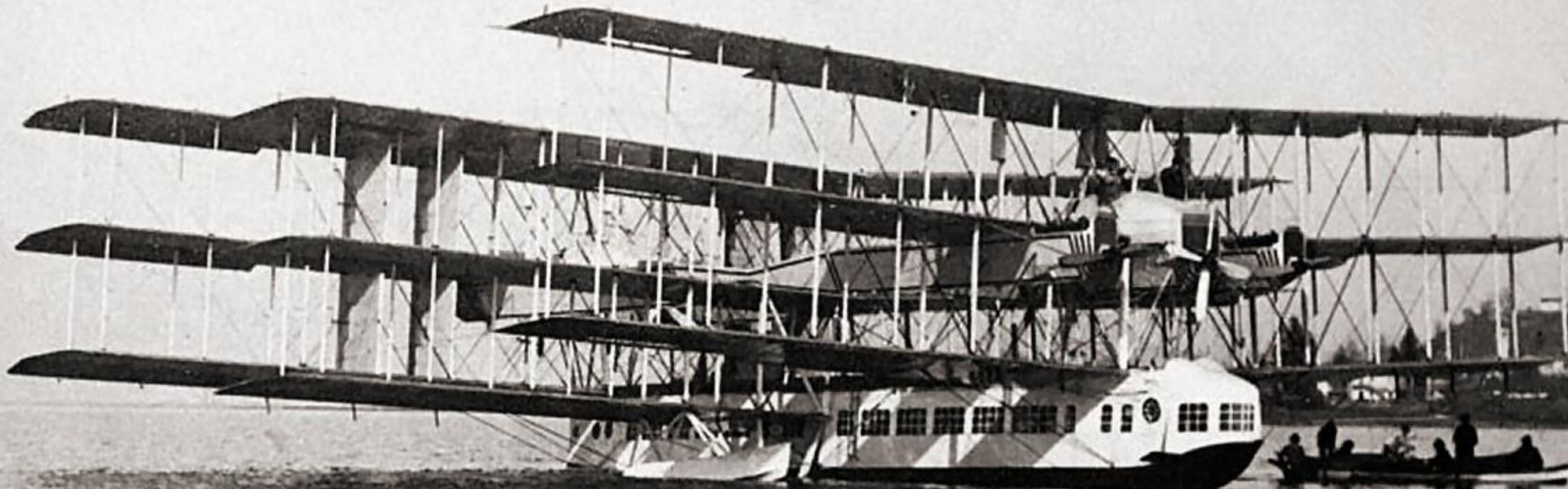
Aeronautics & Mechanics
AENG11301
Lecture 4: Drag



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Outline for today

- *Sources* of drag
- *Types* of drag
- Dodo birds?!

Aims for today

- Define the different classifications of sources of drag
- Calculate induced drag for a finite wing

Where Does Drag Come From?

- Two underlying *sources* of drag:

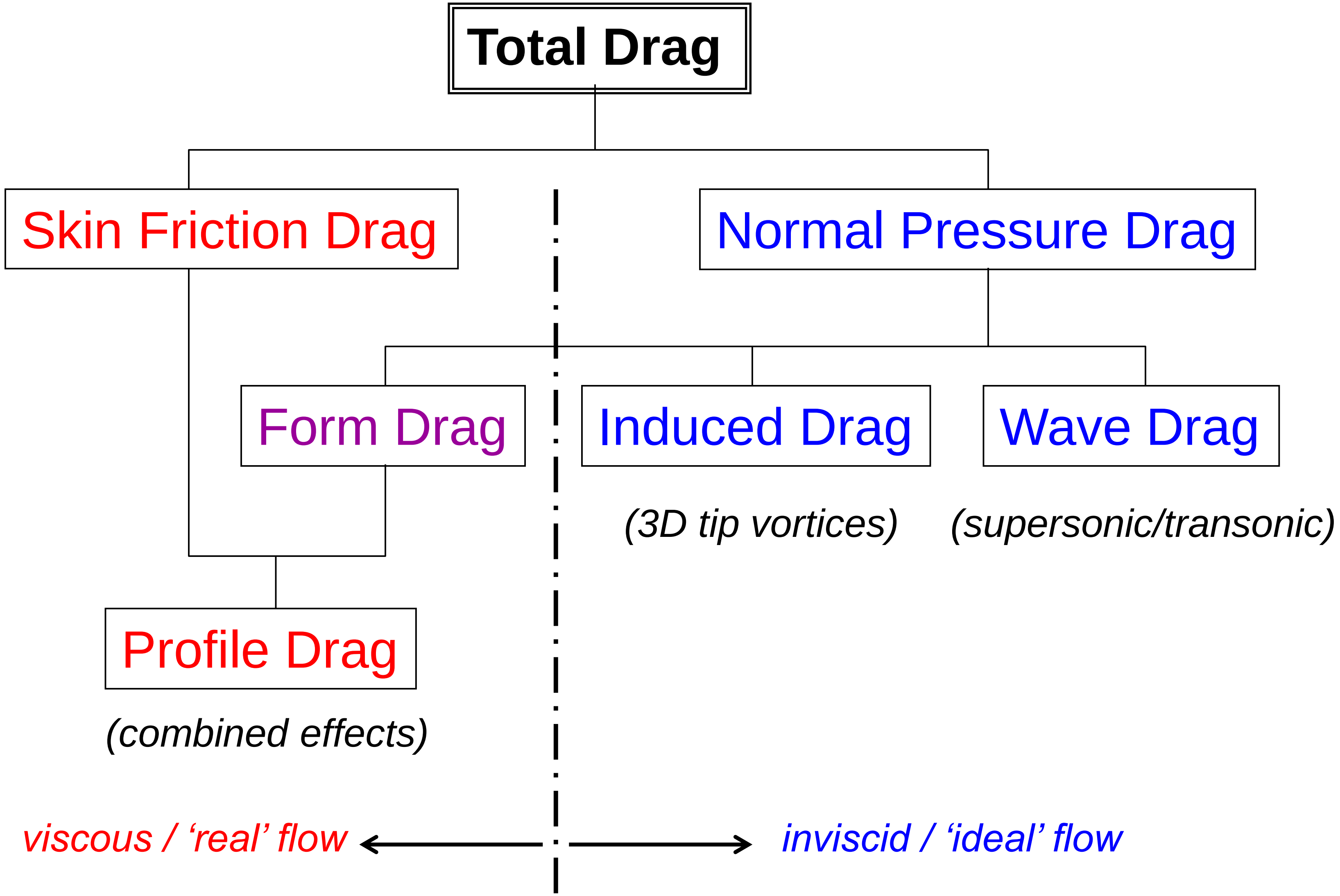
1. **skin friction drag**
   - or **surface friction drag**
   - streamwise component of **tangential stresses** acting at the surface
   - a direct result of the fluid viscosity
2. **pressure drag**
   - streamwise component of pressure forces acting **normal** to the surface

   a) **form drag** due to **boundary layer** growth

   b) **induced drag** due to formation of trailing vortex system at wing tips

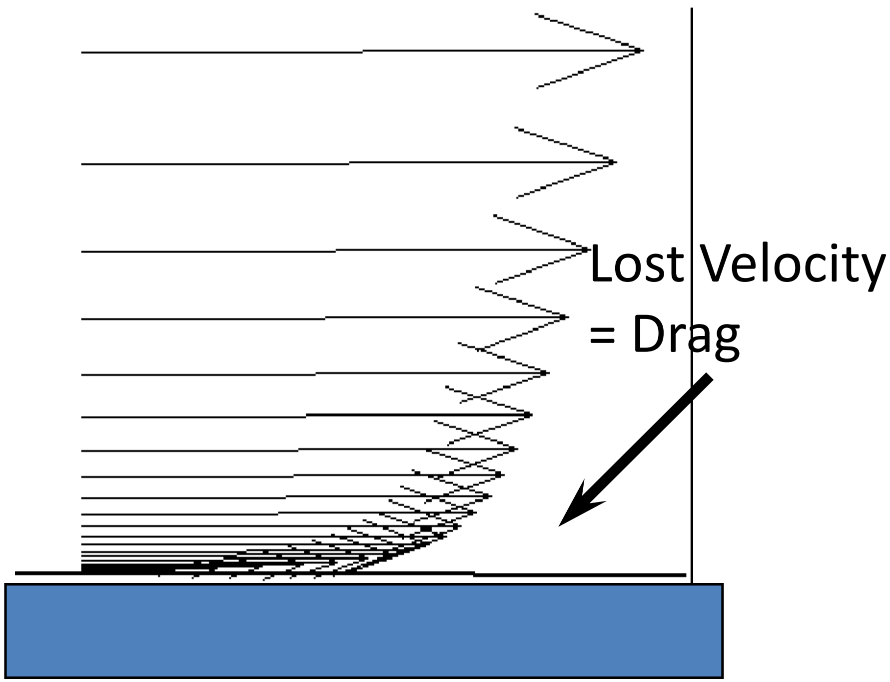
   c) **wave drag** due to shock formation at high speeds

Drag Breakdown



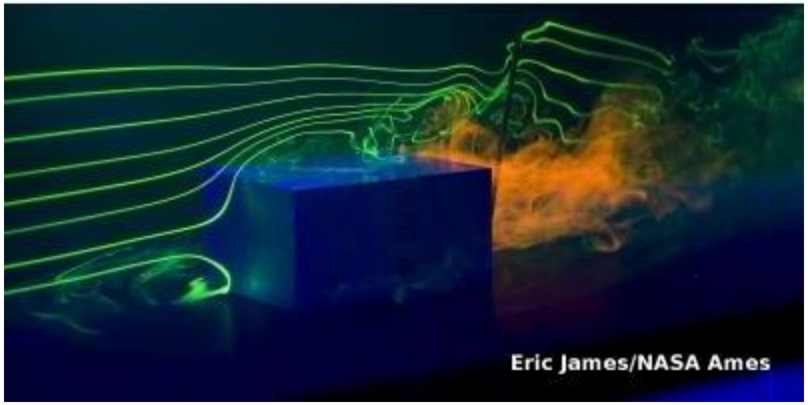
Skin Friction Drag

Aerofoil drags air along with it

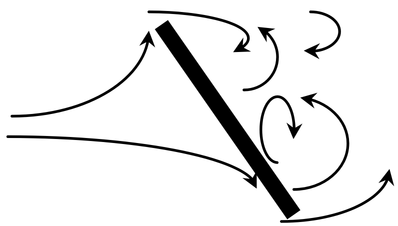


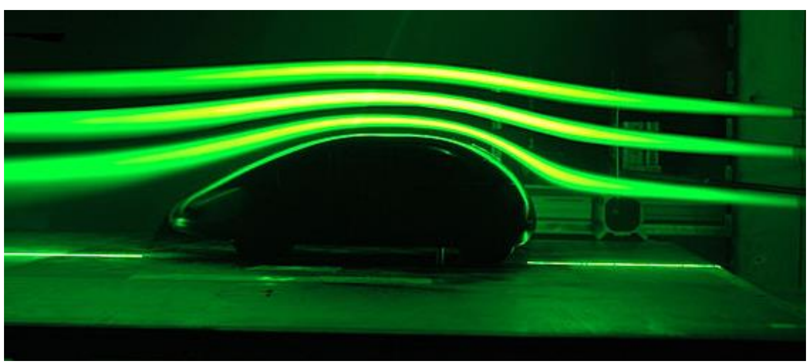
- tangential shear stress on surface opposes aircraft motion
- friction causes flow very close to the surface to slow down, forming a **boundary layer** which grows downstream:
  a) changes effective shape of body by **displacing** flow outwards
  b) leads to **flow separation** and formation of a turbulent **wake**
- friction drag coefficient *reduces* with Reynolds Number
- greater for **turbulent** flow (compared to **laminar** flow)

Form Drag

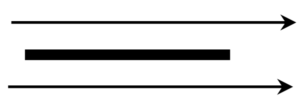


High Form Drag





Low Form Drag

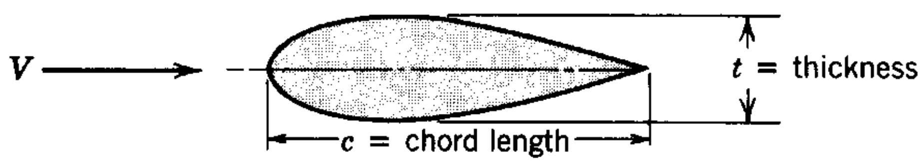


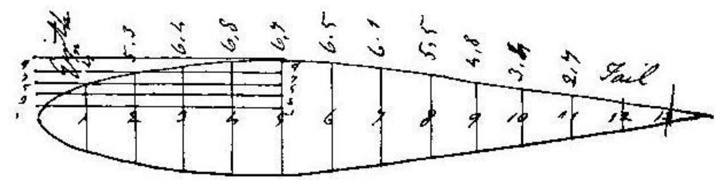
- Front-to-rear asymmetry in surface pressure distribution generates **form drag**
- Sometimes referred to as "pressure drag"
- Form drag coefficient *increases* with increasing wake size
- Form drag is the most intuitive drag

Profile Drag = Skin Friction Drag + Form Drag

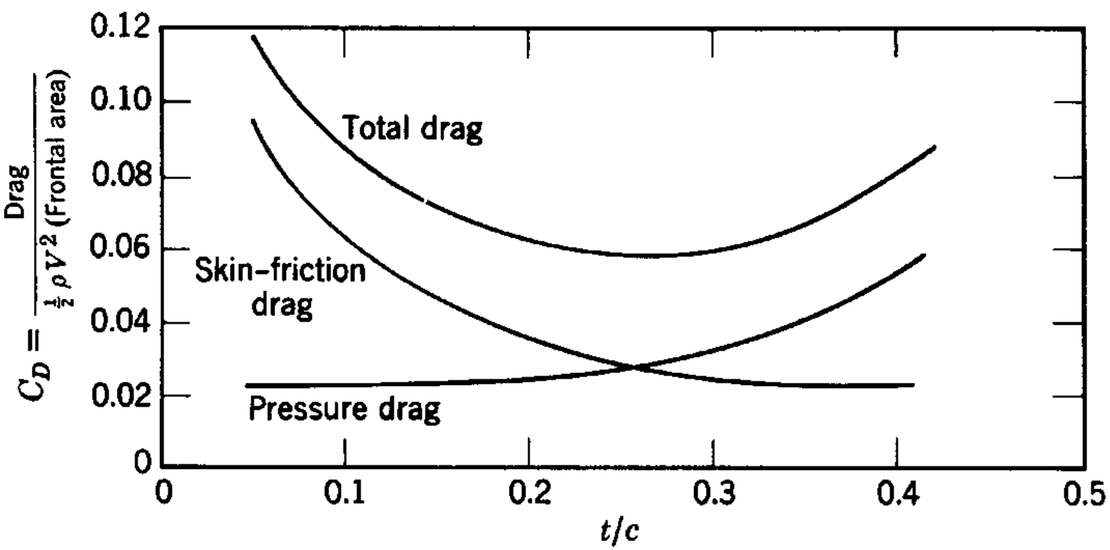
- low form drag and low skin friction drag tend not to go together
  - form drag can be reduced by fairing off **aft** part of a body
  - but this increases surface area and hence skin friction drag
- minimum profile drag is often a compromise

(profile drag is also sometimes called **Parasitic Drag**)





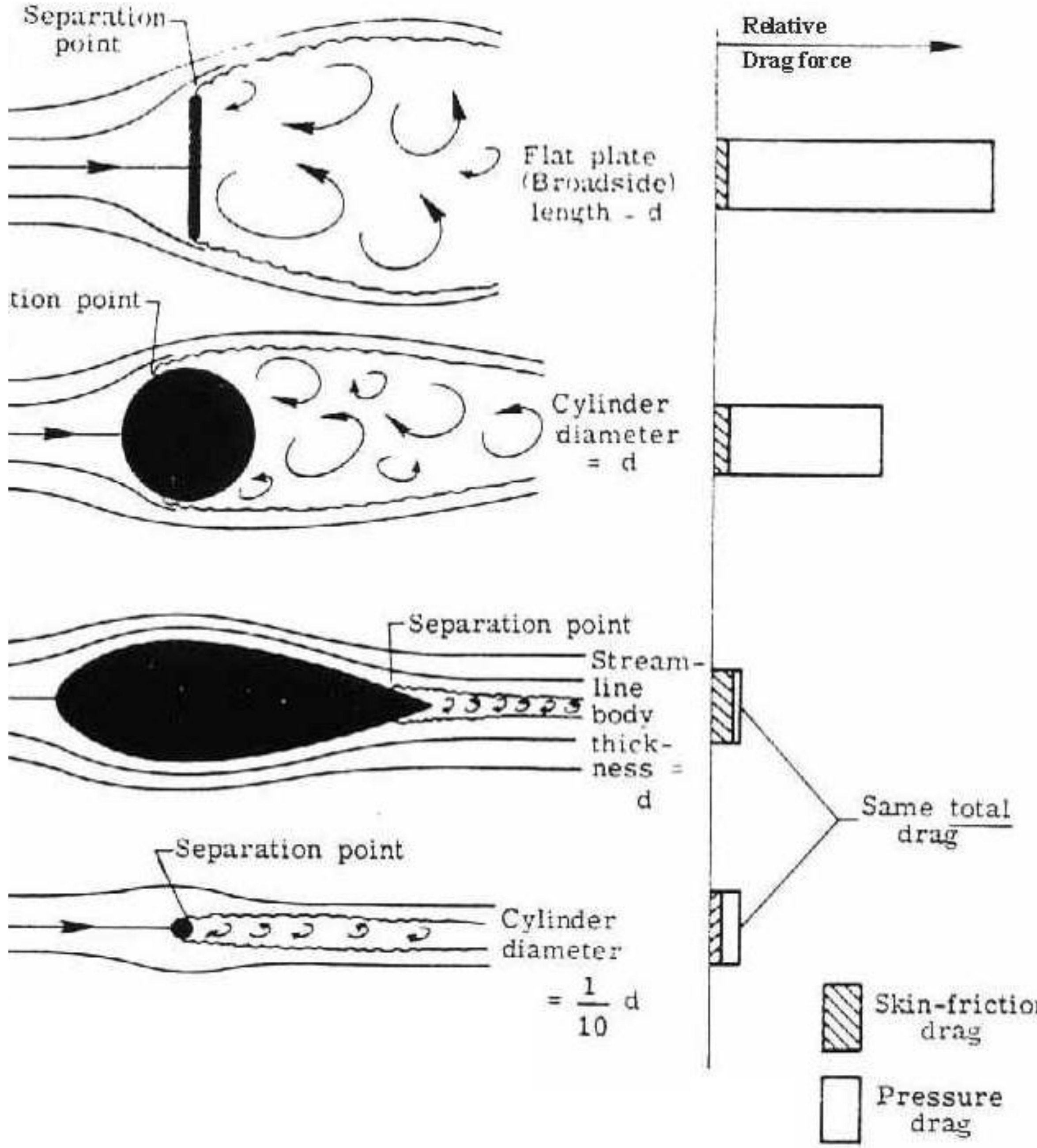
Sir George Cayley's 'minimum drag' shape based on a trout (1810?)



What a legend

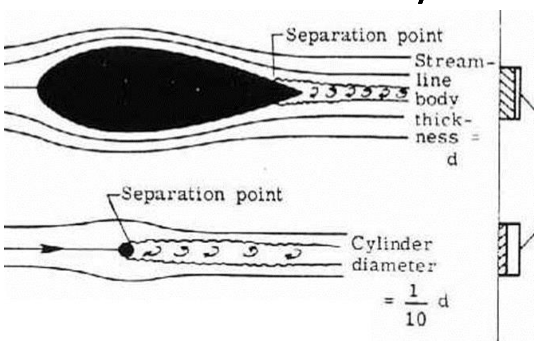
Profile Drag

Bluff body drag can be very high - even simple 'boat-tail' fairing gives a large reduction in drag



Historical Note: Why biplanes went the way of the dodo

- Before WWI people thought “aerodynamic” meant “thin”
- Wings were thin so structure had to be external:
  - Two spaced wings held together with struts and bracing wires
  - Wing acts like a truss, which is efficient structurally but…



Wires have terrible drag!

Estimates of wire drag and power:

	V	Wire length	Drag Power	Engine Power	% Power
Spad XIII	125	272	62	220	28
Staggerwing B-17	180	132	89	450	20
Breguet 14	114	220	38	300	13
Stearman PT-17	104	148	19	220	9

http://forums.x-plane.org/index.php?/forums/topic/57371-wire-drag-on-biplanes/

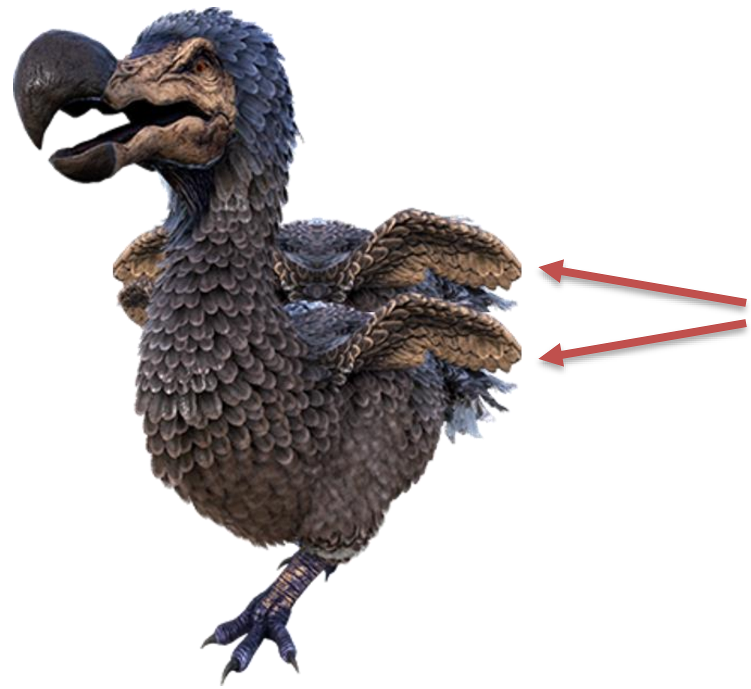
Sopwith Camel

Fokker D.VII: thicker airfoil allows stiffer wing = struts, but no wires + better stall behavior!

But two wings is still less efficient than one…

Thought experiment

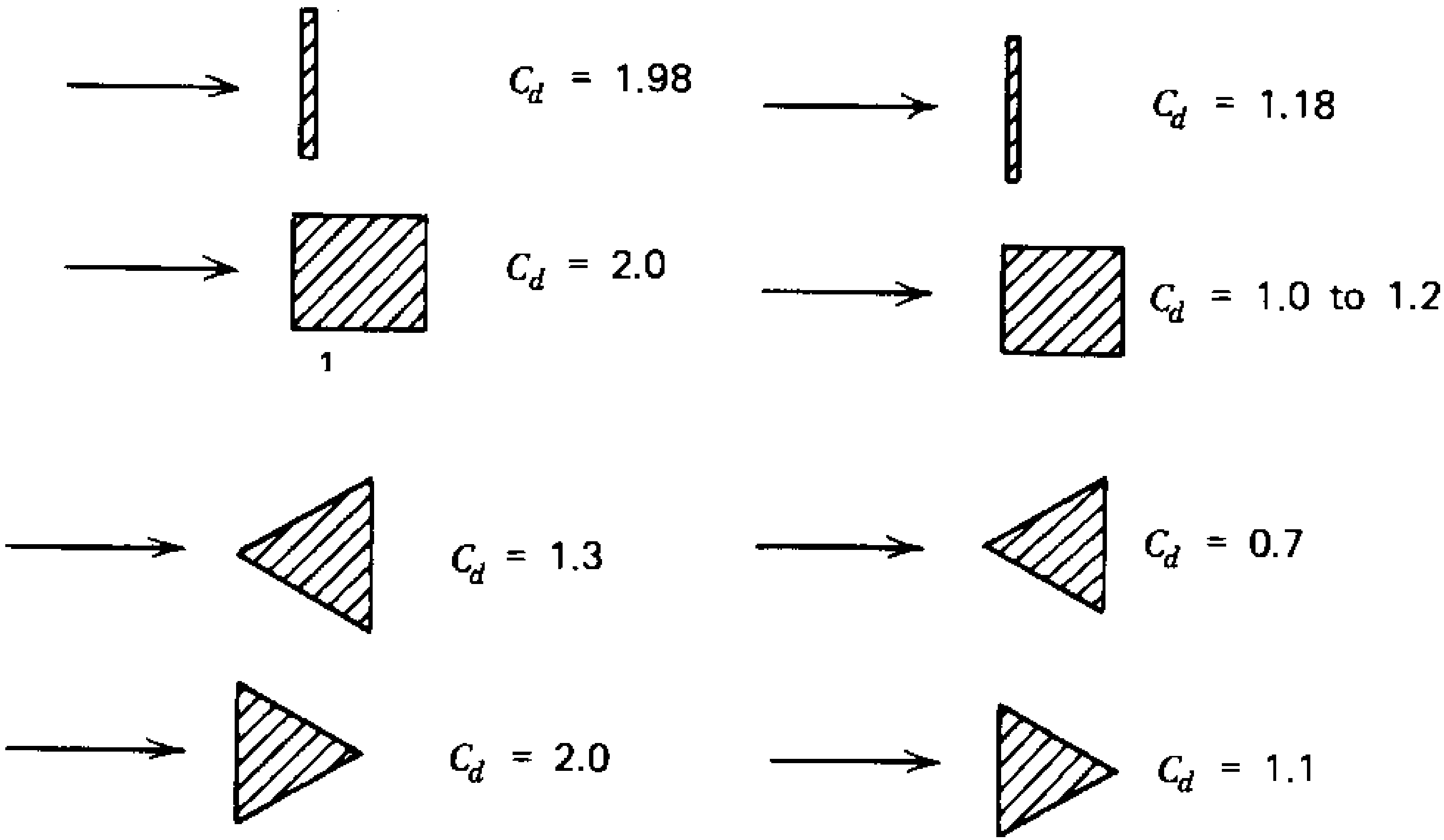
So we’ve seen some reasons why biplanes have for the most part gone the way of the dodo…



Woah

But what if the dodo had
been a biplane?

3D flow reduces profile drag



2D

3D

Induced Drag

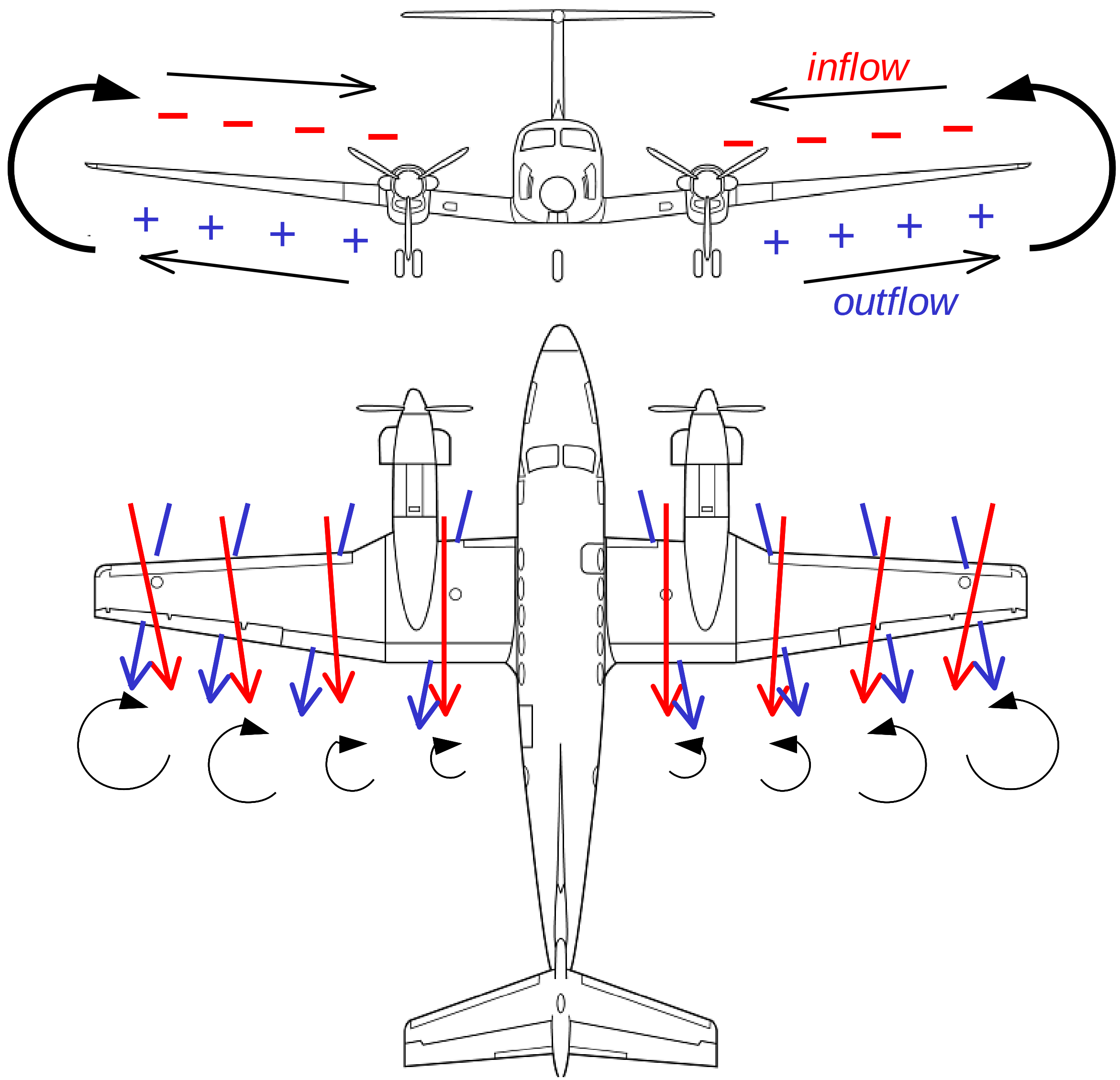
- In 2D flow we only have profile drag
- In 3D flow an additional drag component appears which is proportional to the lift^2
  - **lift-dependent drag** or **lift-induced drag** or **vortex drag**
- The most visible part of the downwash are two counter-rotating vortices from its tips
- vortices have kinetic energy

  rate of change of energy = power

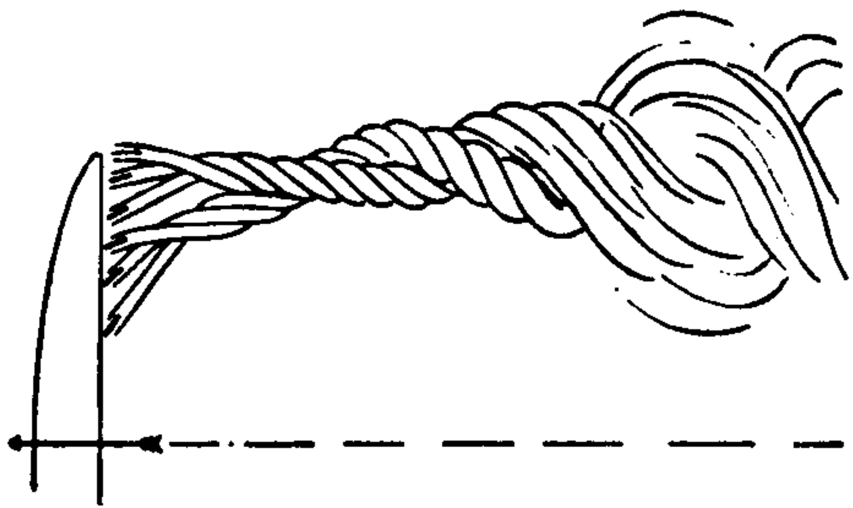
  = force $\times$ velocity $\rightarrow$ drag

Wake Roll-up

- pressure difference between upper & lower surfaces
  - spanwise flow around tips



Tip Vortices Visualised

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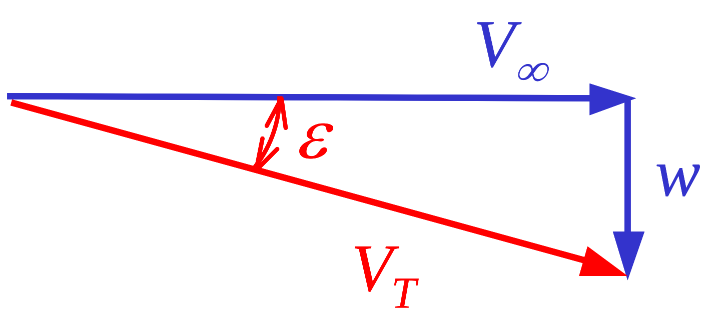
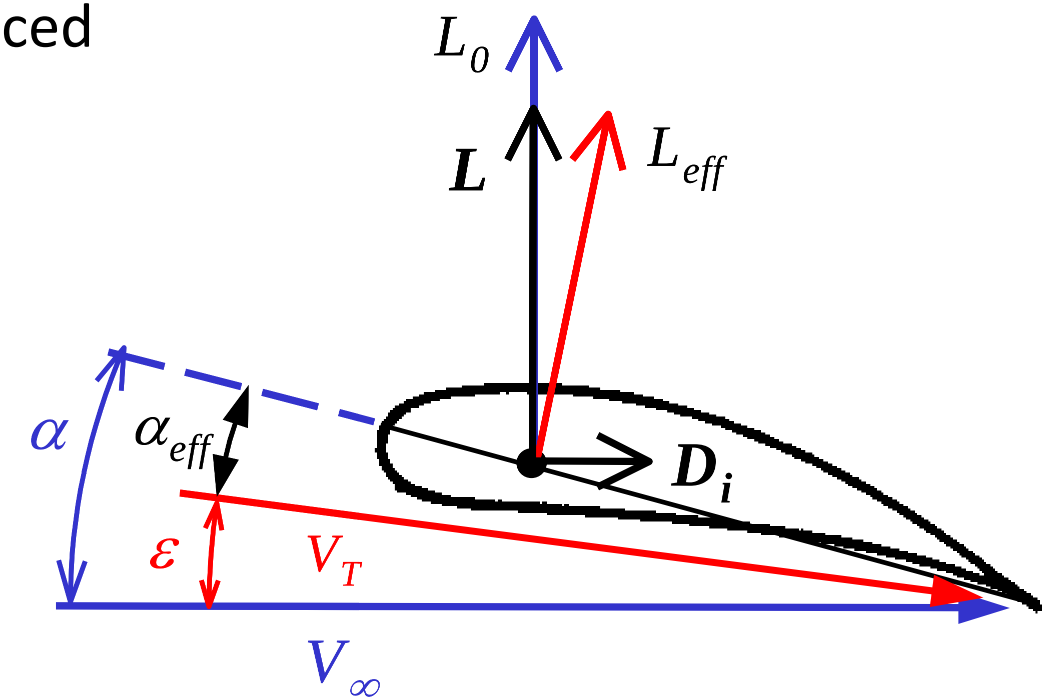
Downwash

- tip vortices induce **downwash** , a downward flow component (w) over the wing span
- rotates local velocity vector downwards by a small angle ε :
  a) reduces incidence to α_{eff} and hence <u>*reduces* lift</u> to L_{eff}
  b) rotates lift vector L_{eff} rearwards by angle ε
- lift vector now has a induced drag component (D_i)





Span efficiency

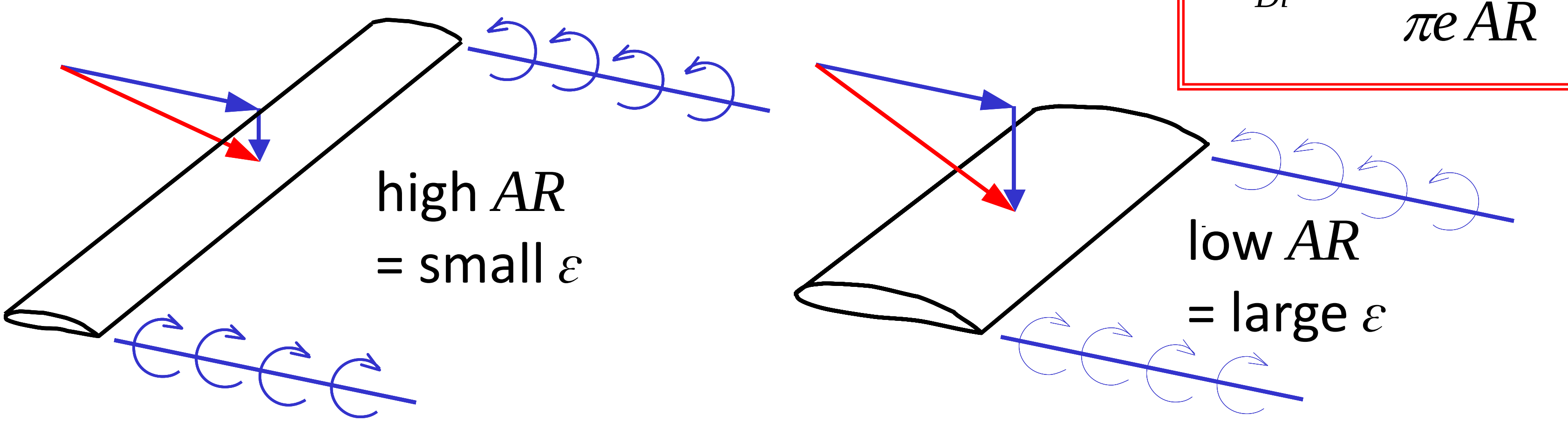
- induced incidence ε is proportional to C_L
  - tip vortex strength related directly to lift

$$D_i = L\sin\varepsilon \approx L\varepsilon \Rightarrow C_{Di} \approx C_L\varepsilon$$

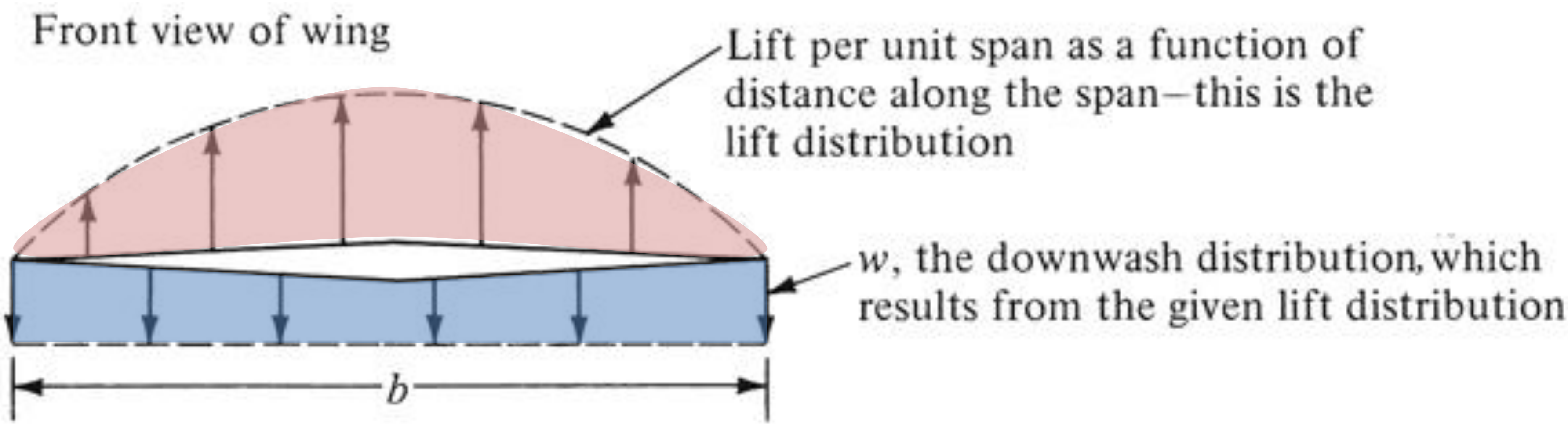
- induced incidence depends on wing **aspect ratio** (AR) $\quad \varepsilon = \dfrac{C_L}{\pi AR}$
  - zero in the limit for a wing of infinite span
  - the closer the tips together the greater the downwash
- **span efficiency factor** $e \leq 1$

  1 = ideal elliptical loading

$$\boxed{C_{Di} = \frac{C_L^2}{\pi e AR}}$$



Lift distribution



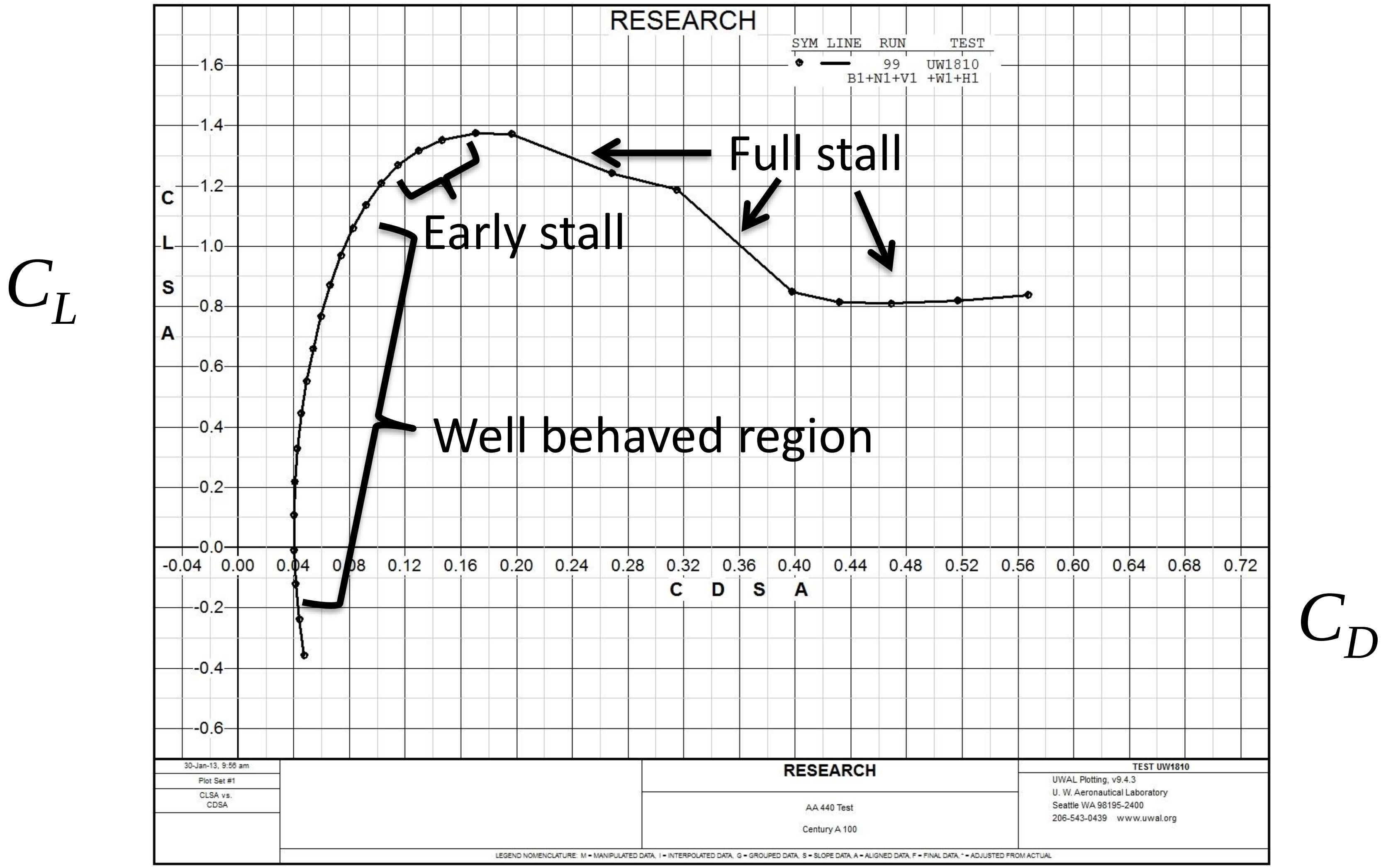
Ideal elliptical loading, e = 1

Lift generation most efficient when the wing has a uniform downwash distribution

- **induced drag factor** (k) used in some texts

$$k = \frac{1}{e} \quad , k \geq 1$$

Drag Polar: C_D vs C_L



"Well behaved" Region

- This looks like $C_D \propto C_L^2$, so, let's say

$$\boxed{C_D = C_{D_0} + K C_L^2}$$

  - C_{D_o} is Profile drag
  - $K\, C_L{}^2$ is induced drag;

K is related to span through Aspect Ratio (AR)

$$\boxed{C_D = C_{D_0} + \frac{C_L^2}{\pi e AR}}$$

e = 1 for the most efficient planar wing, usually < 1

Summary

- The critical Mach number (M_{cr}) is when airflow over any part of the aerofoil reaches the speed of sound
- Skin fiction drag due to viscous shear stress on surface
- Form drag due to front-to-rear pressure asymmetry
- Profile drag = skin friction drag + form drag
- Induced drag due to effect of wing tip vortices on a finite wing

$$\boxed{C_D = C_{D_0} + K C_L^2}$$

$$\boxed{C_{Di} = \frac{C_L^2}{\pi e AR}}$$

$$\boxed{C_D = C_{D_0} + \frac{C_L^2}{\pi e AR}}$$

Follow-up materials

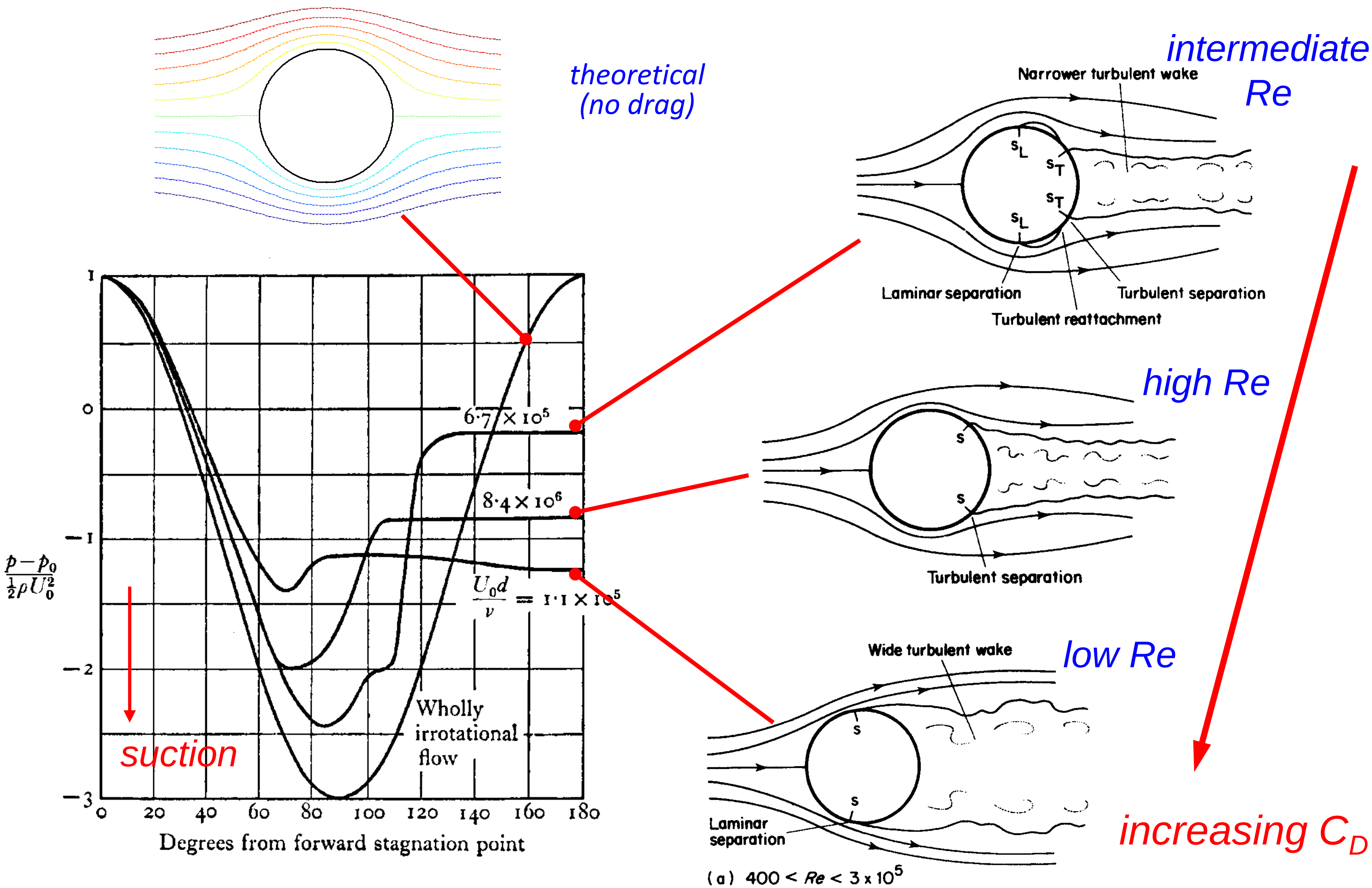
To help with exam:

- Introduction to Flight – 5.12 to 5.14

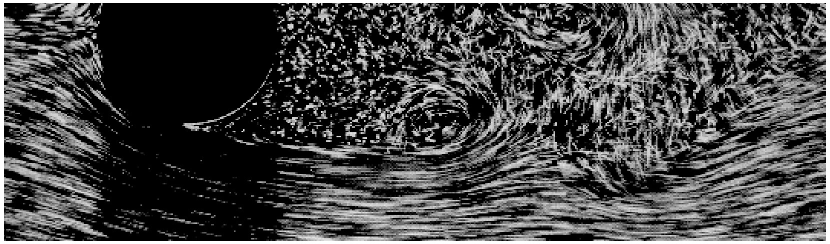
For interest:

- Introduction to Flight – 5.9-5.11 (super sonic effects)

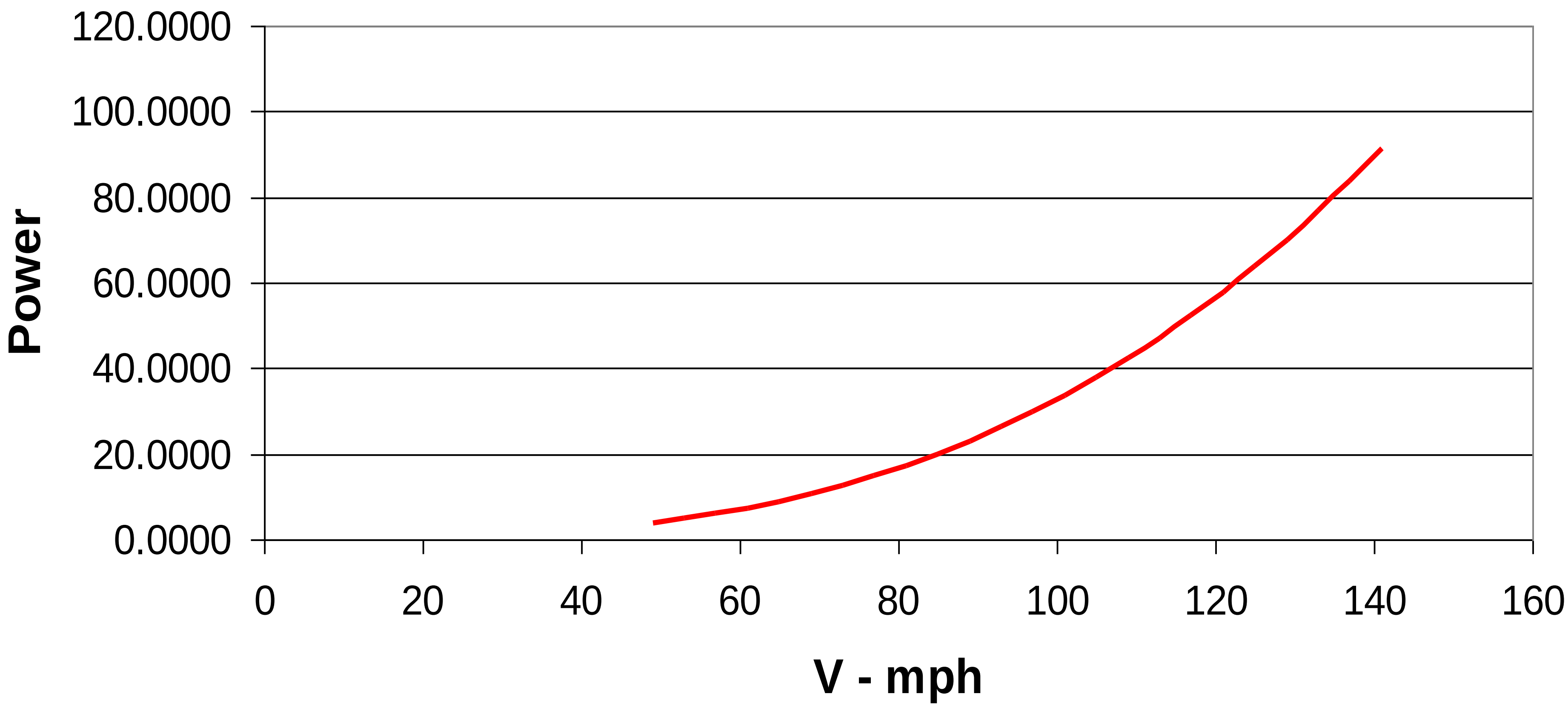
Form Drag on a Cylinder



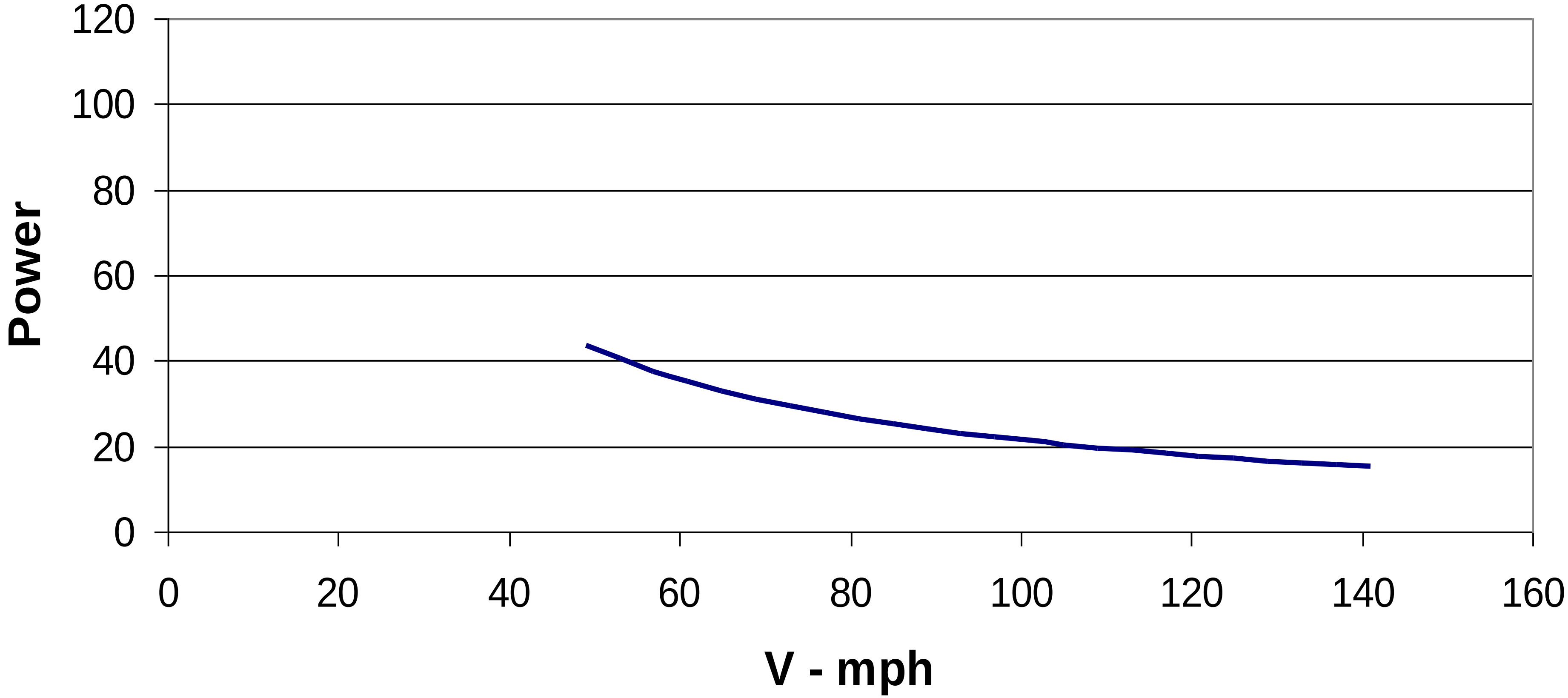
Wake behind sphere



Parasitic (Profile) Power
Cessna 172 “Skyhawk”



Induced Power
Cessna 172 “Skyhawk”



Power Required