Ideas From Classical Aerodynamics

http://www.telegram.com/static/gallery/christo/flight.html
http://www.torben-grael.com/carreira/1999_2000_AmCup/galeria-AmCup/pages/020_LunaRossa_091199.htm
http://www.seriouswheels.com/2005/2005-Chevrolet-Corvette-C6-R-Race-Car-FA-Top-1920x1440.htm

http://www.flug-revue.rotor.com/FRTypen/Fotos/mdhelico/MD530FLR.JPG
http://www.photo.net/photos/ML
http://members.tripod.com/~Stipanovic/Wallpaper14/Dolphin.jpg

Outline

– What we want from aerodynamics

– Basic Ideas from 2-D

– Differences between 2-D and 3-D

– The Importance of Unsteadiness?

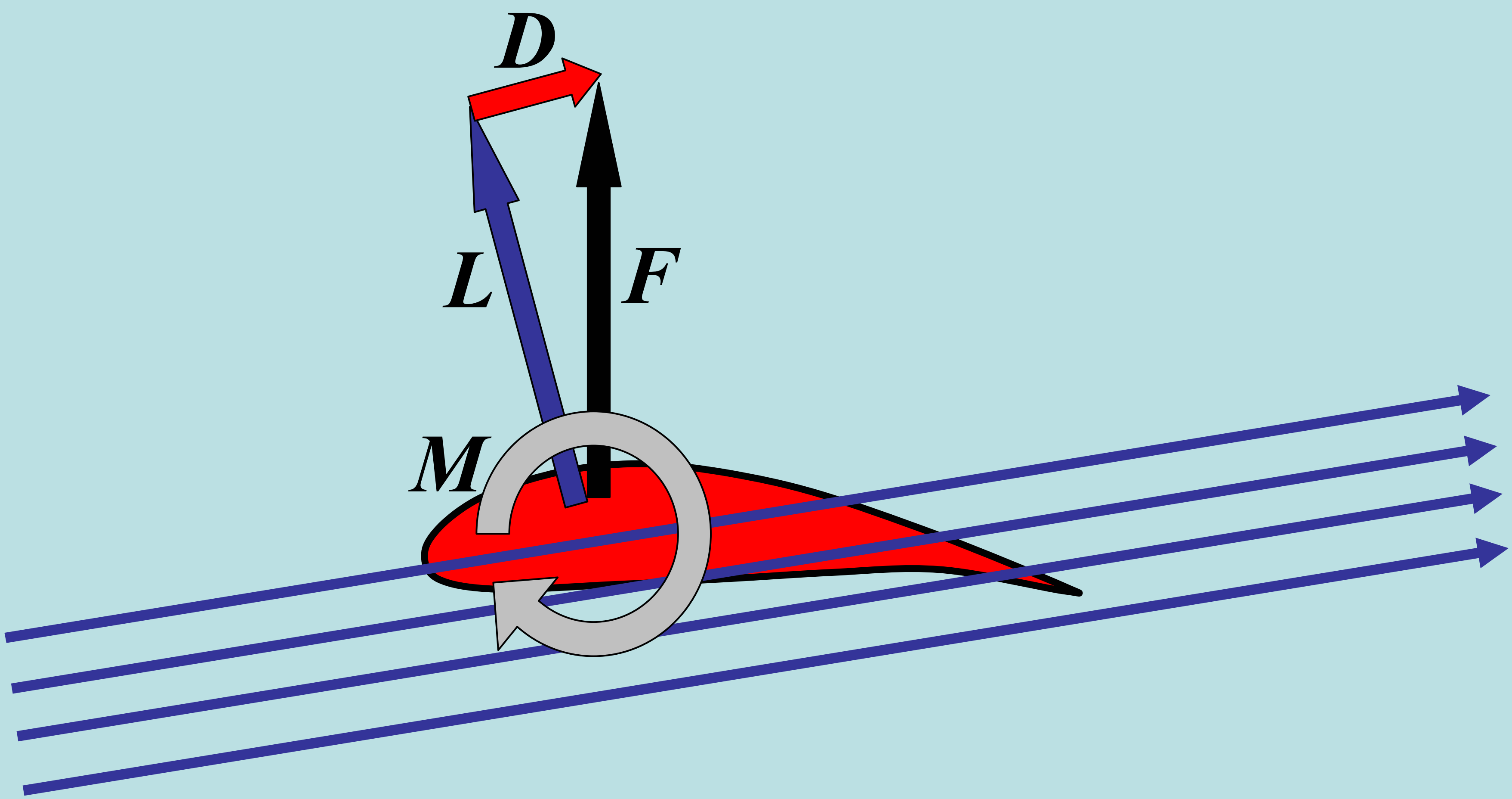
What is aerodynamics?

- **aero·dy·nam·ics** : a branch of dynamics that deals with the motion of air and other gaseous fluids and with the forces acting on bodies in motion relative to such fluids

Source: Merriam Webster's Dictionary.

What Forces and Moments?

Lift, drag, pitching moment



Governing Principles

What we want:

Predict forces and moments on a body due to motions relative to a fluid

What we have:

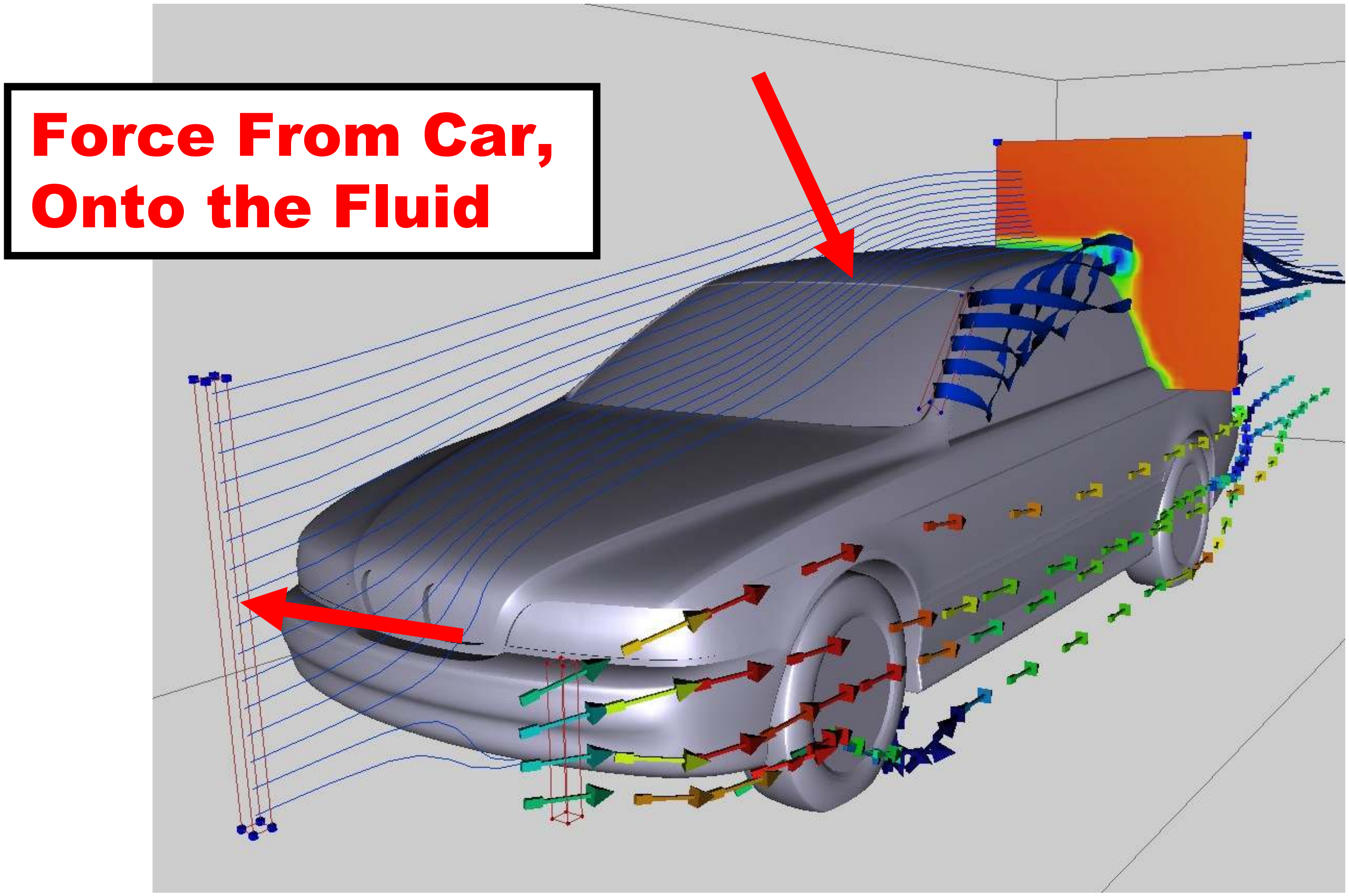
*A fluid which obeys physical laws: **conservation of mass, conservation of momentum** and conservation of energy.*

Newton’s Laws

- *Force = mass * acceleration.*
  - What is acceleration?
    - Change in velocity over time
    - Change in direction over time

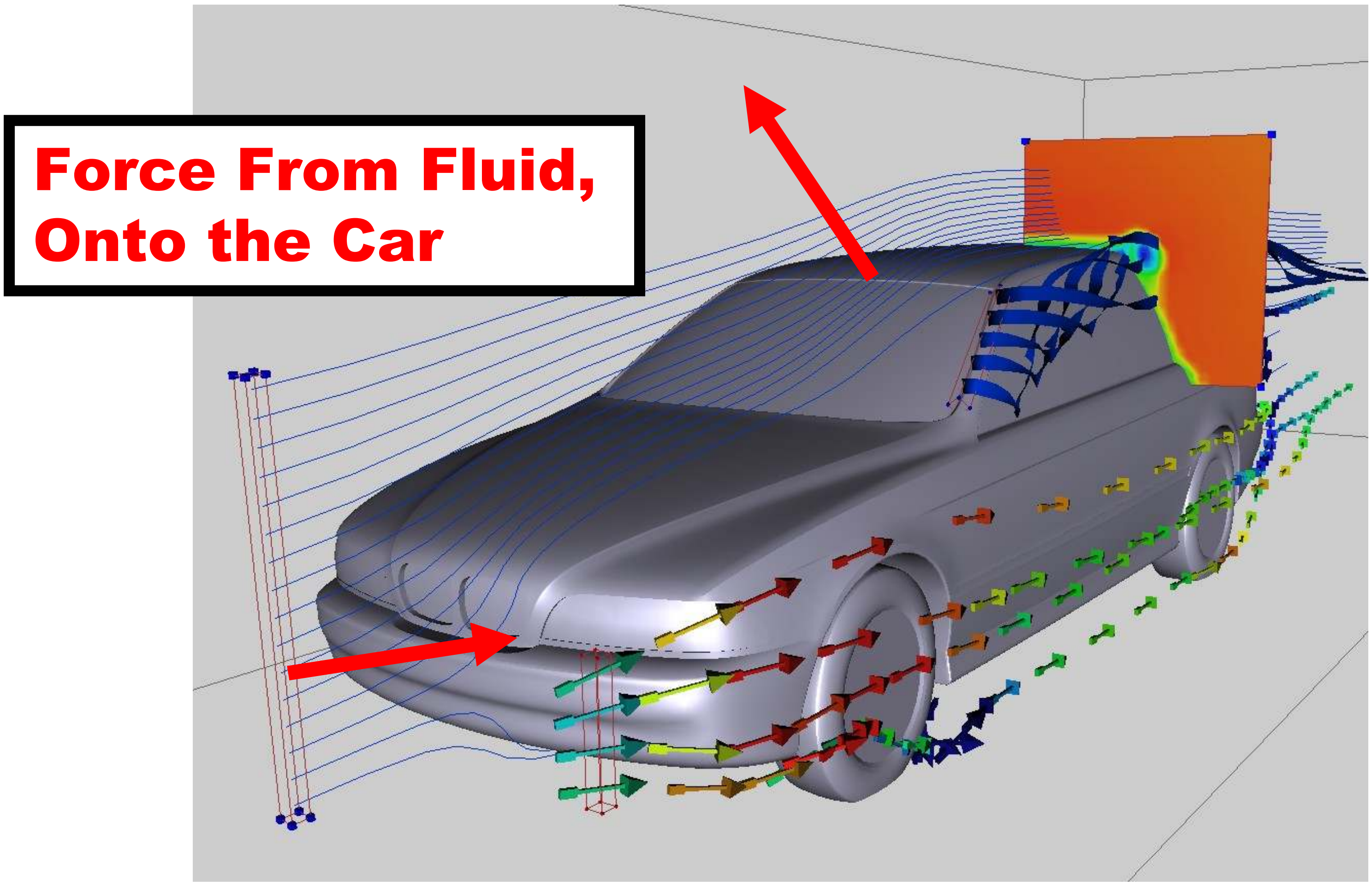
- *For a non-accelerating body, every force has an equal and opposite reaction.*

Newton's Laws Applied : Force on fluid causes acceleration



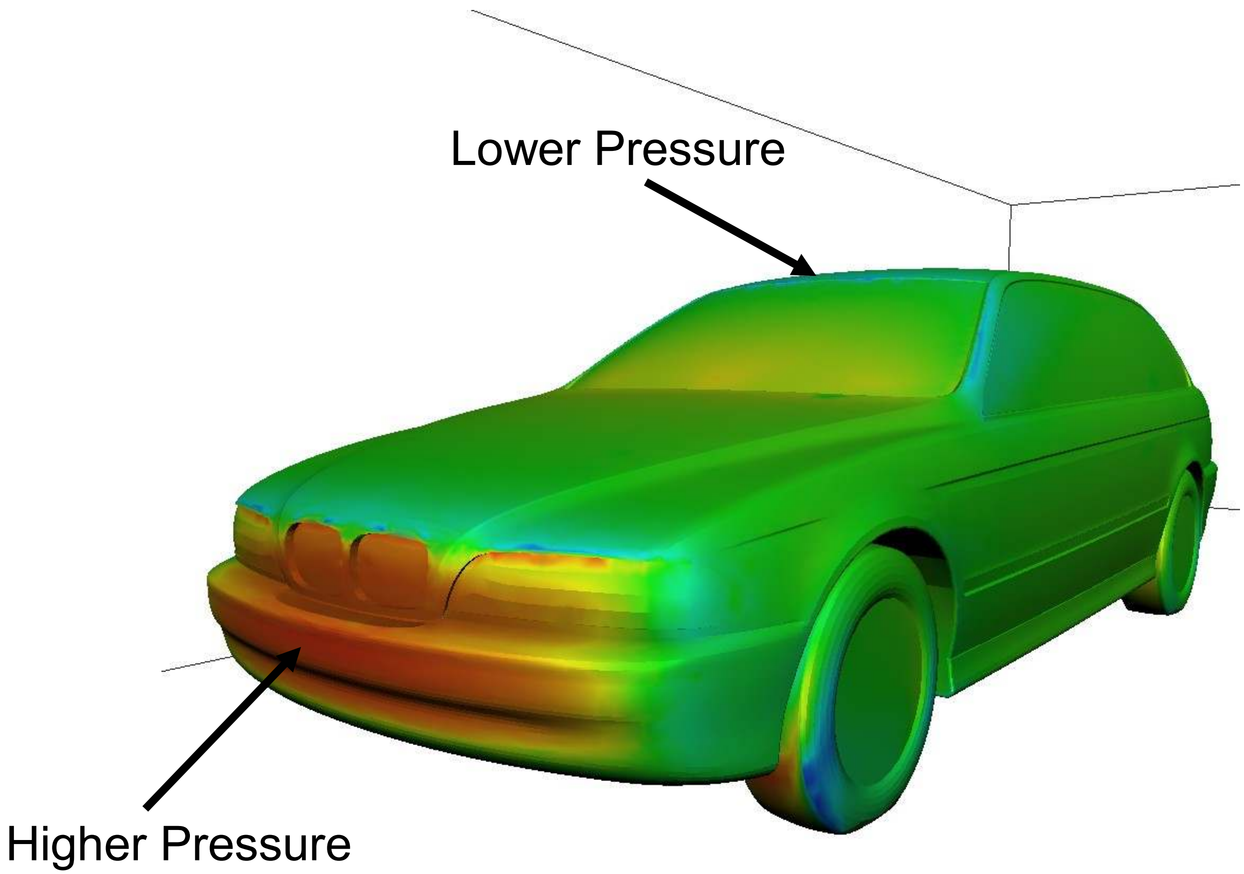
www.vis.uni-stuttgart.de/.../ html/Main/flow.html

Newton's Laws Applied : Force On Fluid



www.vis.uni-stuttgart.de/…/ html/Main/flow.html

Pressures



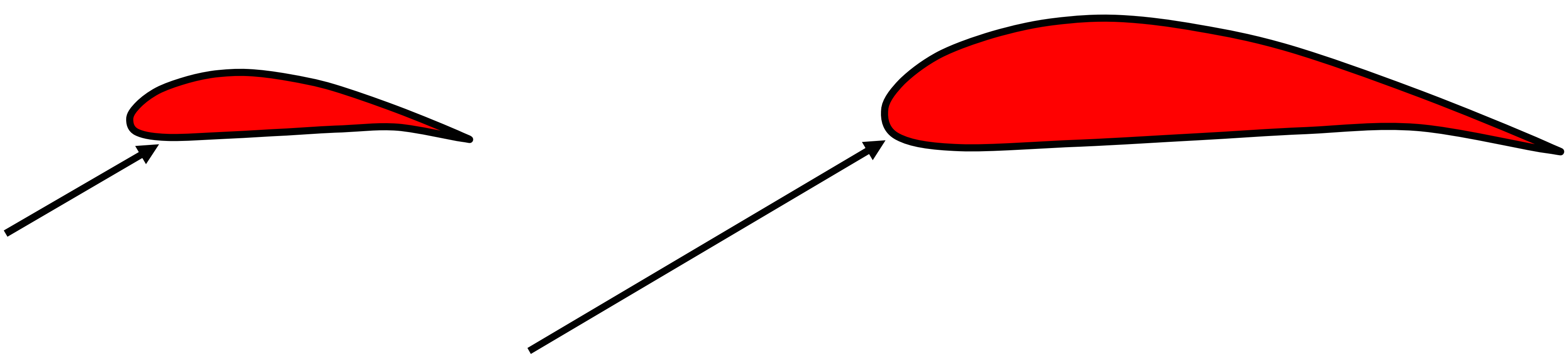
www.vis.uni-stuttgart.de/.../ html/Main/flow.html

Non-Dimensional Coefficients

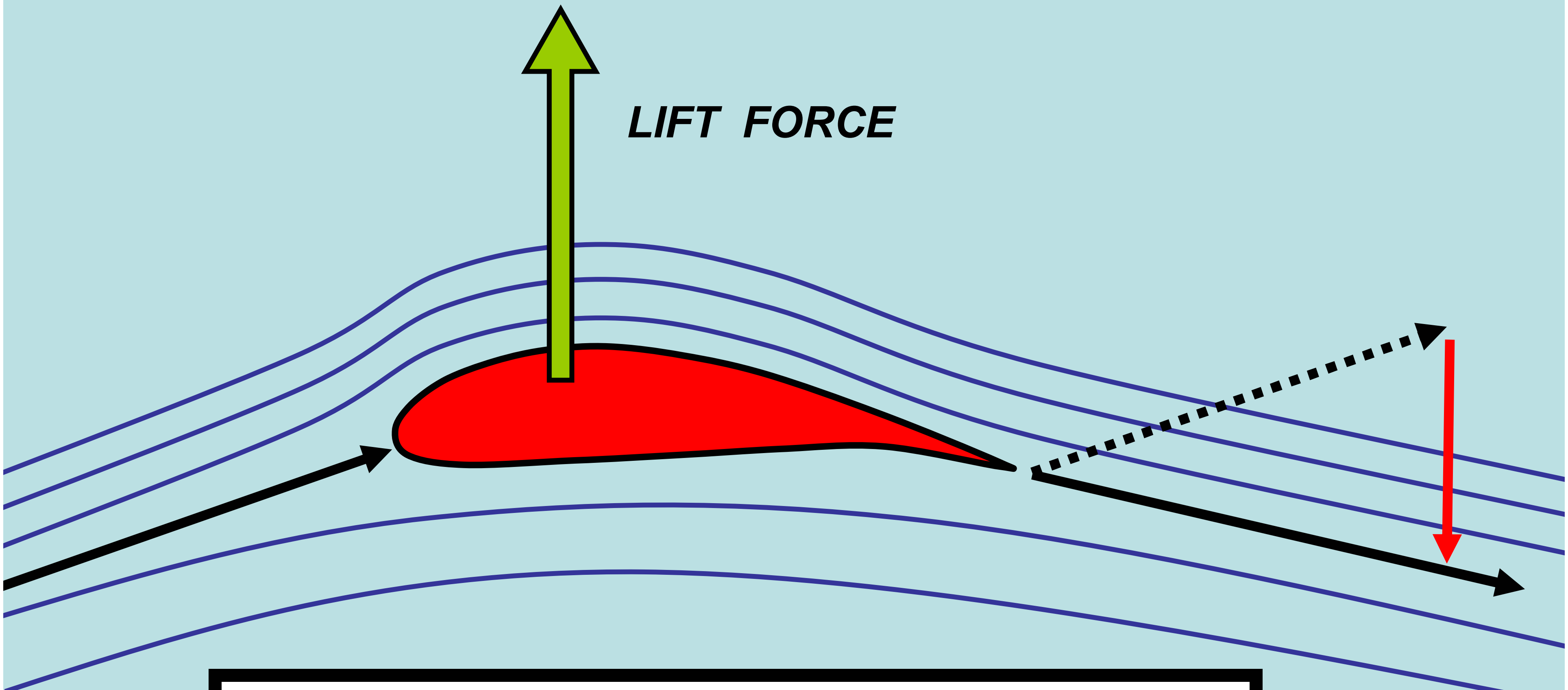
- Lift Coefficient
  - $C_L = L/(0.5*\rho*U^2S)$
  - $C_L = f(AoA, Camber/c, Re, LE\ Radius/c)$
- Drag coefficient
  - $C_D = D/(0.5*\rho*U^2S)$
  - $C_D = f(AoA, Camber/c, Re, LE\ Radius/c)$
- Reynold's Number
  - $Re = (\rho*U*L)/\mu$

Lift vs. Lift Coefficient

- If we know C_L
  - $L = C_L\,(0.5*\rho*U^2S)$
- So, we can test a smaller model (or larger model) and still be able to predict the behaviour of an untestable subject!

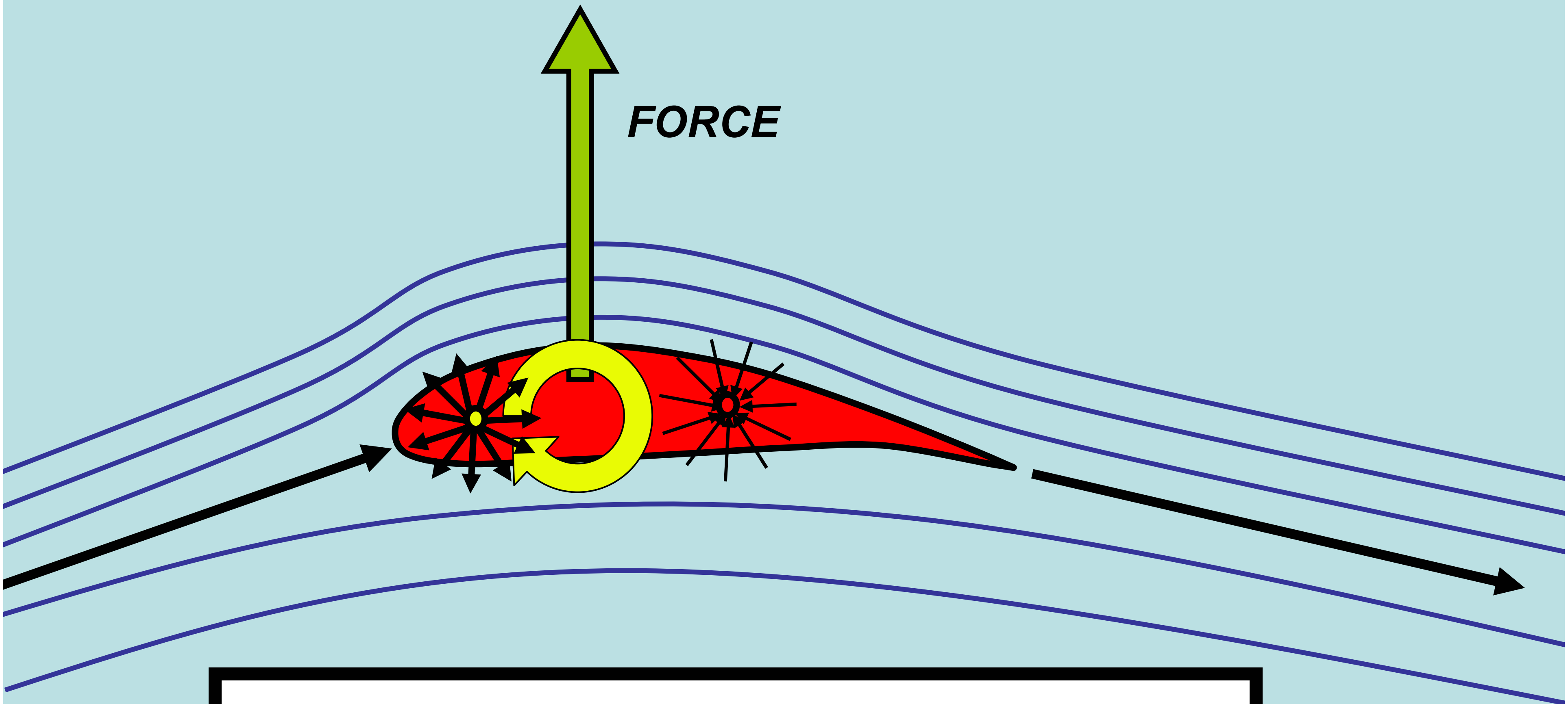


Where does lift come from?



Change in Momentum

Where does lift come from?



Circulation

Bernoulli Equation

- Bernoulli's equation (for an ***inviscid, incompressible*** flow):

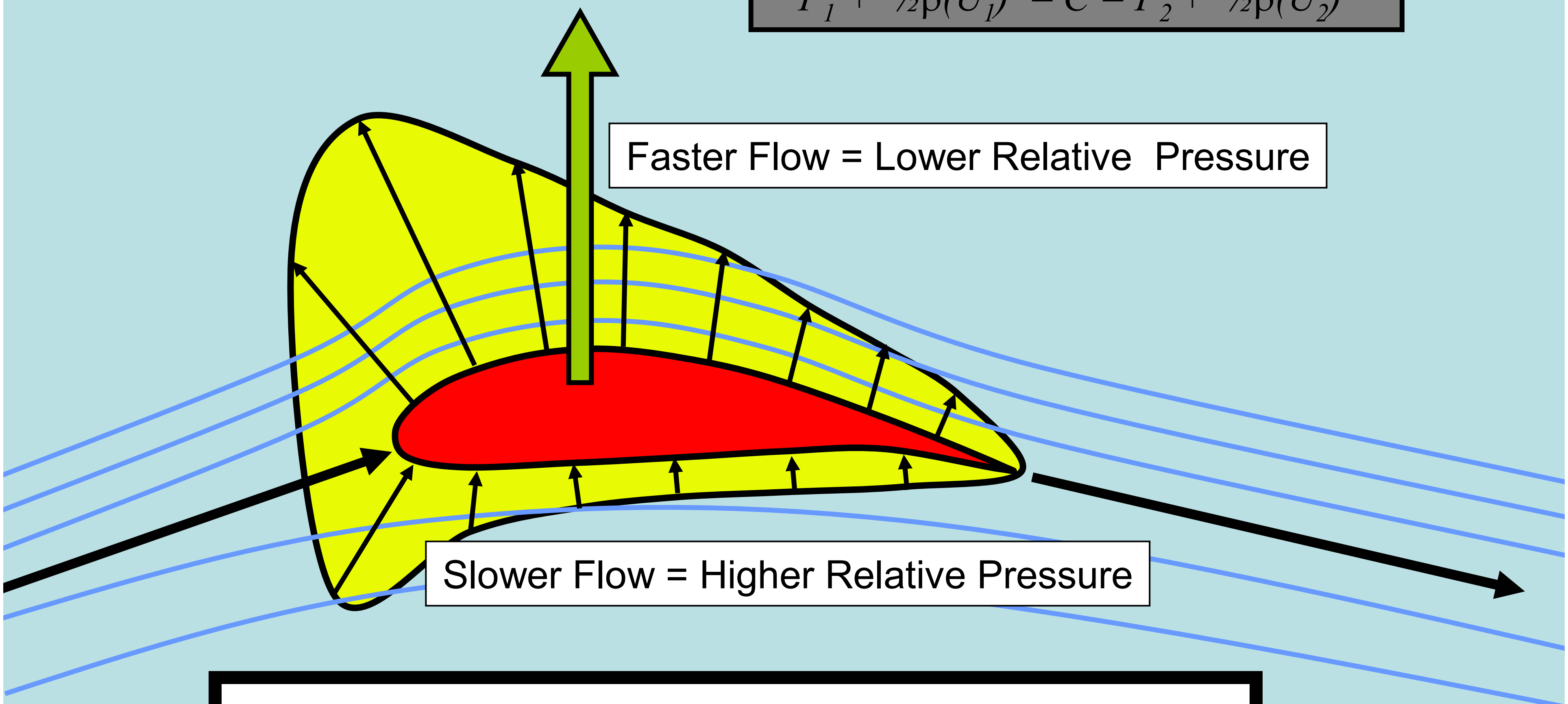
$$P_1 + \tfrac{1}{2}\rho(U_1)^2 = C = P_2 + \tfrac{1}{2}\rho(U_2)^2$$

Applied from point 1 to point 2, along a streamline.

Flow velocity will increase as fluid travels from higher pressure region to lower pressure region.

Where does lift come from?

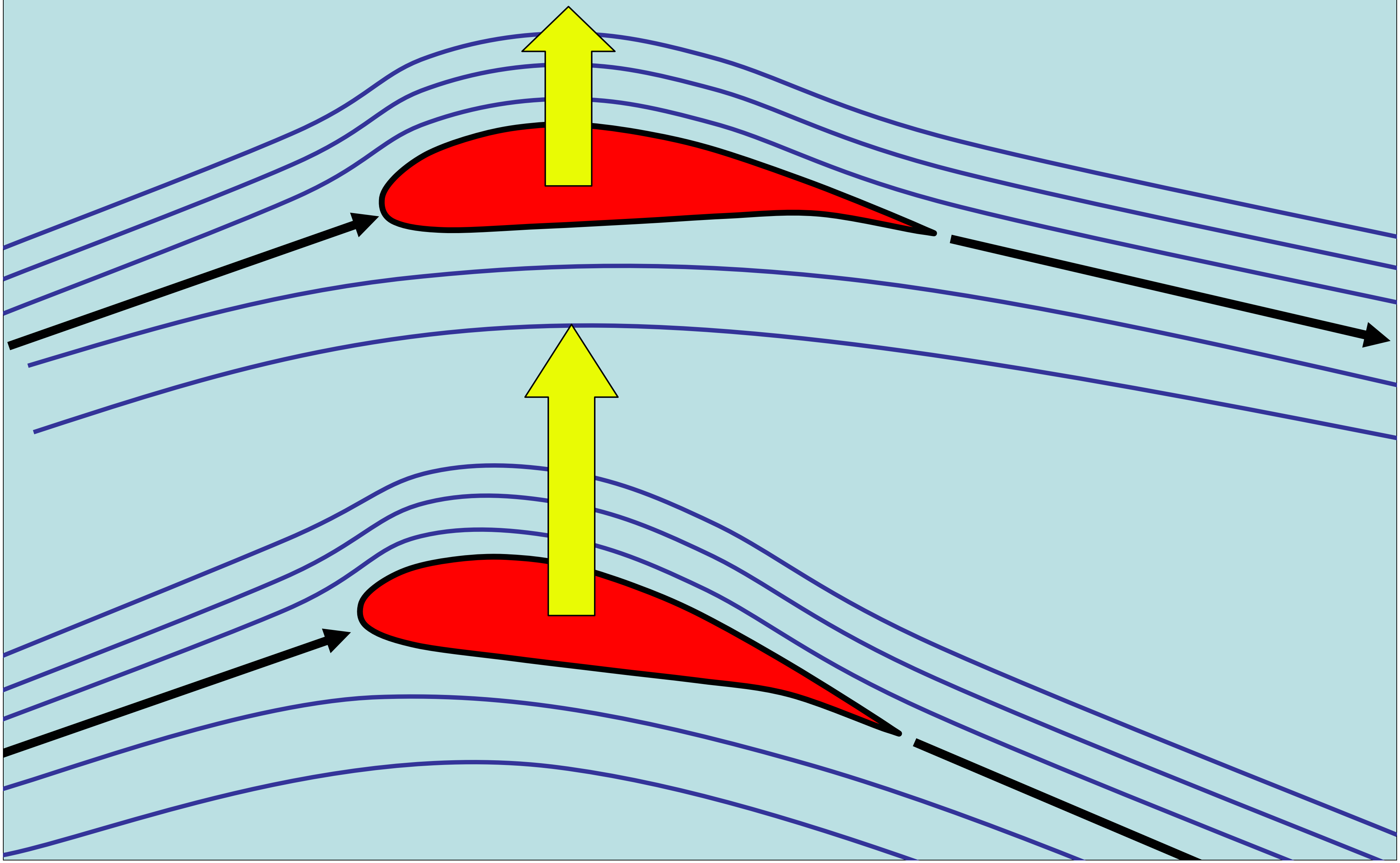
$$P_1 + \tfrac{1}{2}\rho(U_1)^2 = C = P_2 + \tfrac{1}{2}\rho(U_2)^2$$



Pressure Difference

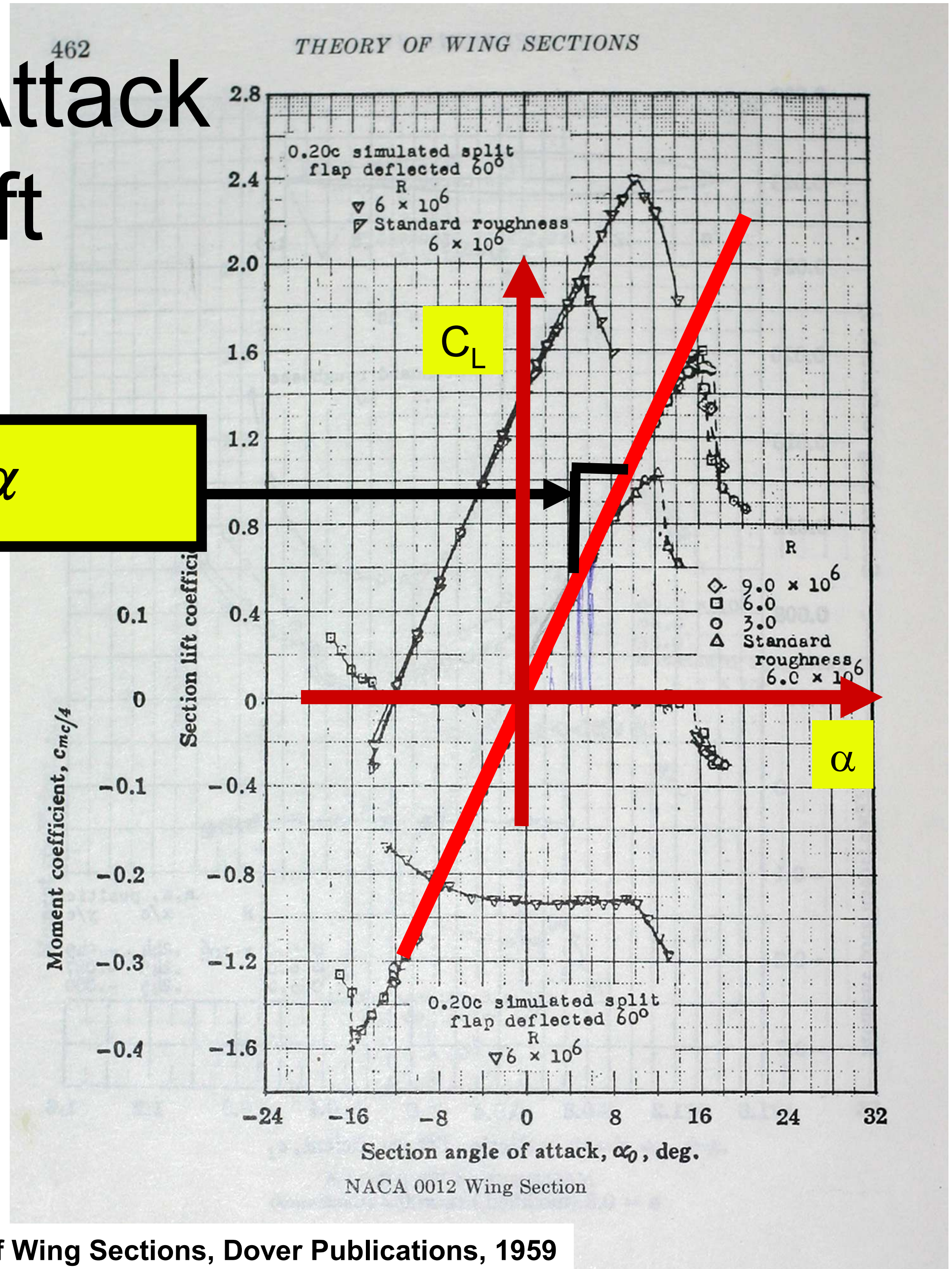
How do we change the Lift Coefficient to our advantage?

Angle of Attack



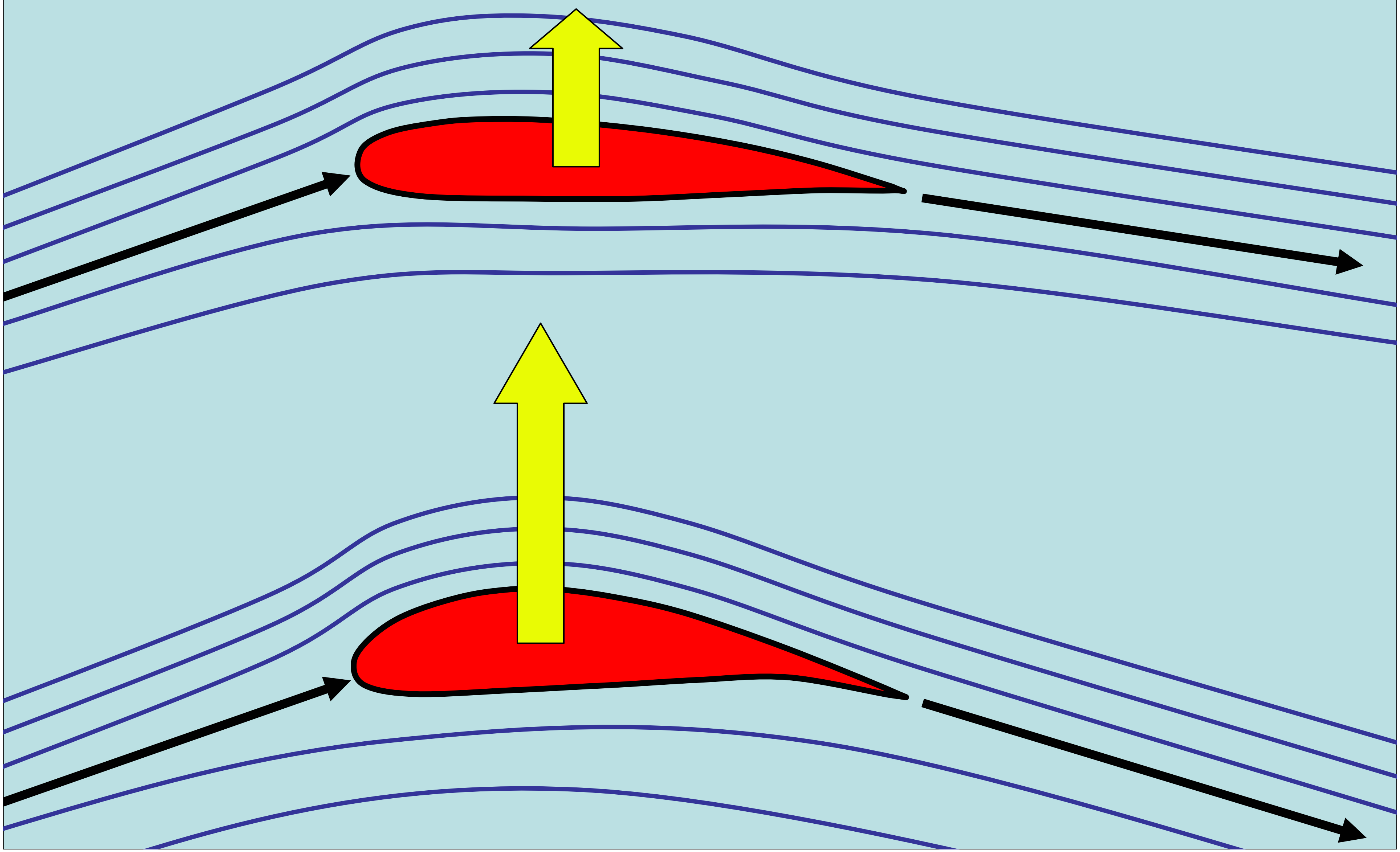
Angle of Attack vs. Lift

$$C_l \sim 2\pi\alpha$$



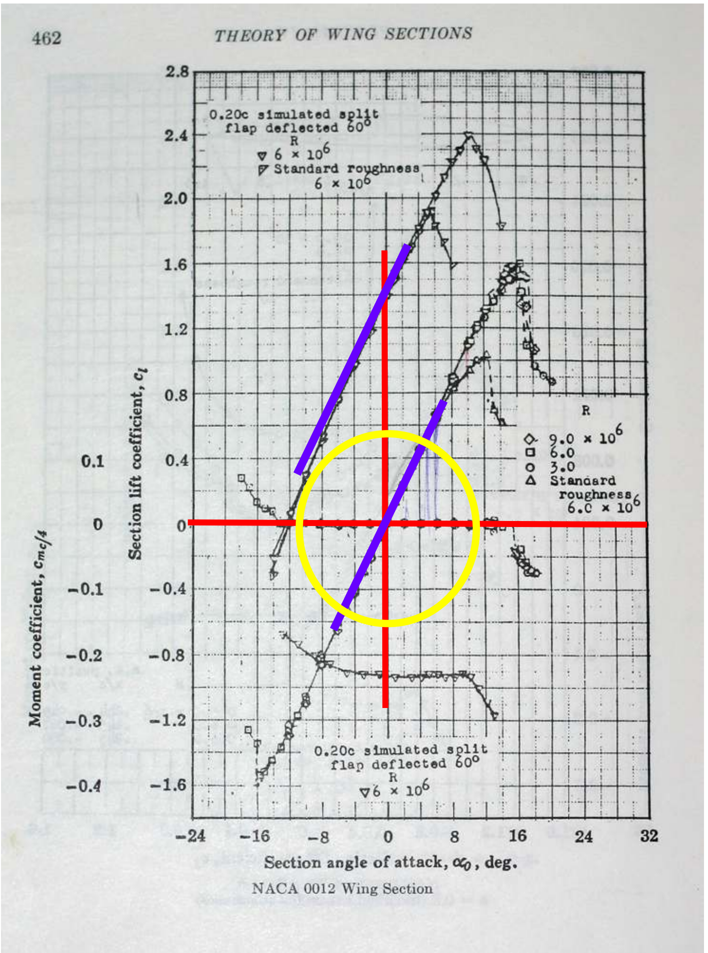
Abbott and Von DoenHoff, Theory of Wing Sections, Dover Publications, 1959

Airfoil Camber

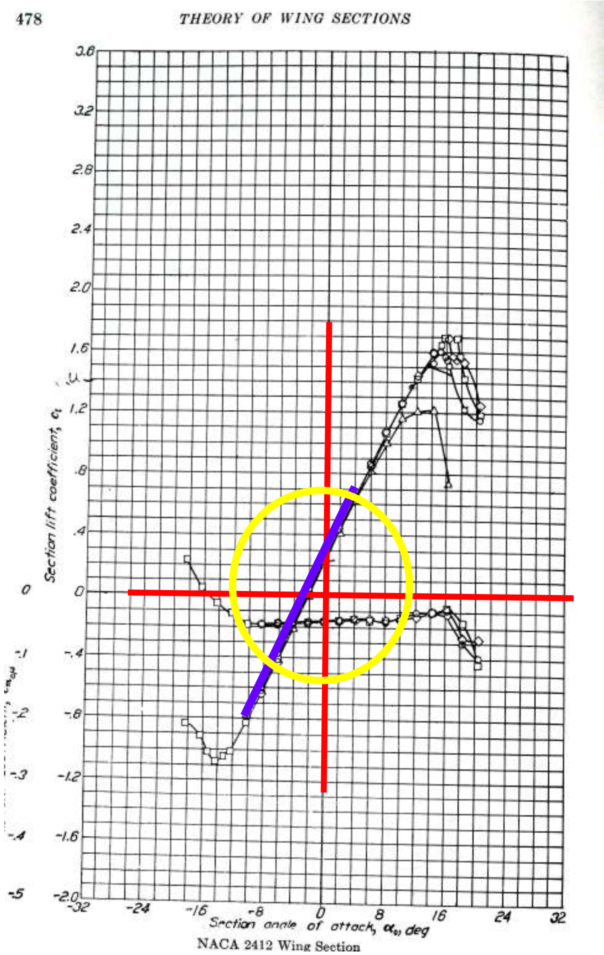


Camber in Actual Airfoils

Abbott and Von DoenHoff, Theory of Wing Sections, Dover Publications, 1959

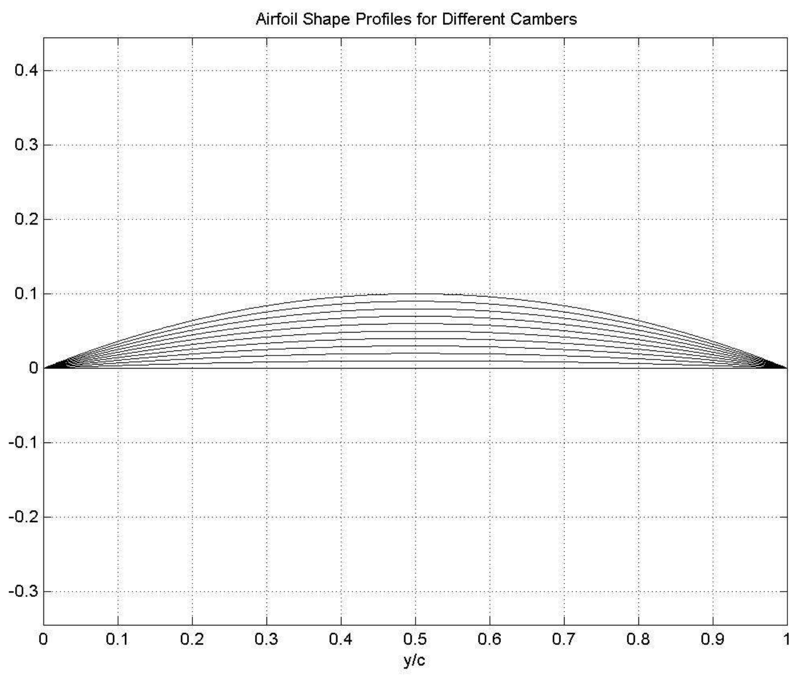


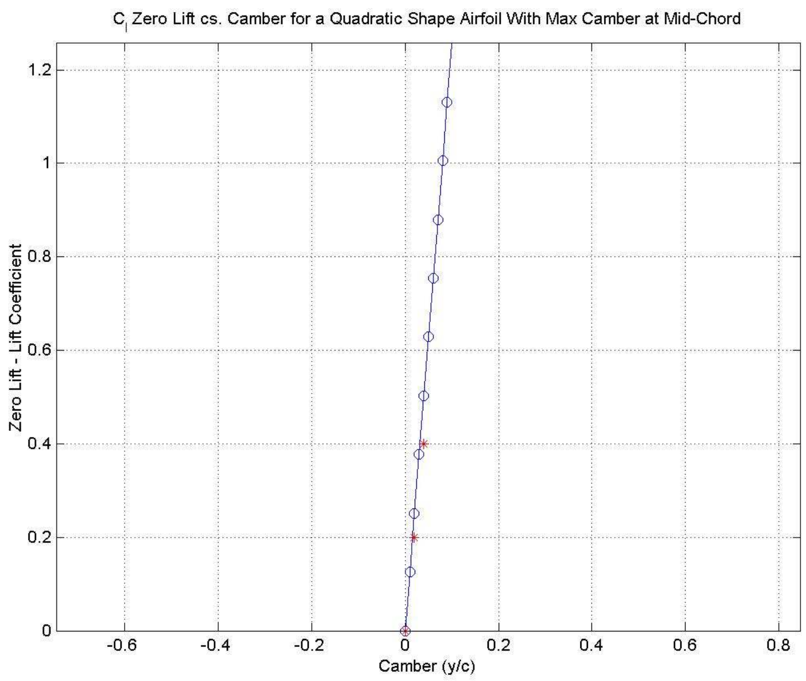
0% Camber



2% Camber

Effects of Camber

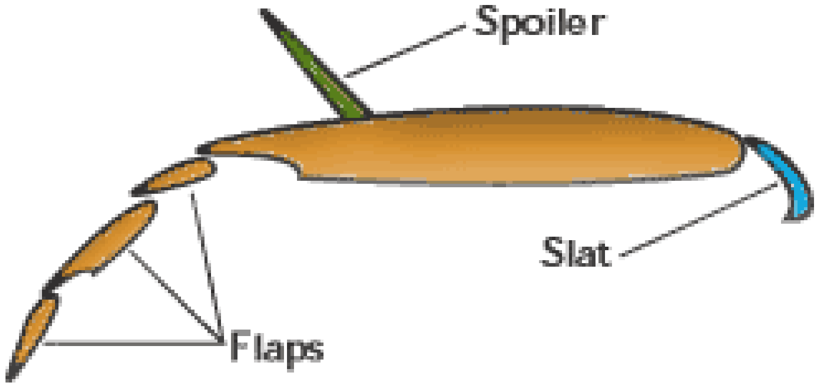




$$C_l \sim C_{l\alpha} + 12.6(y/c)$$

$$C_l \sim 2\pi\alpha + 12.6(y/c)$$

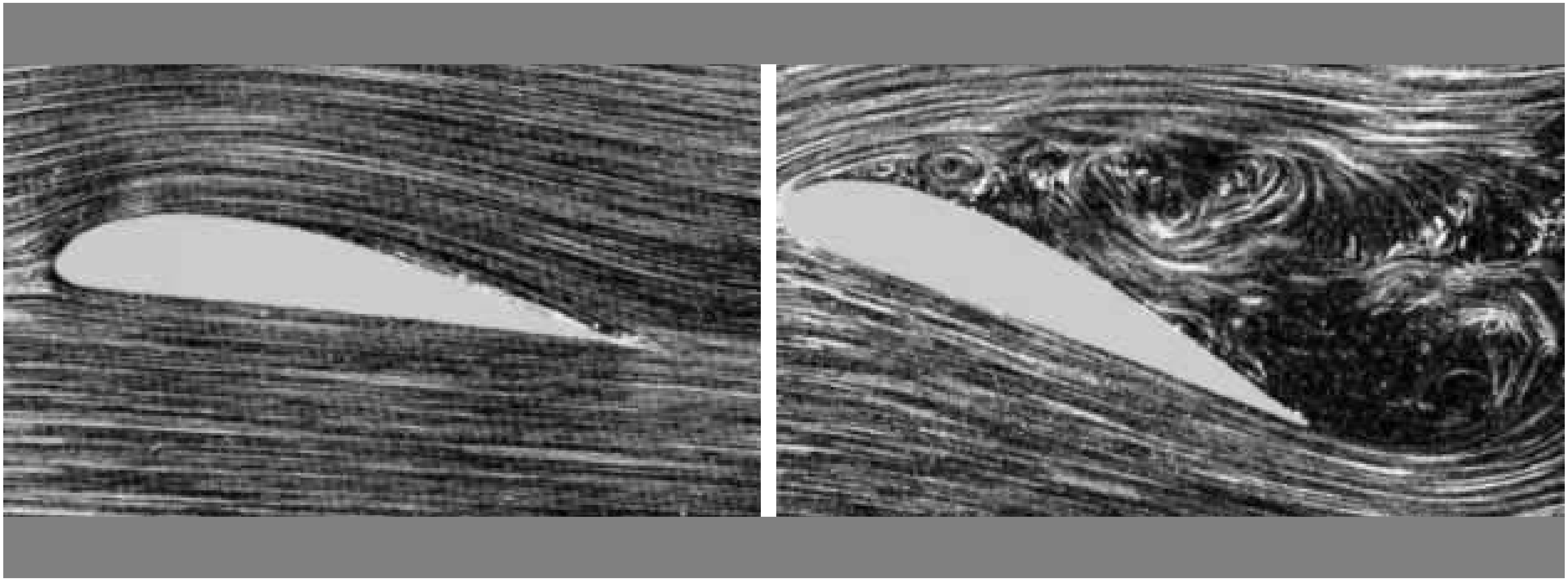
Other Camber Augementers



- http://www.virtualskies.arc.nasa.gov/aeronautics/tutorial/images/flap,slat,spoiler.gif

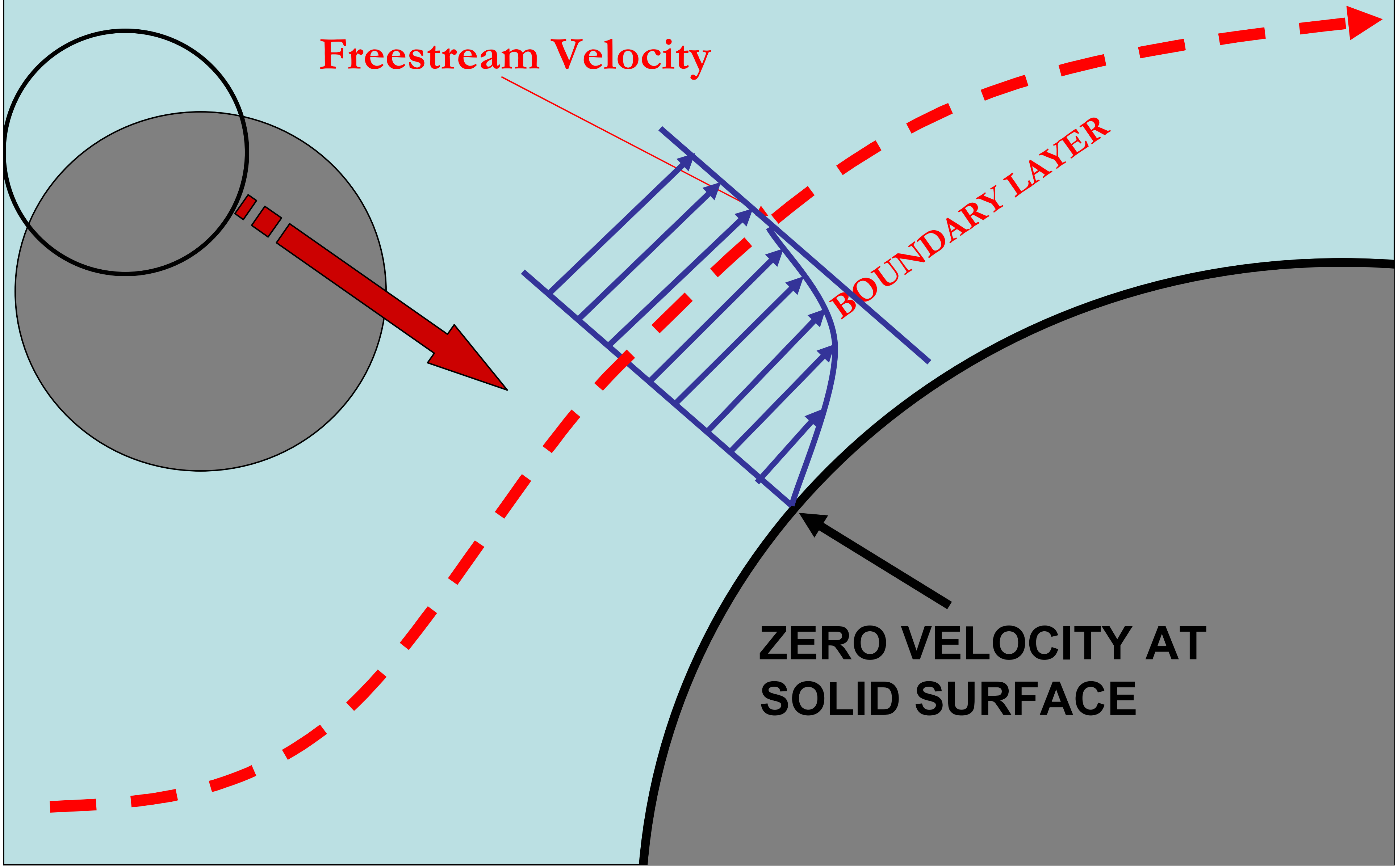
http://www.totalwind.net/windsurf/wp-content/uploads/finian-maynard-record.jpg

But…one big problem!
SEPARATION



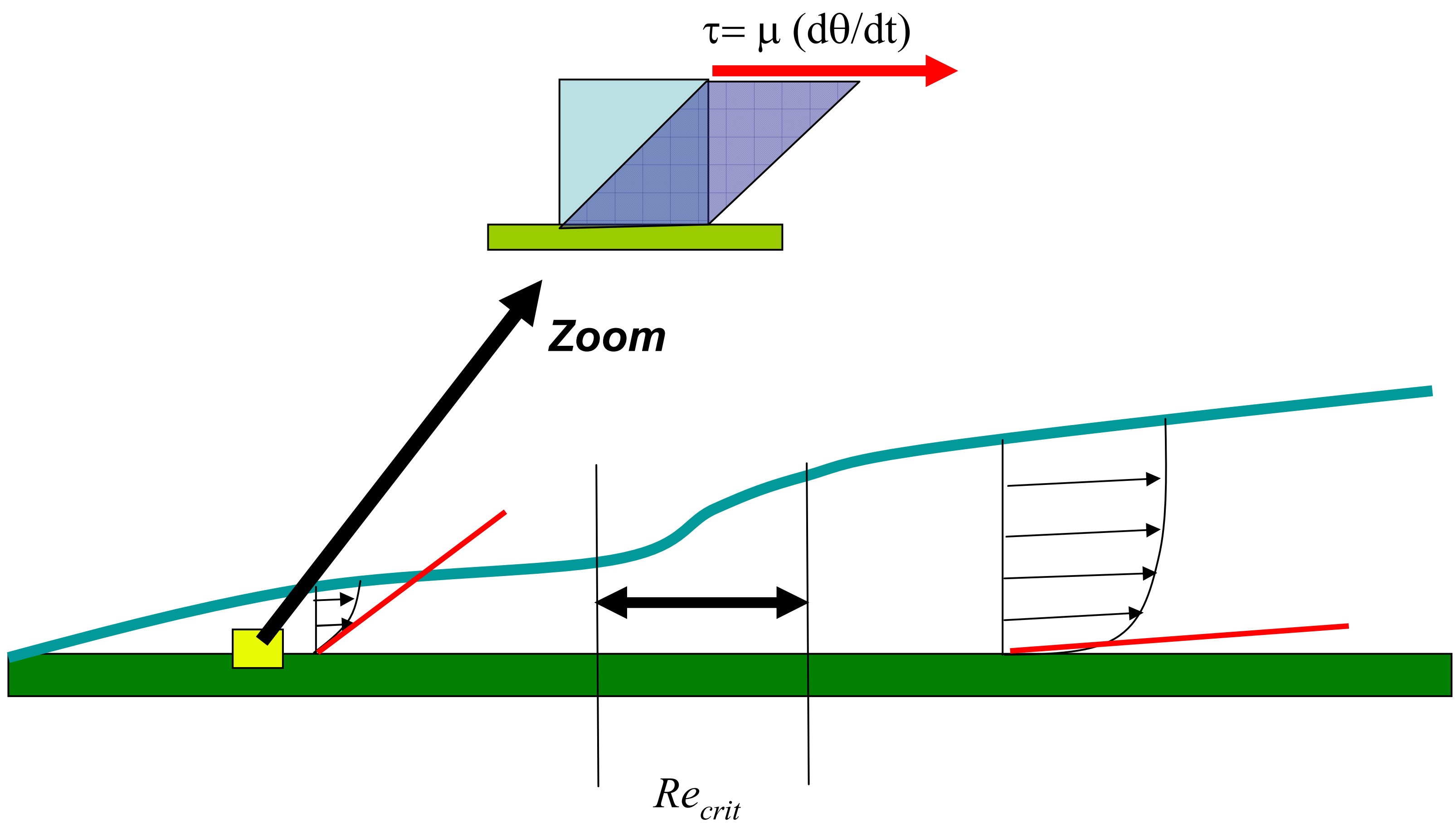
Prandtl, L. Strömungslehre. Vieweg, Braunschweig, 1956

Aside: Boundary Layers

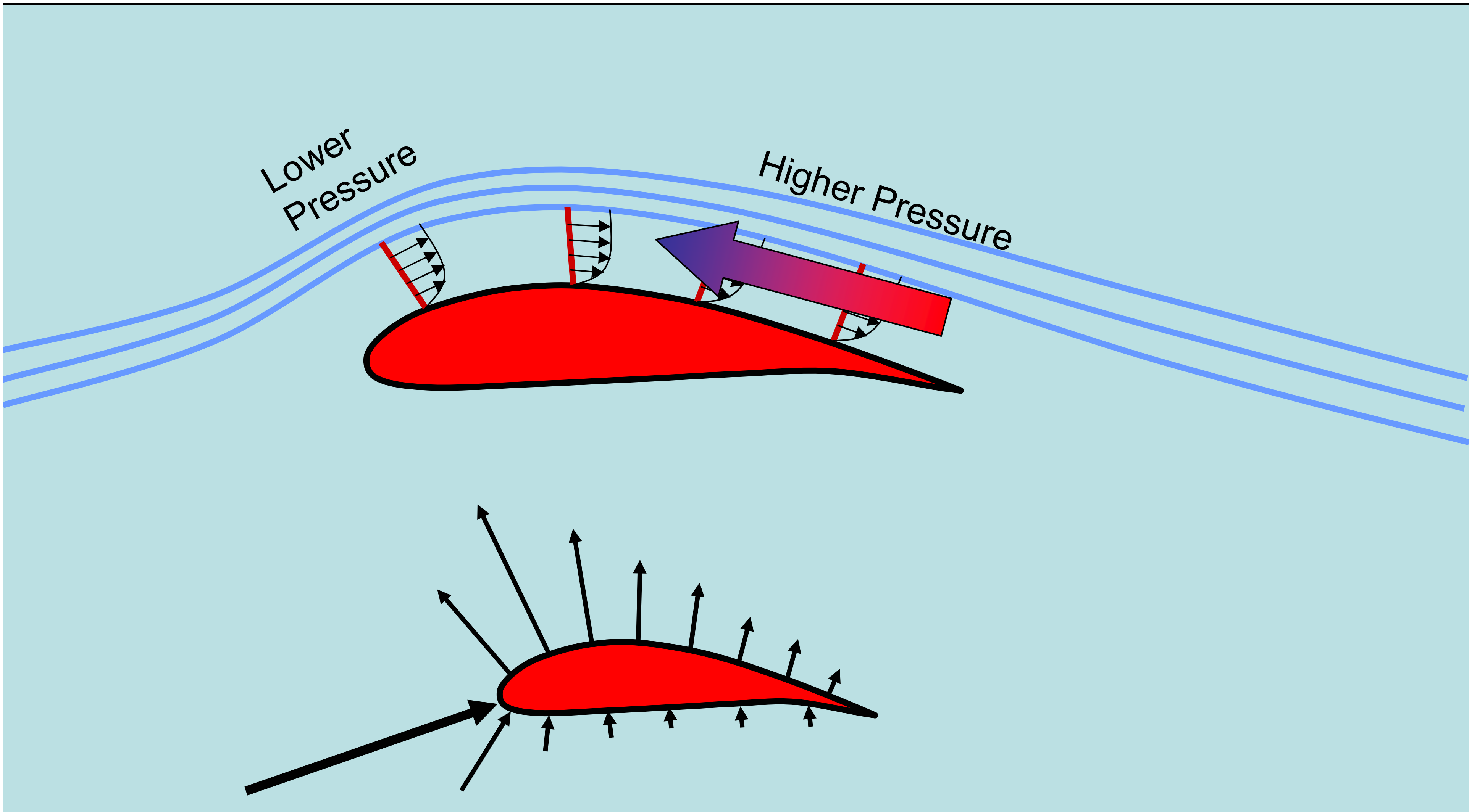


Boundary layers…

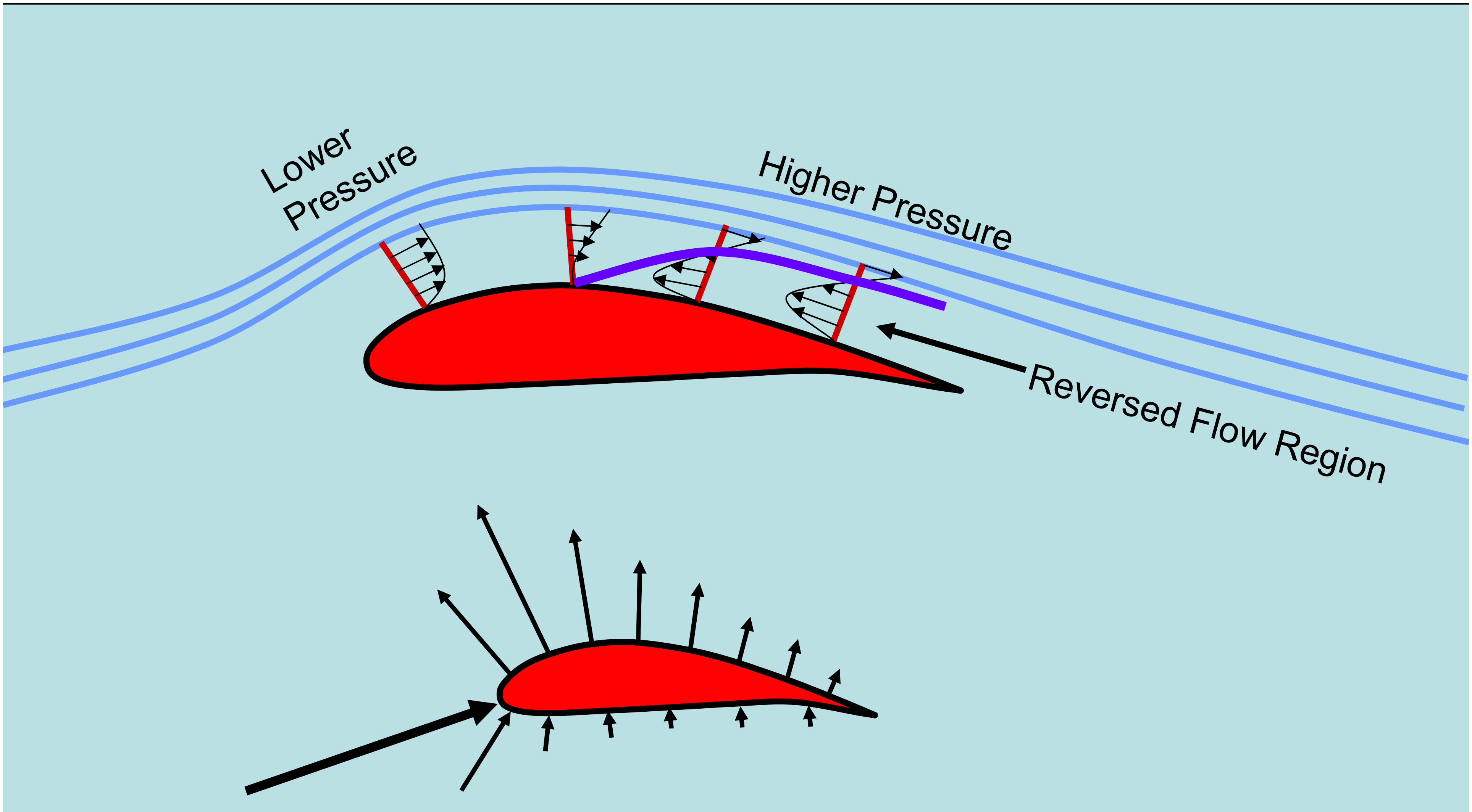
- What causes the boundary layers?



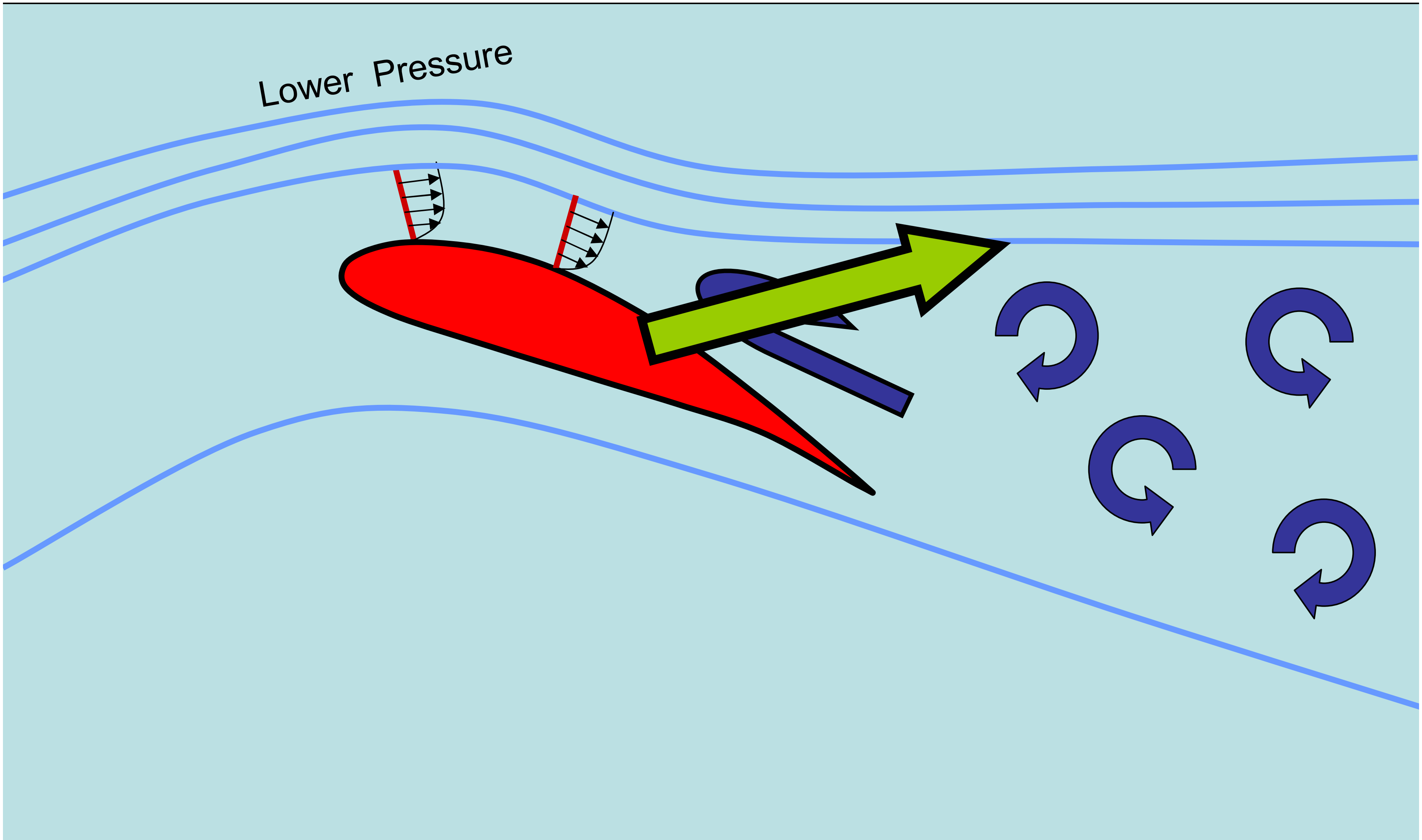
What Causes Separation?



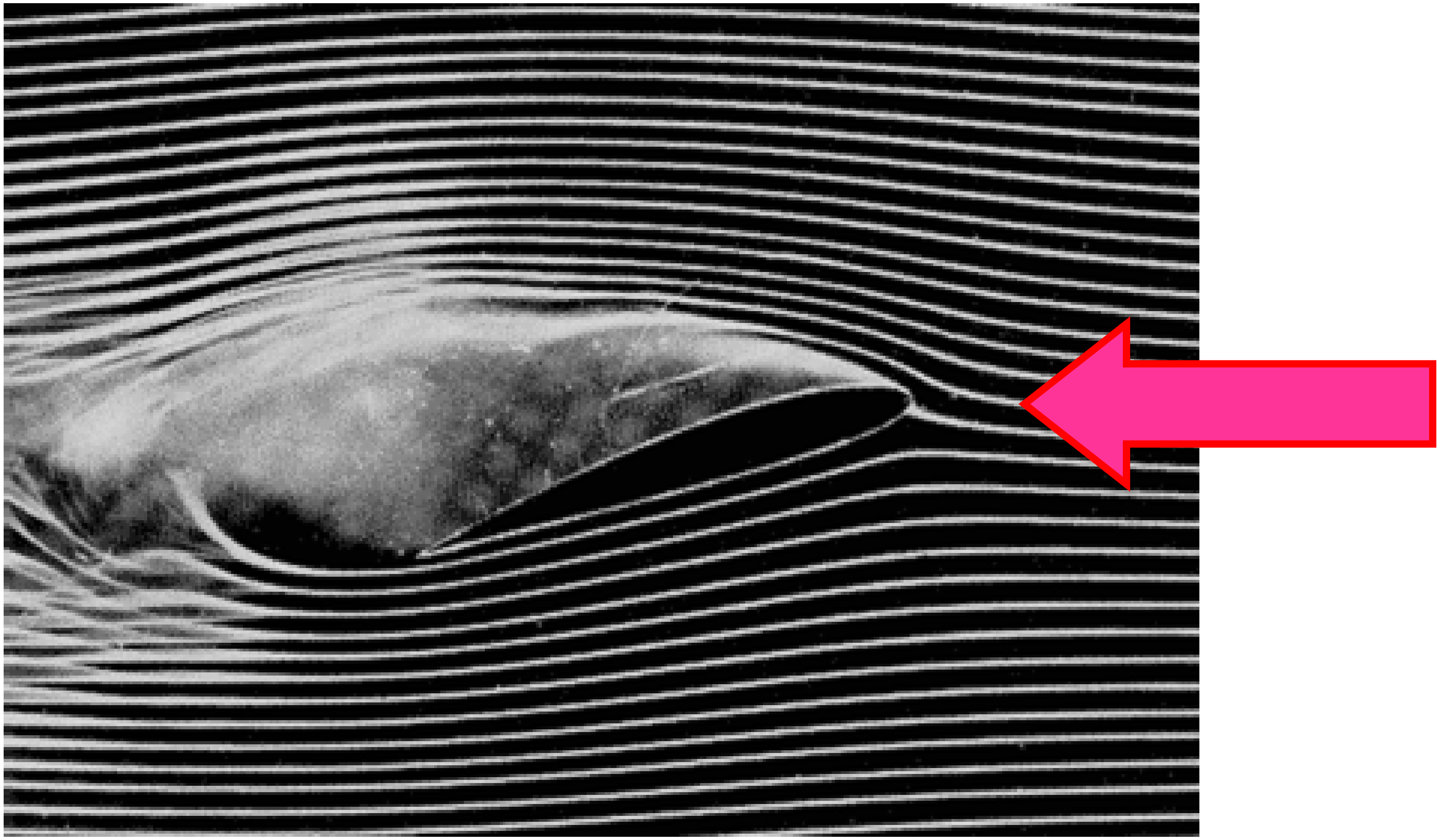
What Causes Separation?



What Causes Separation?

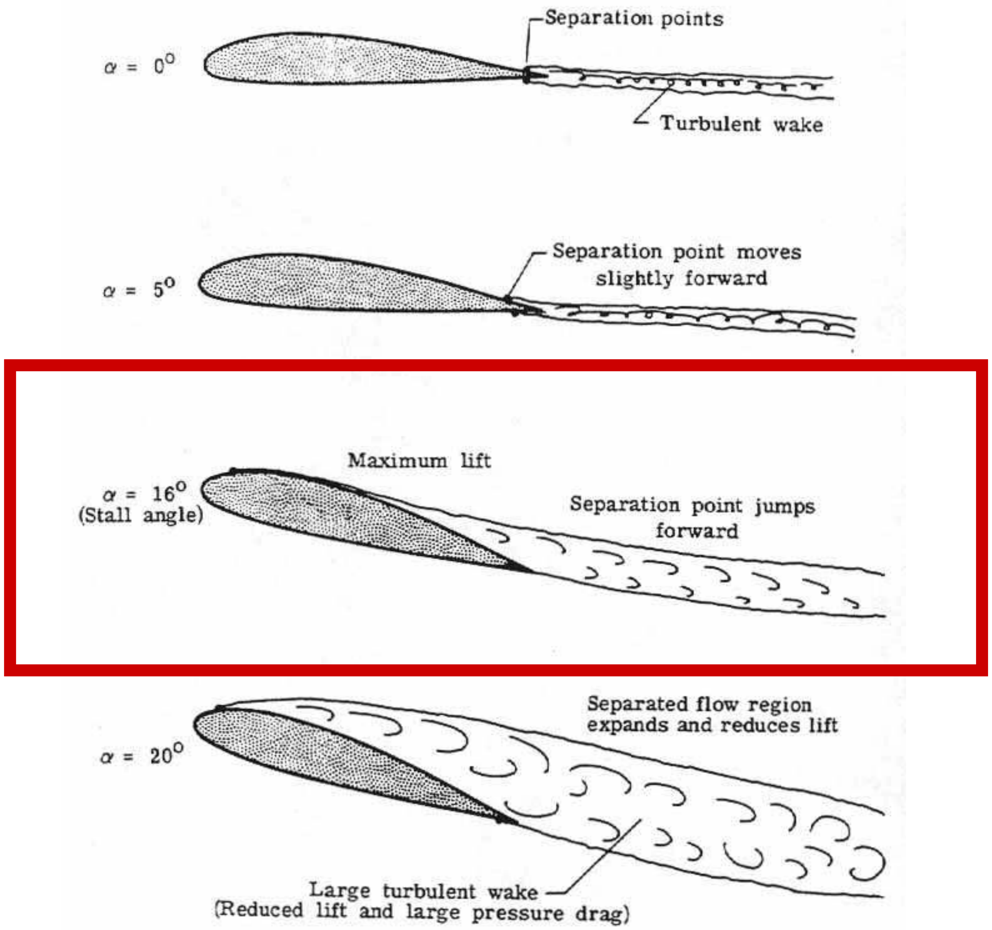


Separation…

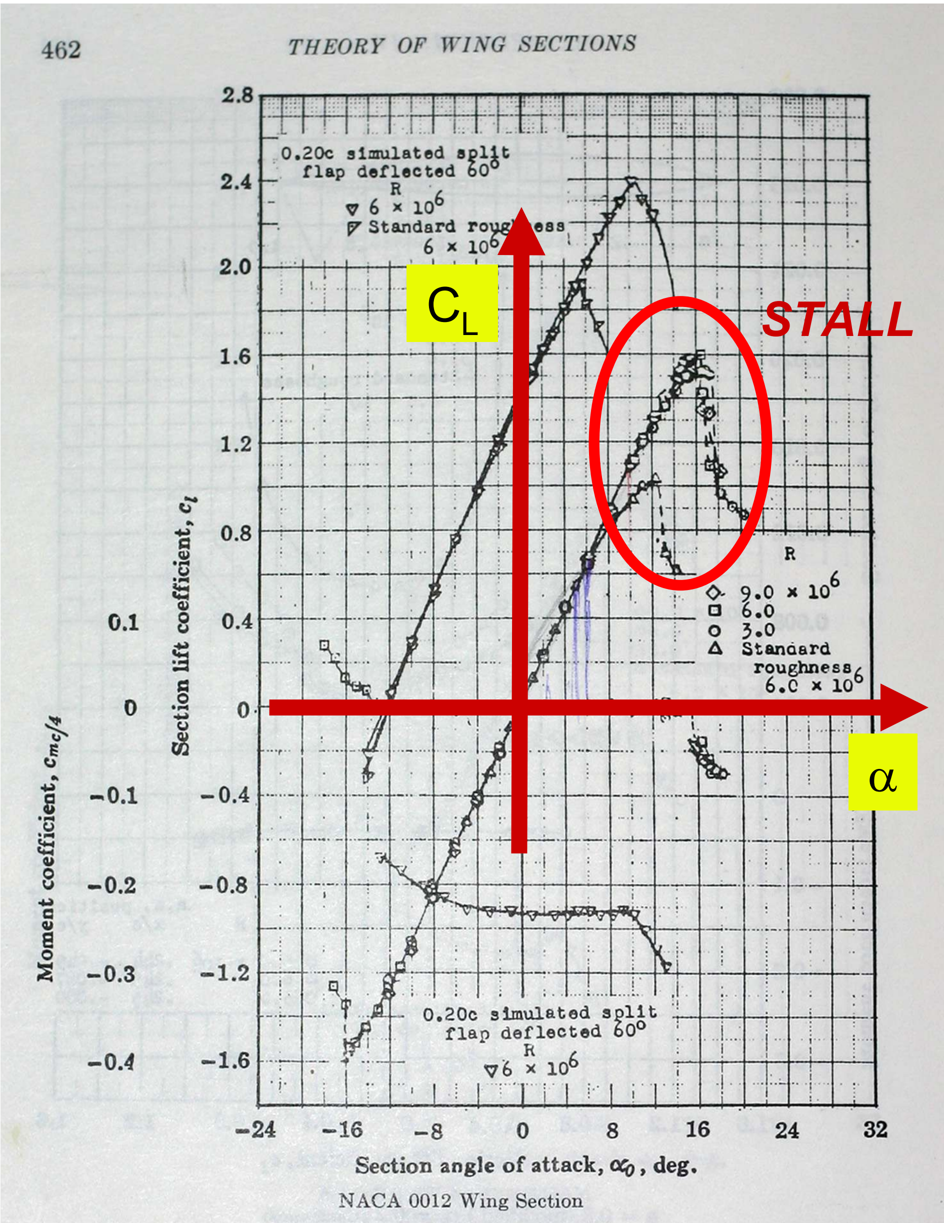


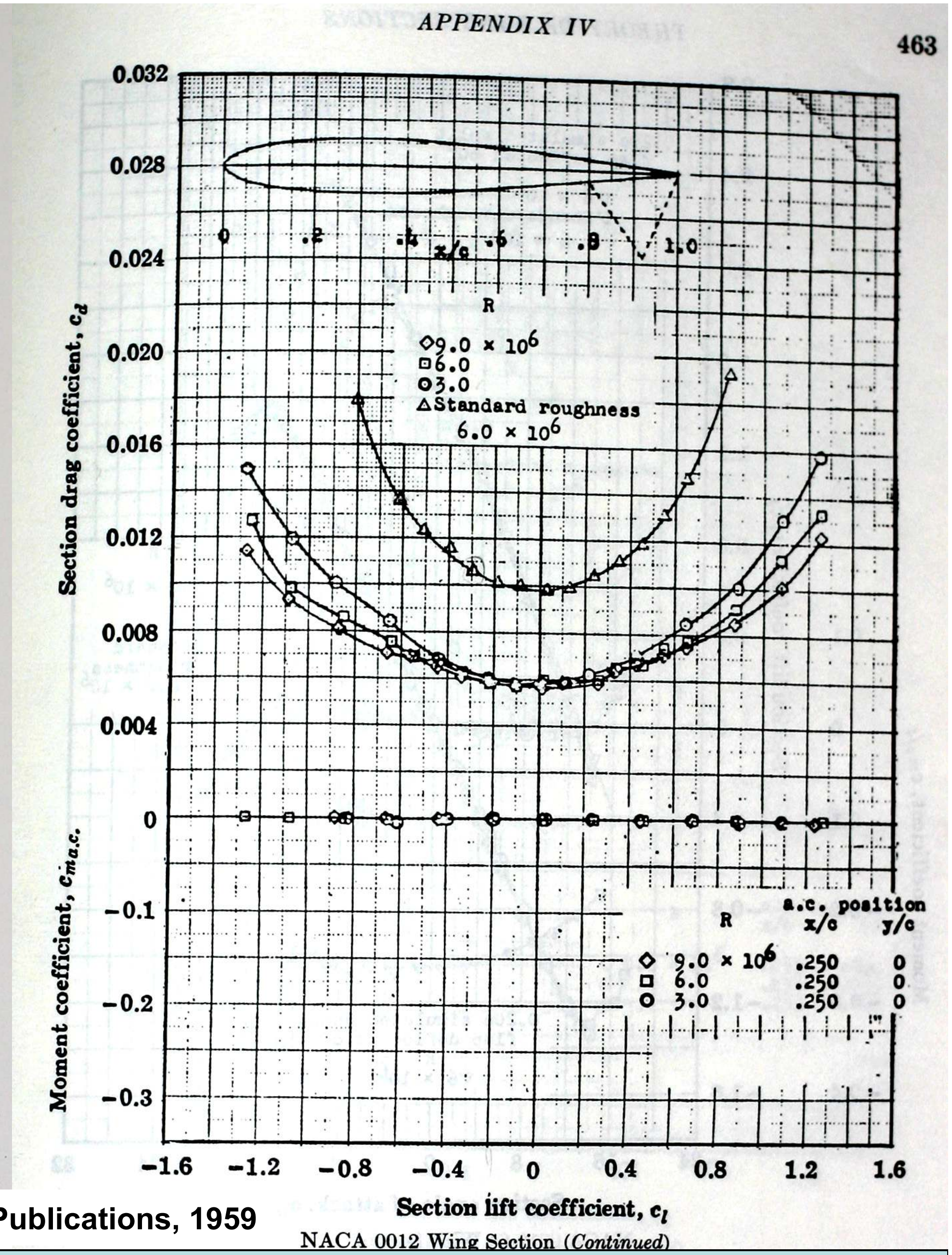
http://users.pandora.be/elvo/c7/turbulent.gif

Separation and Stall



http://images.google.com/imgres?imgurl=http://www.centennialofflight.gov/essay/Theories_of_Flight/thumb/TH14G4.jpg&imgrefurl=http://www.centennialofflight.gov/essay/Theories_of_Flight/Two_dimensional_coef/TH14.htm&h=113&w=100&sz=7&hl=en&start=33&tbnid=9A1zzBsK1rBJeM:&tbnh=86&tbnw=76&prev=/images%3Fq%3Dairfoil%2Bseparation%26start%3D20%26ndsp%3D20%26svnum%3D10%26hl%3Den%26lr%3D%26sa%3DN



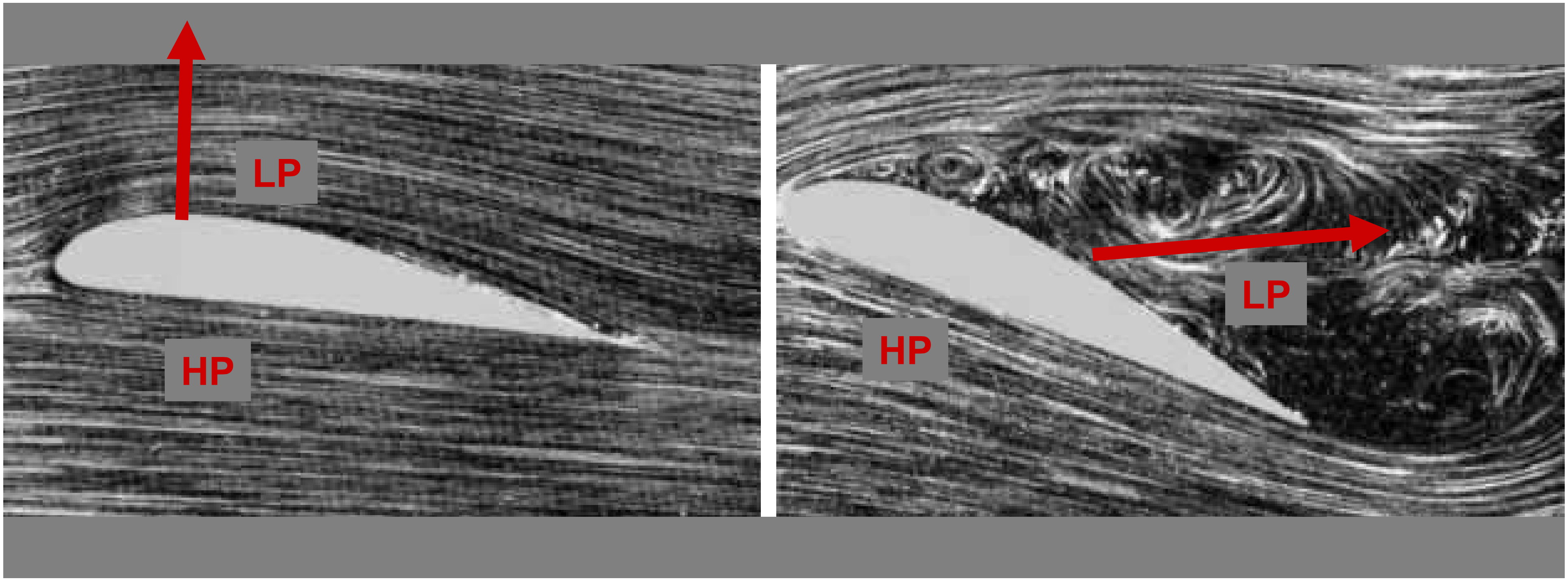


Abbott and Von DoenHoff, Theory of Wing Sections, Dover Publications, 1959

How does separation affect things?

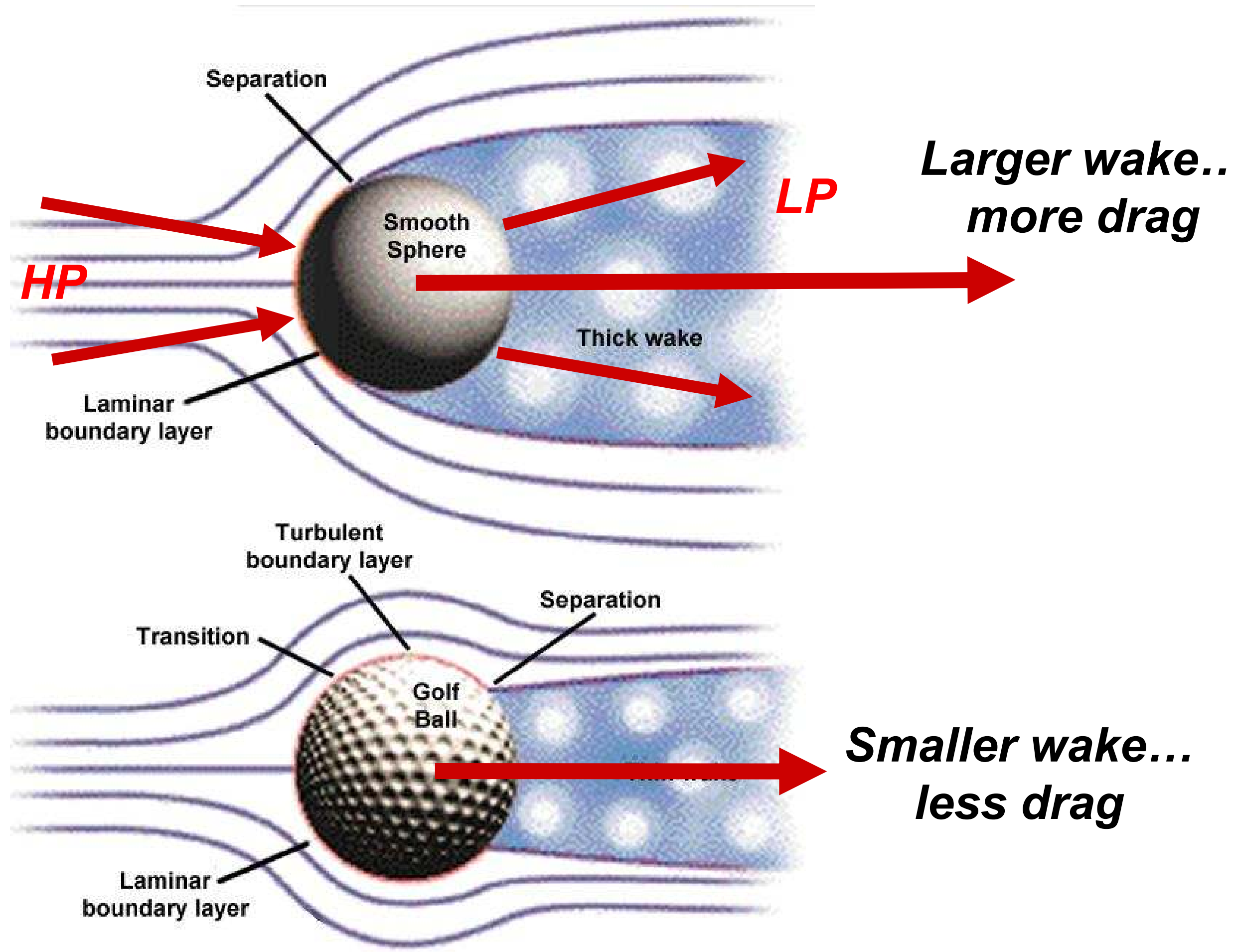
Sources of DRAG in 2D

One obvious source…*SEPARATION*



Prandtl, L. Strömungslehre. Vieweg, Braunschweig, 1956

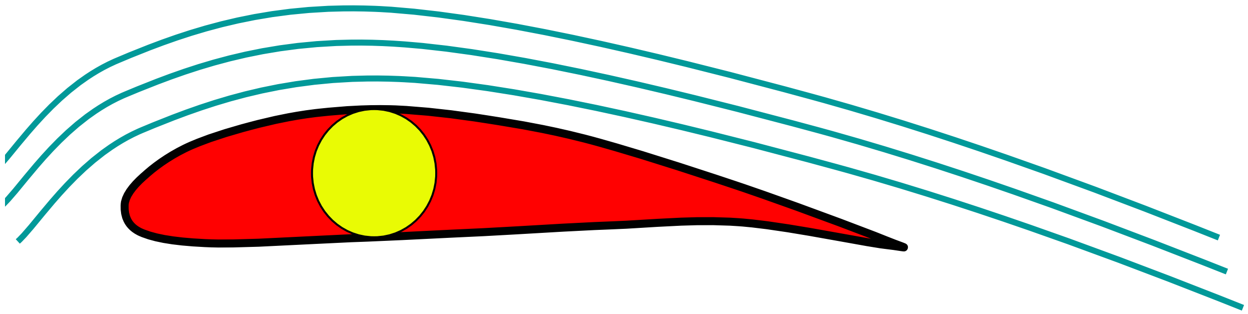
Separation and Boundary Layer Type

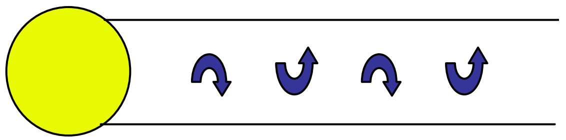


http://www.aerospaceweb.org/question/aerodynamics/sports/sphere-flow-comparison.jpg

Pressure/Form Drag

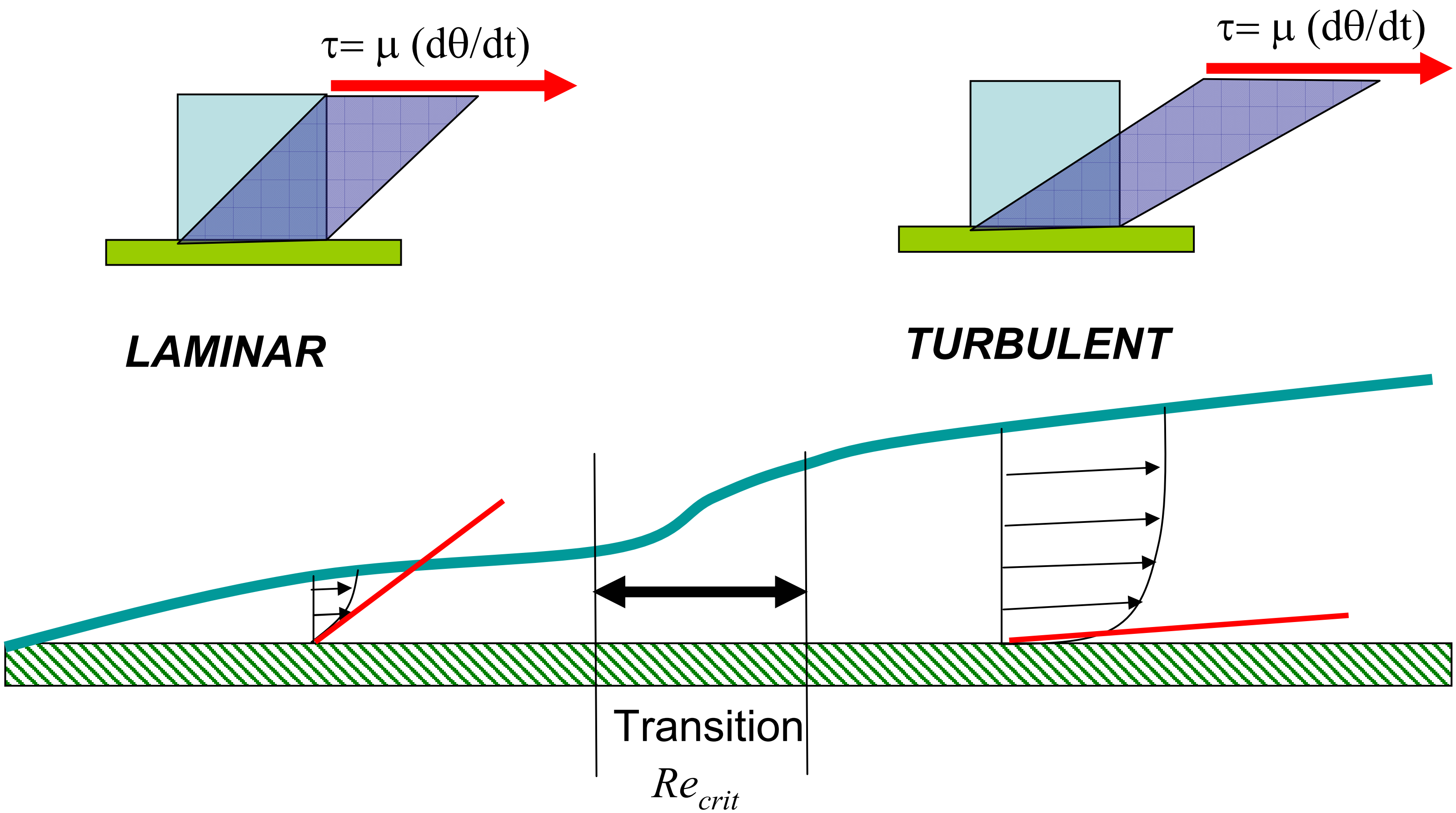
- The drag due to separation effects is Pressure/Form drag.
  - Want to minimize separation
    - Turbulent boundary layer
    - Change the shape!





Another Form of Drag… Friction Drag

- Turbulent vs. Laminar boundary Layers:



Drag

- ***Friction Drag***
  - Lower for *LAMINAR FLOWS*
  - Higher for *TURBUENT FLOWS*

- ***Pressure Drag***
  - Larger Wake = More Drag
    - Want streamline bodies
  - Separation delayed for turbulent flows (less drag)
  - Earlier separation in laminar flow (more drag)

Reynold’s Number

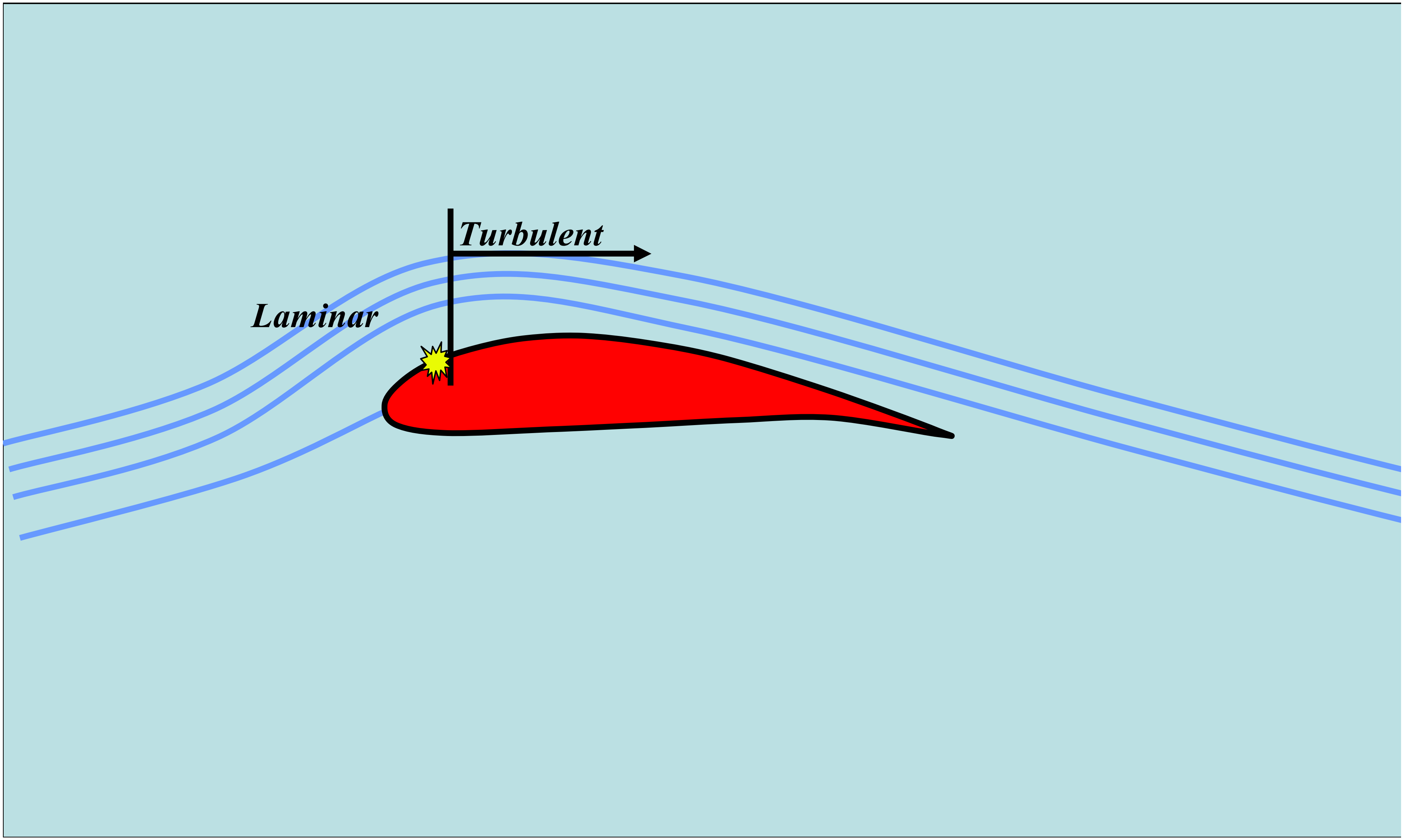
- Reynold’s number plays a significant role in the prediction of laminar vs. turbulent flow (Reynold’s number = indication of dynamic similitude)

$$Re = (\rho * U * L)/\mu$$

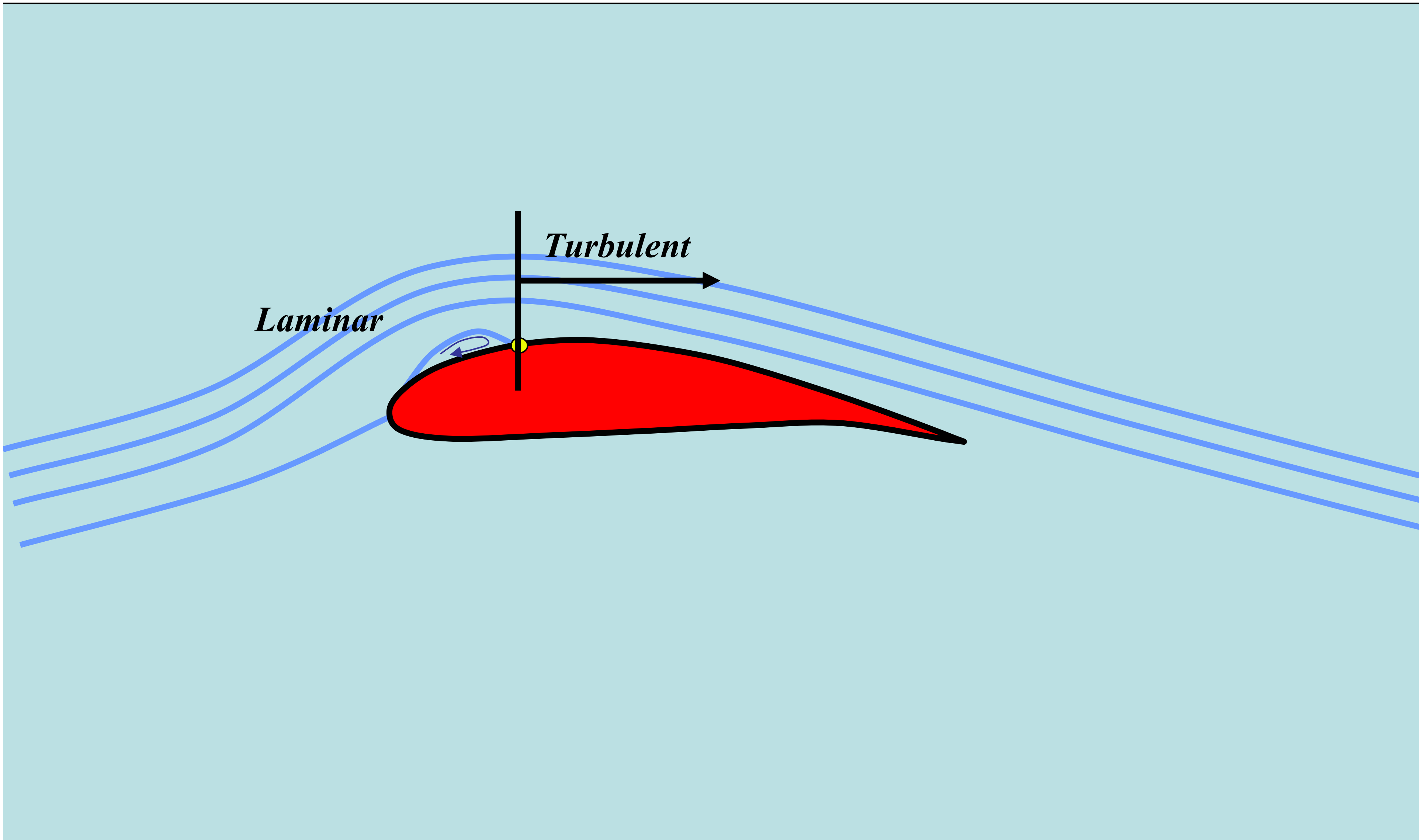
  - Ratio of inertia forces/viscous forces
  - At low Re, viscous forces dominate, while at high Re inertial forces dominate.

- ***BUT…***

How do we make a Turbulent BL?

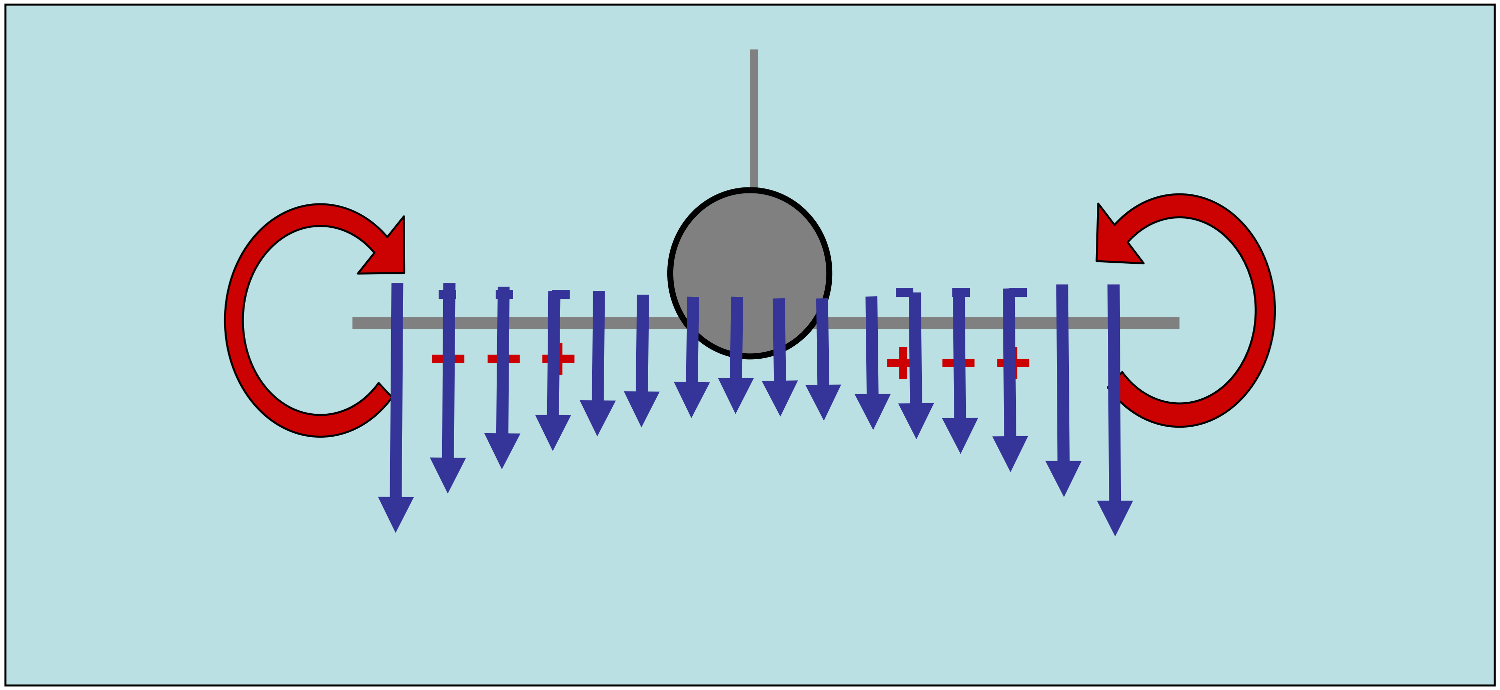


Laminar Separation Bubbles



Wake Vortex Study at Wallops Island
NASA Langley Research Center 5/4/1990 Image # EL-1996-00130

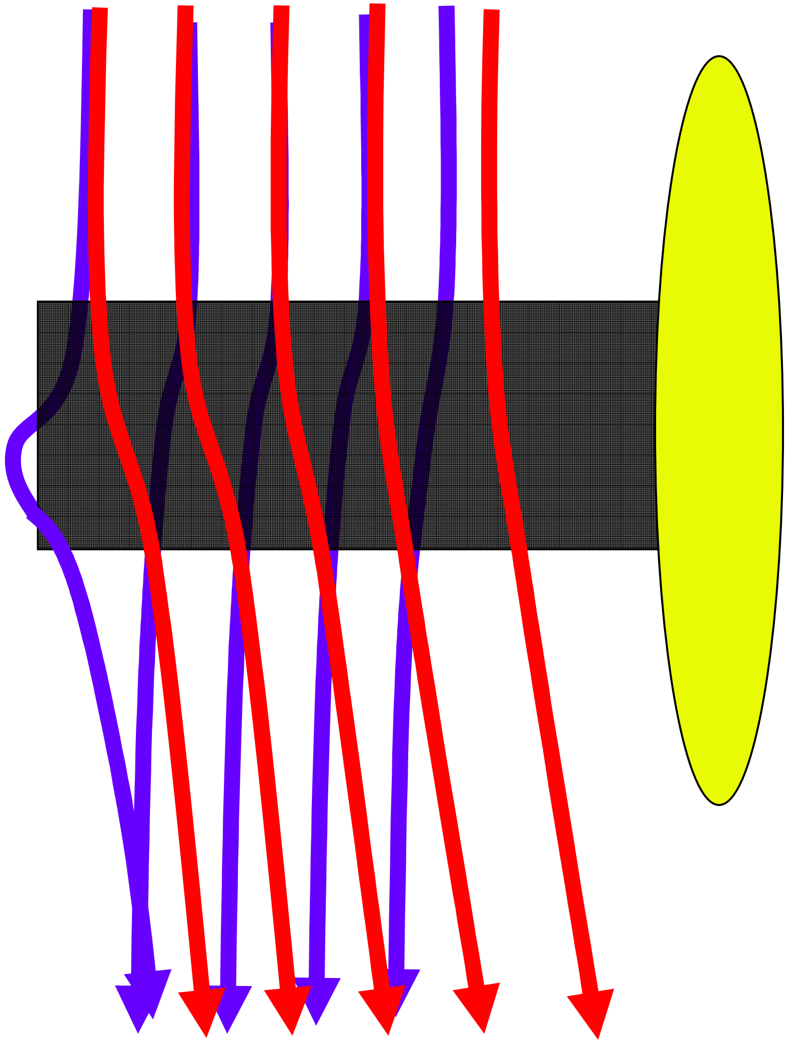
What’s Going On?



The vortices trailing the wings produce downwash!!!!

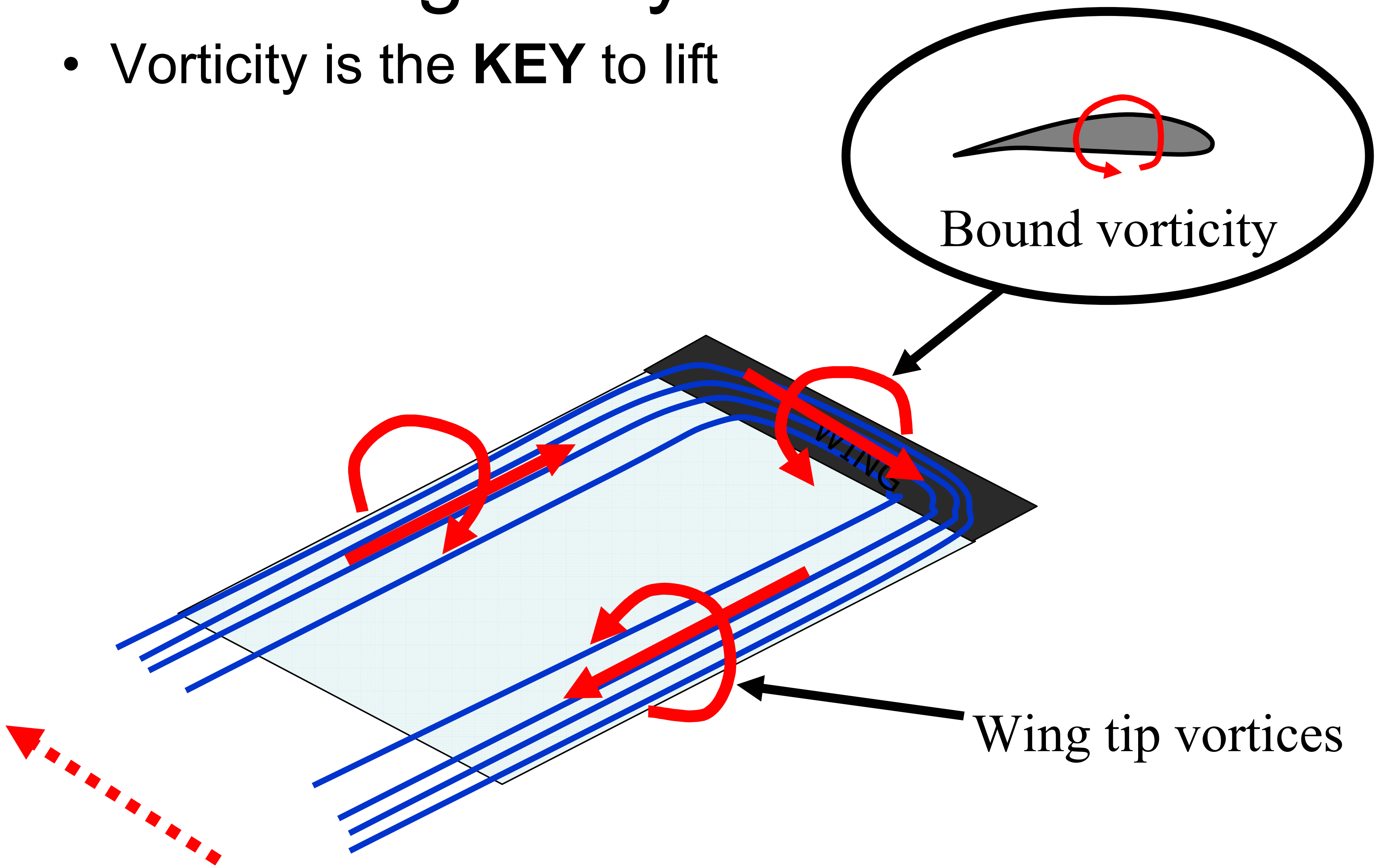
1) Flow from the lower side (Higher Pressure – HP) side wants to “leak” to the low pressure side of the wing
2) At the wing tips this leakage starts (the flow on the upper surface flows inwards Along the wing, while the flow on the lower surface flows outwards)
3) Vorticity is released at the trailing edge

Vorticity



Lifting Body Problems

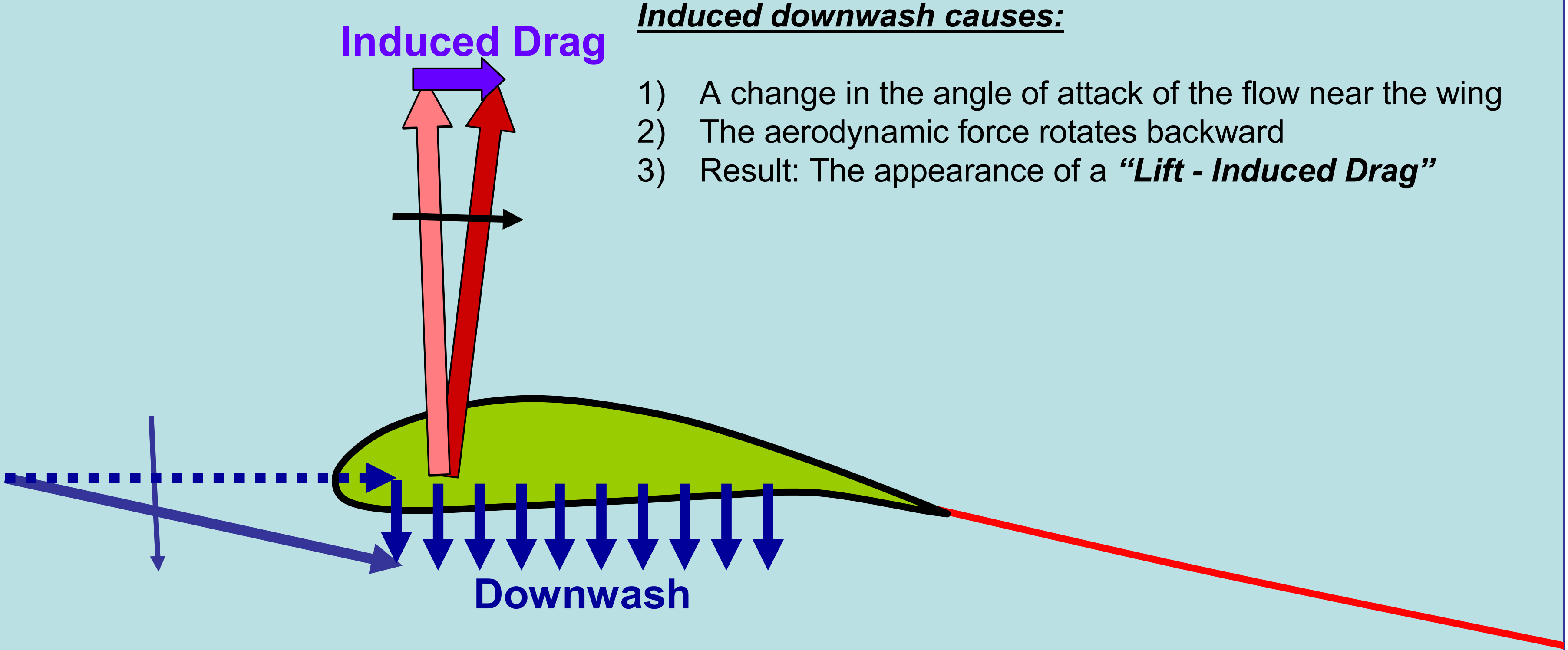
- Vorticity is the **KEY** to lift



Ramifications of Downwash

Induced downwash causes:

1) A change in the angle of attack of the flow near the wing
2) The aerodynamic force rotates backward
3) Result: The appearance of a ***"Lift - Induced Drag"***



What does this mean?

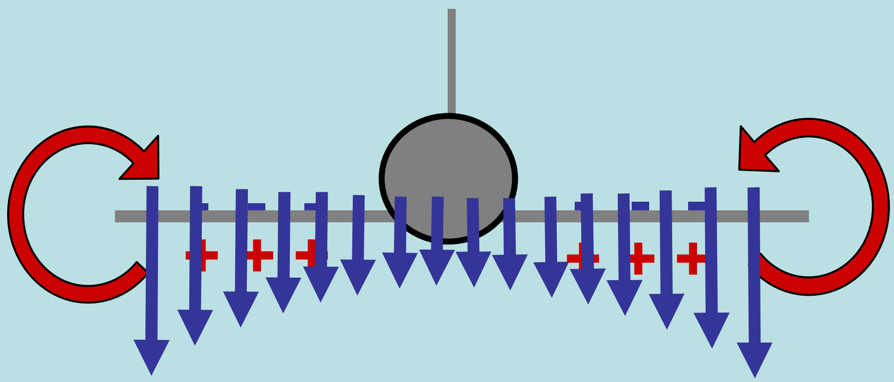
- Induced Drag:

  - $C_D = C_{Dpro} + (C_L)^2 / [\pi(AR)e]$
  - $C_D = C_{Dpro} + C_{Di}$

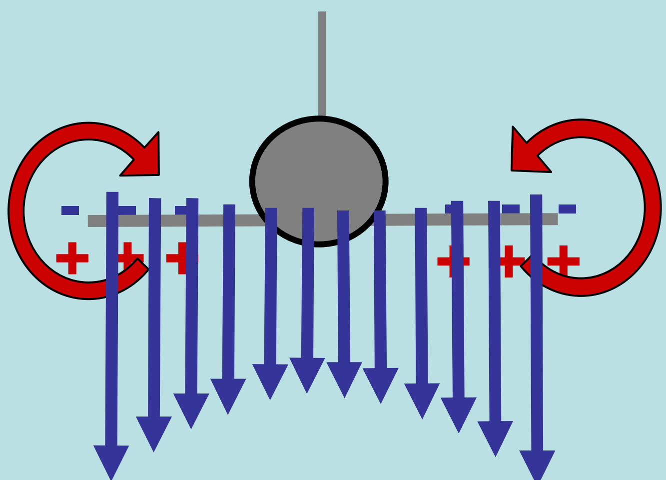
- Lift Reduction:

  - $C_L = 2\pi\alpha/(1+2/AR)(1+\tau)$

Aspect Ratio

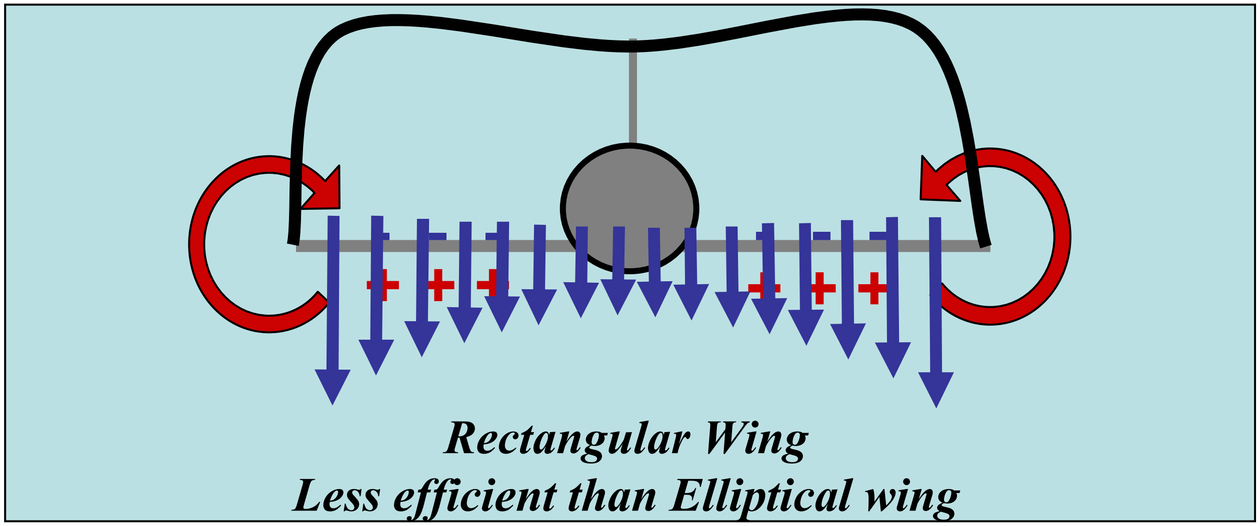


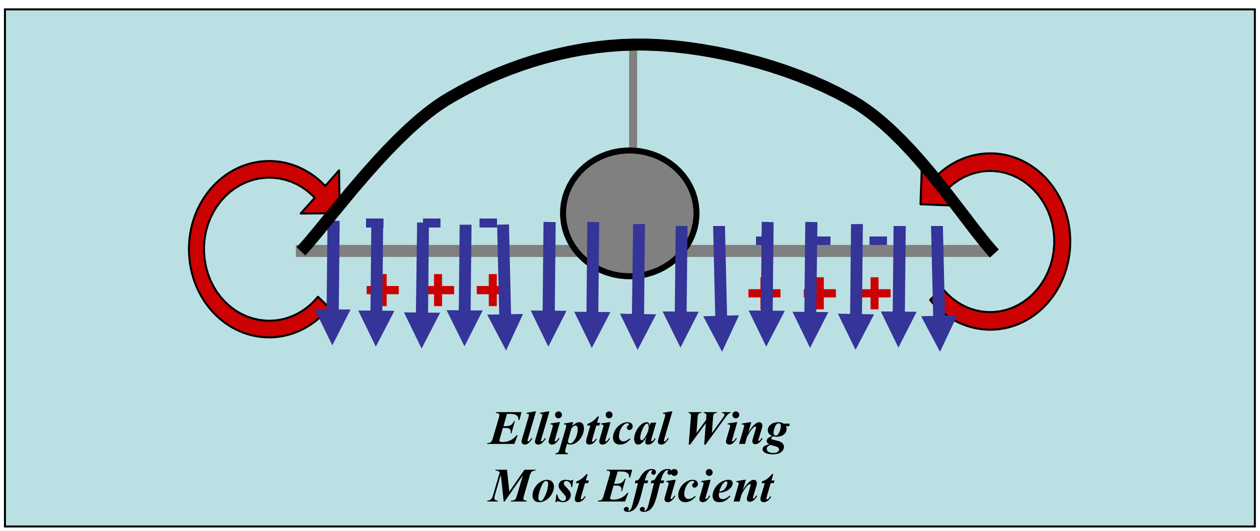
Higher aspect ratio: Vortex separation is greater,
less downwash



Low aspect ratio: Vortex separation is small,
more downwash for same lift

e: Oswald's Efficiency



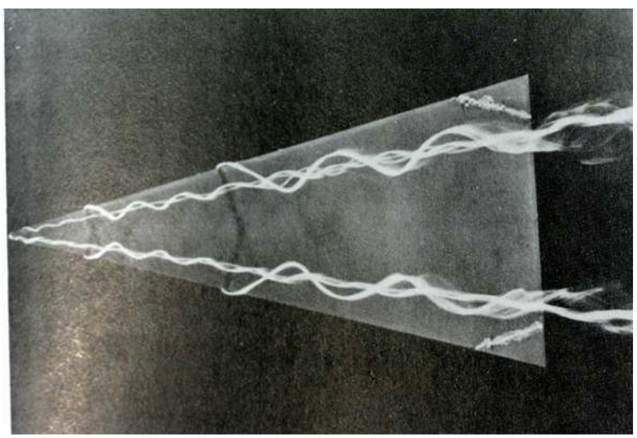


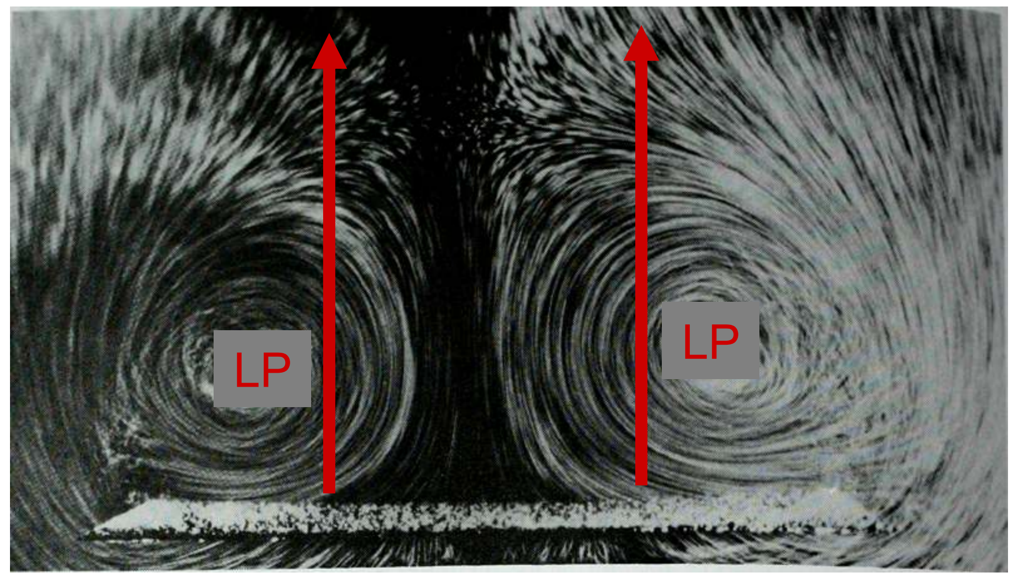
Lift Distribution…

- For level flight, minimum induced drag occurs when the lift distribution is elliptical.
  - Either:
    a) The wing shape is elliptical
    b) The incidence angle produces an elliptical lift.

Other 3-D Effects

- LEV's. Vortex induced lift.





J.D.Anderson, Fundamentals of Aerodynamics, 2nd Edition, McGraw Hill, 1991

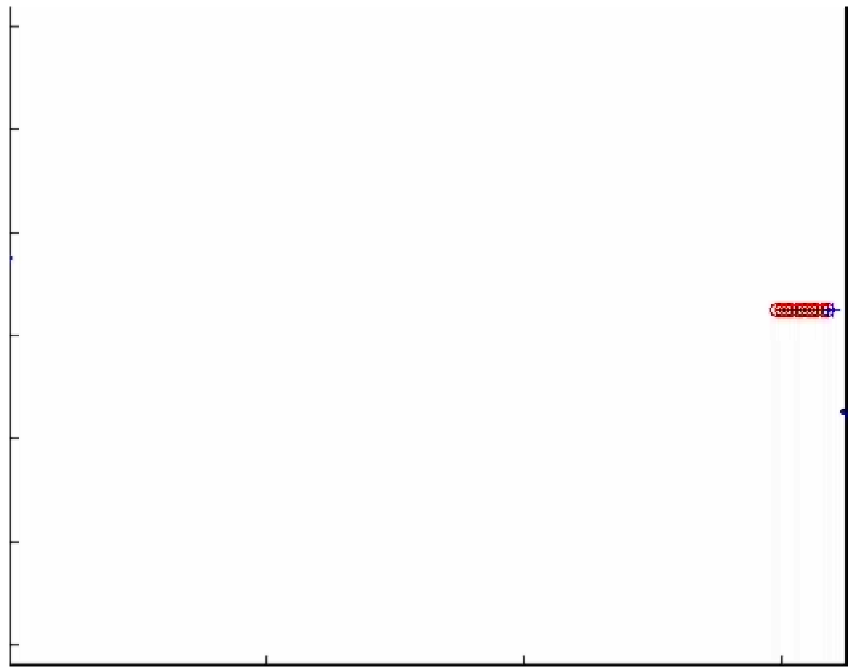
So WHAT?!

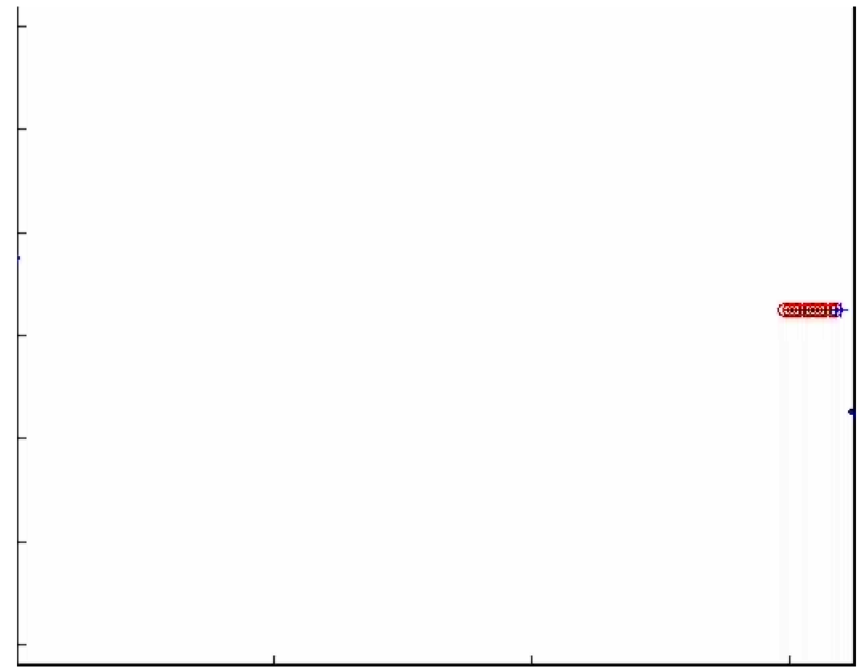
- We’ve got all this lift/drag etc. garbage…
  - How to use it?

Range & Endurance Equations

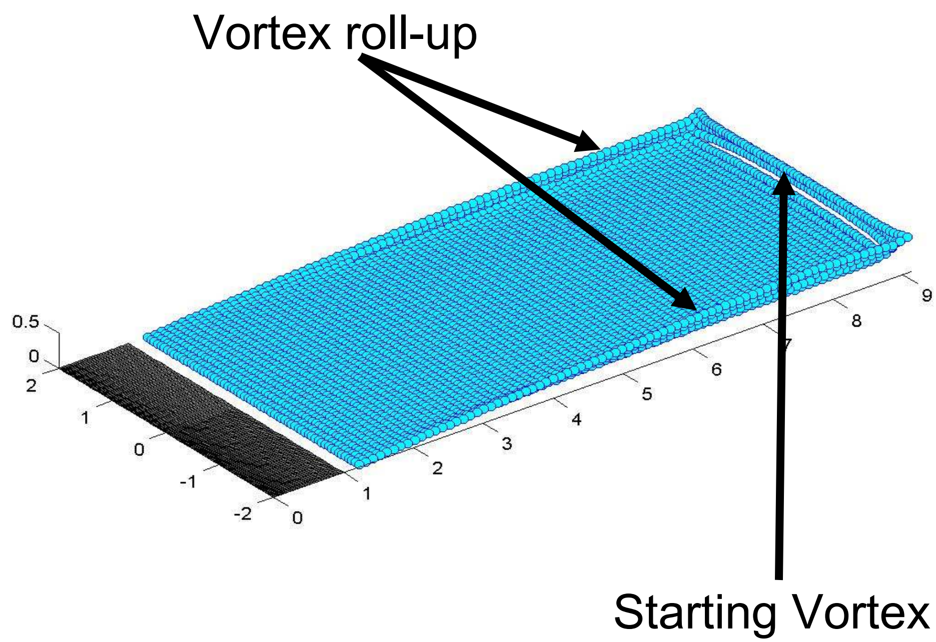
- ***Range*** $= (1/c)(C_L/C_D)\,\eta_{overall}\,\ln(w_i/w_f)$
  - *Max efficiency*
  - *Max* C_L/C_D
- ***Endurance*** $= (\eta_{overall}/c)(C_L^{3/2}/C_D)\,\mathrm{sqrt}(2^*\rho^*S)(1/w_f - 1/w_i)$
  - *Max efficiency*
  - *Max density (ie. Sea level)*
  - *Large* $(C_L^{3/2}/C_D)$*: Fly at a velocity where this occurs*

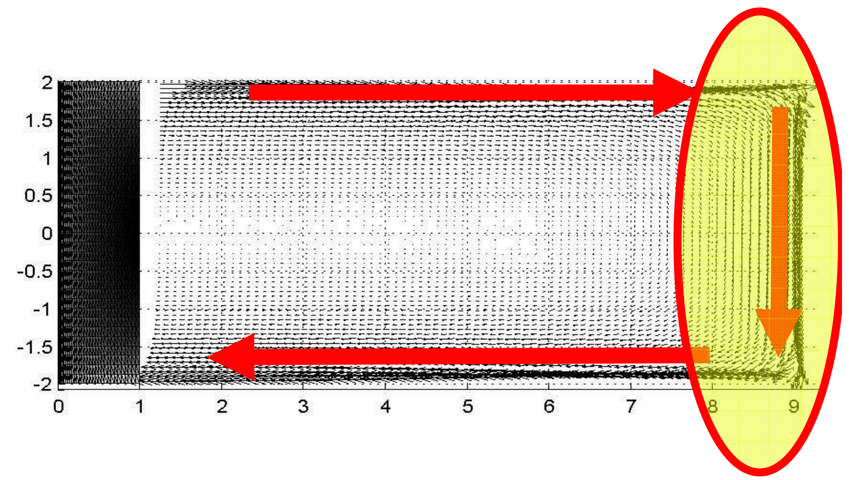
Unsteady Aerodynamics



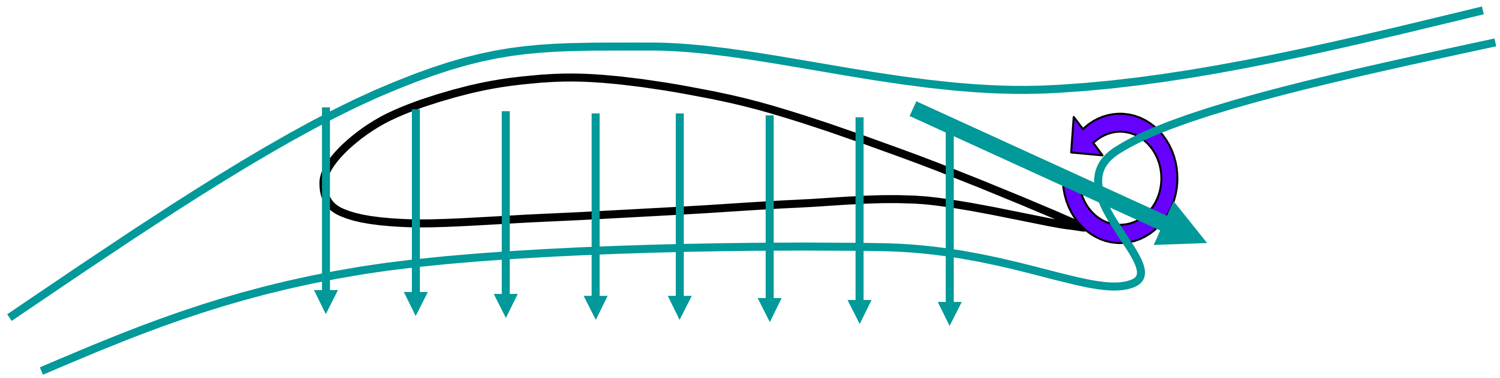


Finite Wing Start-Up Flow

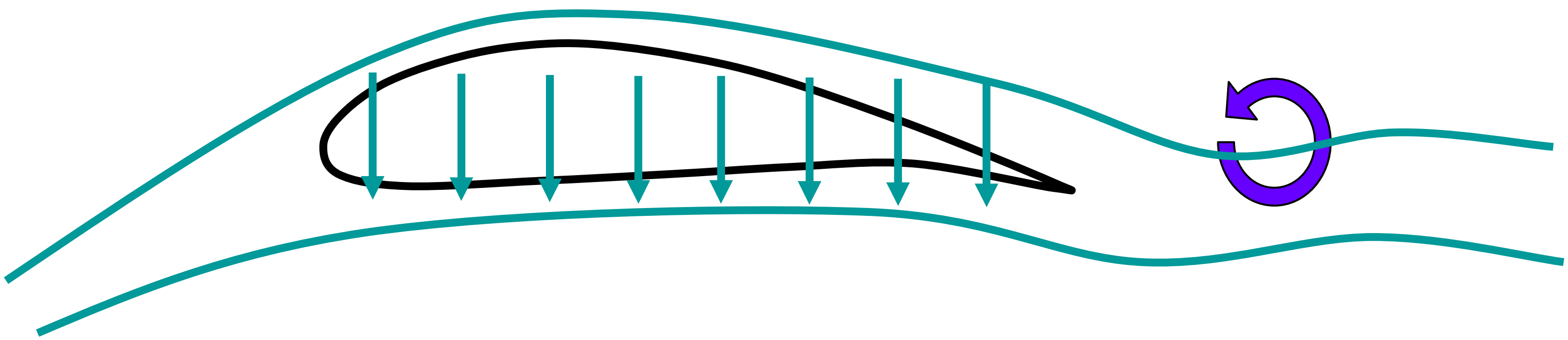




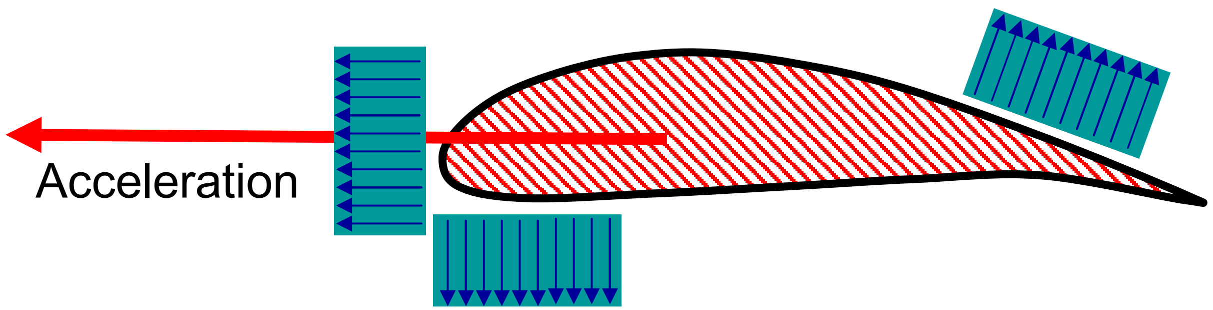
Starting Vortex Effect



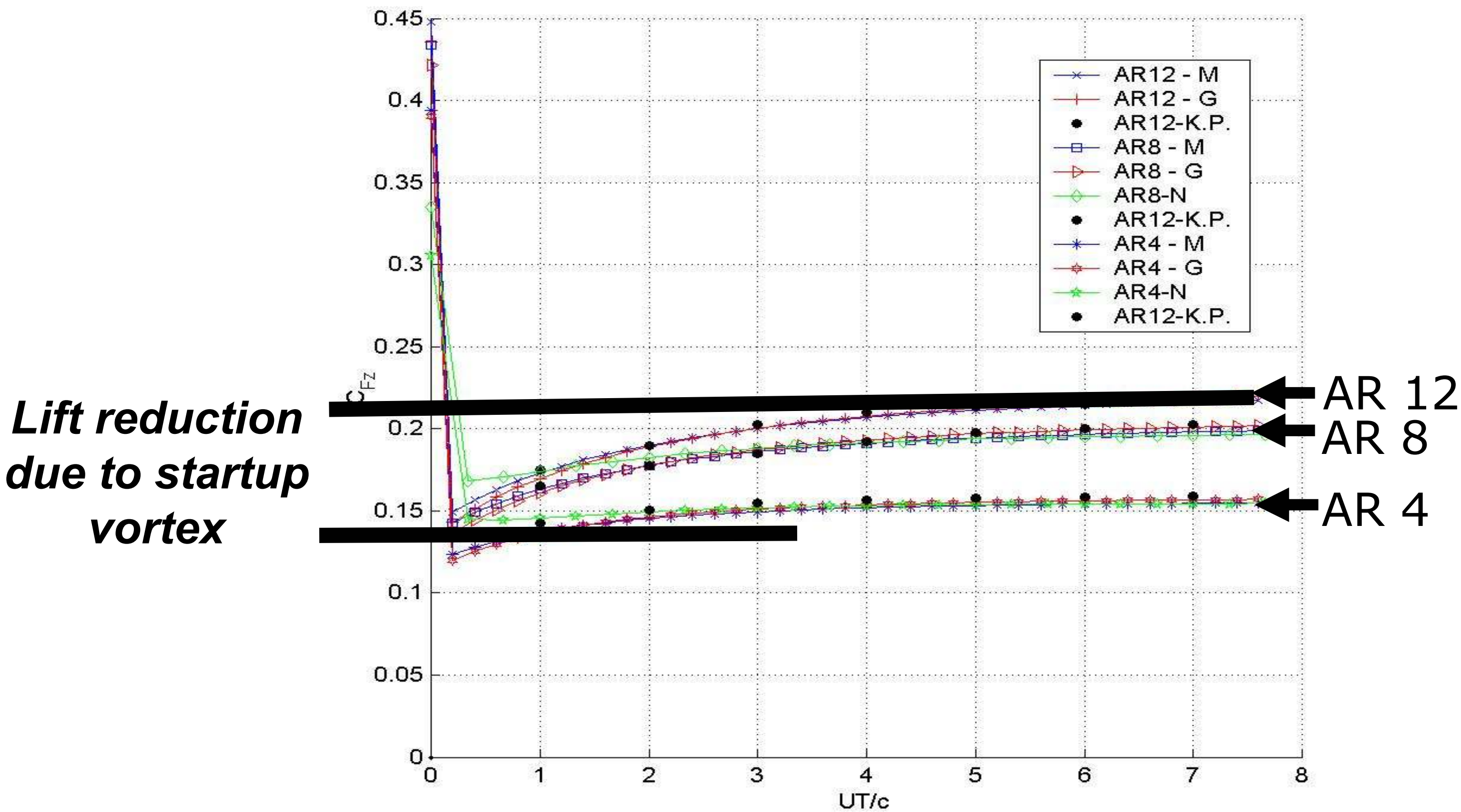
Starting Vortex Effect



Acceleration of the Fluid



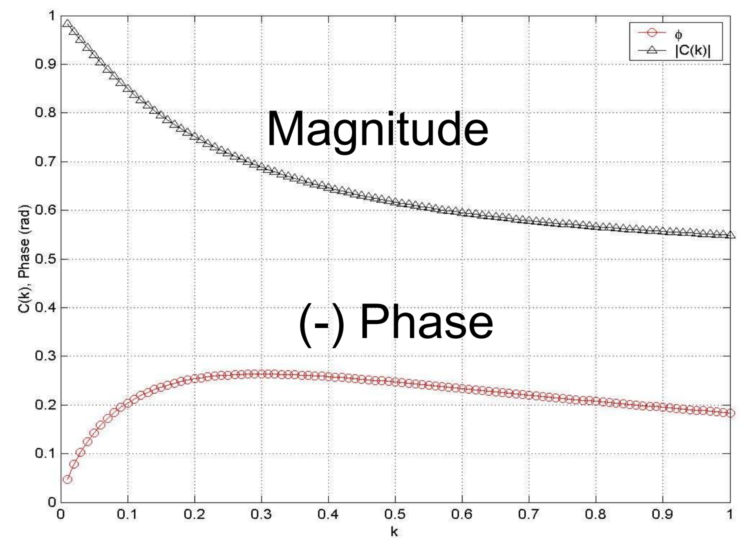
Startup Flow Comparisons



Finite Wing Heave Oscillations

Theodorsen 2-D flat plate heaving motions Z-Force component

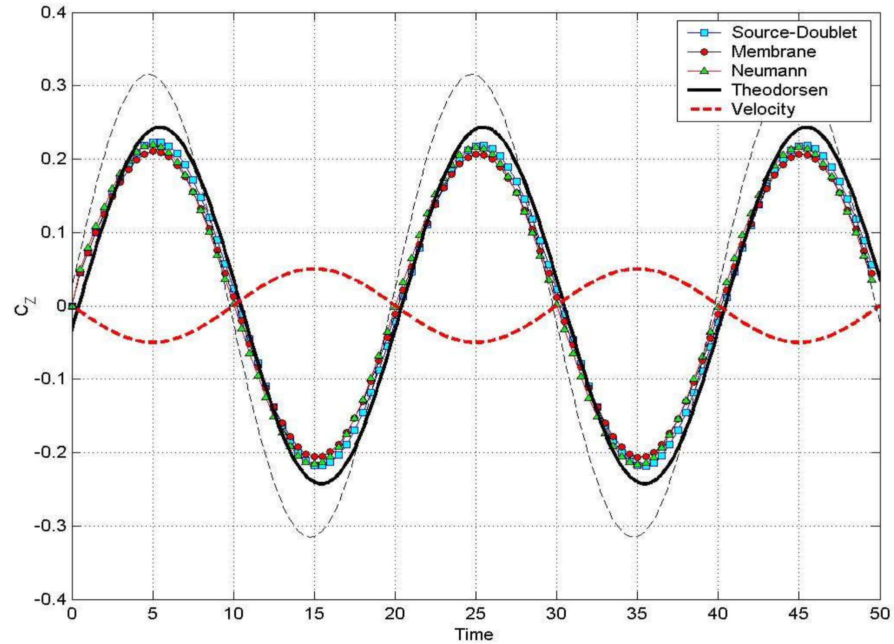
$$F_Z = -\pi\rho c\left(\underbrace{UC(k)\frac{dh}{dt}}_{\text{Circulatory}} - \underbrace{\frac{c}{4}\frac{d^2h}{dt^2}}_{\text{Added Mass}}\right)$$



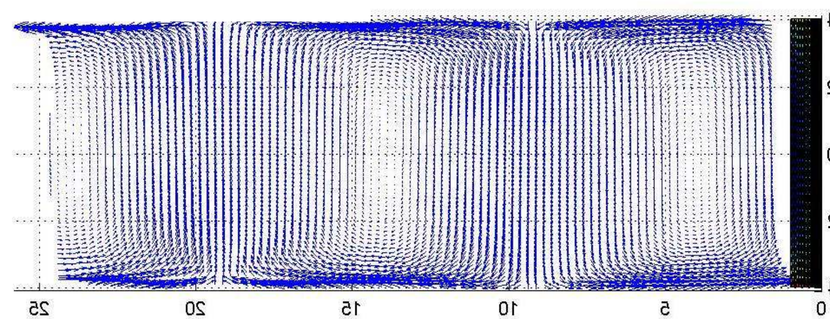
Theodorsen's : *C(k)*

$$k = \frac{\omega c}{2U}$$

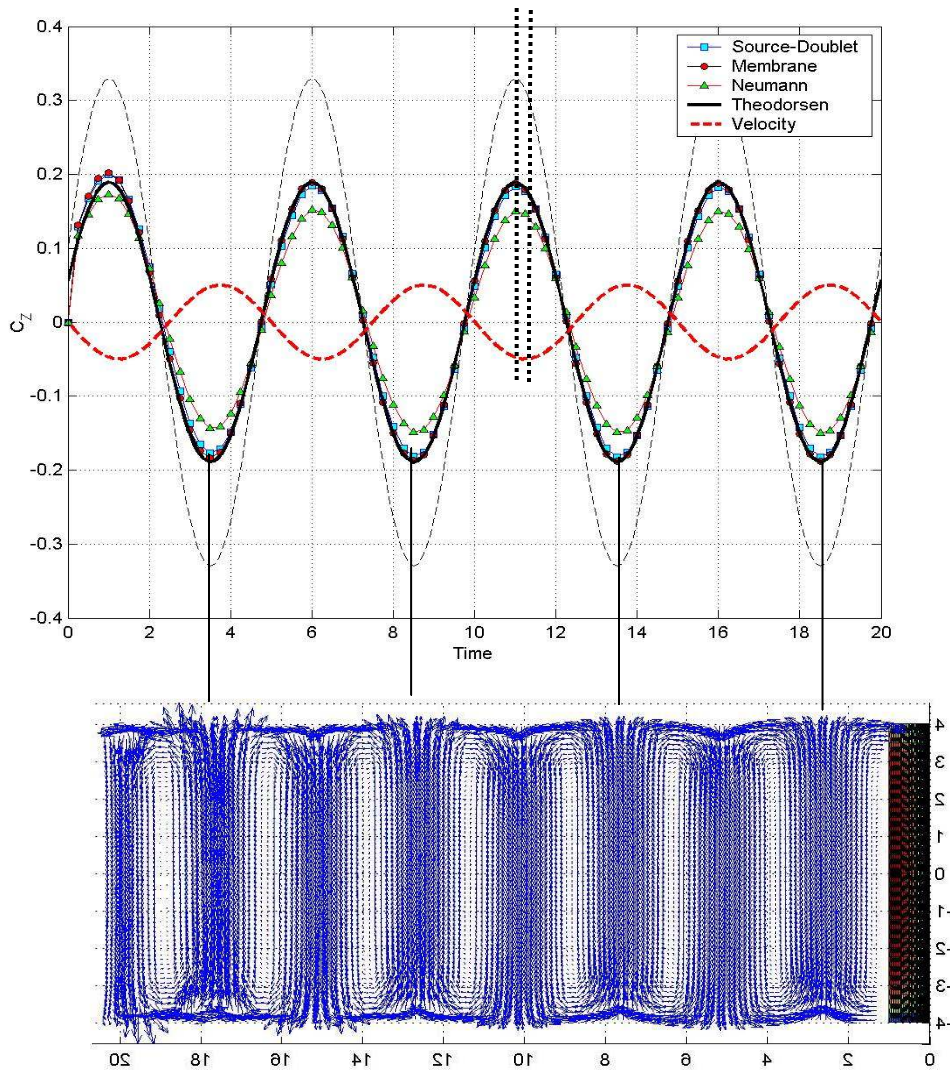
Slow Heave Oscillations



$$F_Z = -\pi\rho c\left(\underbrace{UC(k)\frac{dh}{dt}}_{\text{Circulatory 3D effects!}} - \underbrace{\cancel{\frac{c}{4}\frac{d^2h}{dt^2}}}_{\text{Added Mass Negligible}}\right)$$

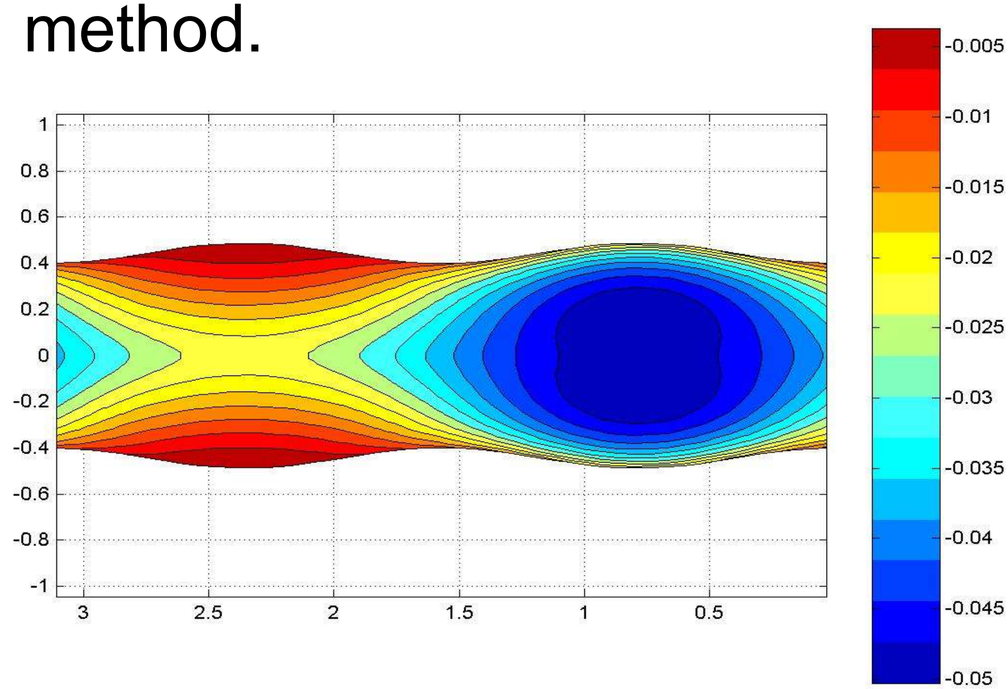


Fast Heave Oscillations

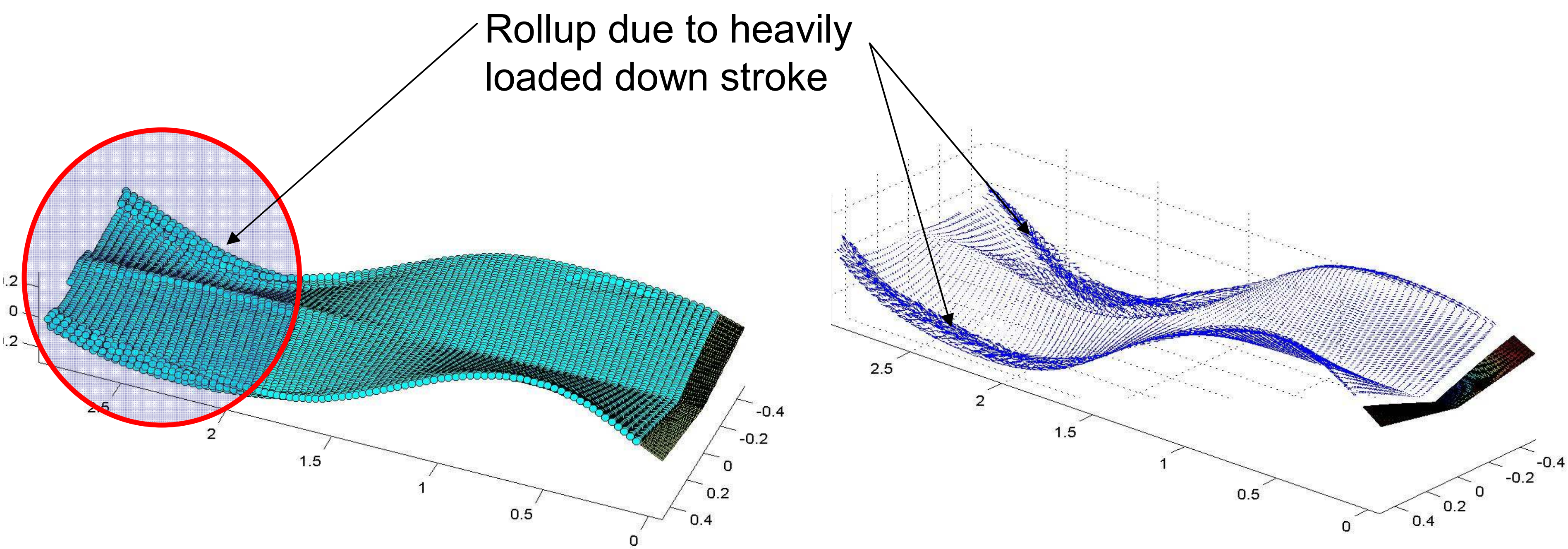


Example: Flapping Wing Simulations

- Solve Hall et al. method for optimal vorticity wake
- Determine the zero lift flapping wing geometry
- Augment it with the local angle of attack predicted by Hall et. al. method.



Flapping Flight Results



Vortex Particles

Vorticity Vectors

Conclusions

- Used physical conservation principles to gain insight into fluid flow
- Saw that in 3-D the system of trailing vortices plays an important role:
  - Reduces lift and increases drag
- Unsteady effects are complicated due to vorticity “distributions” and added mass acceleration effects.