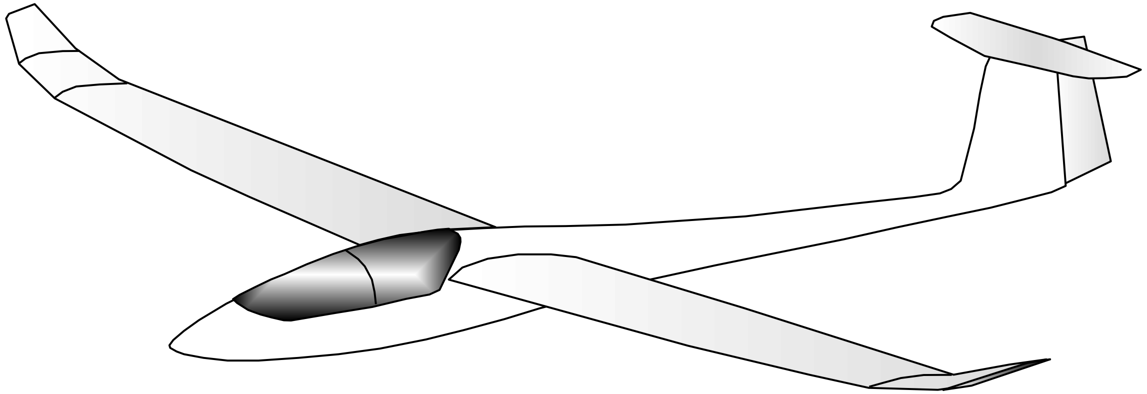
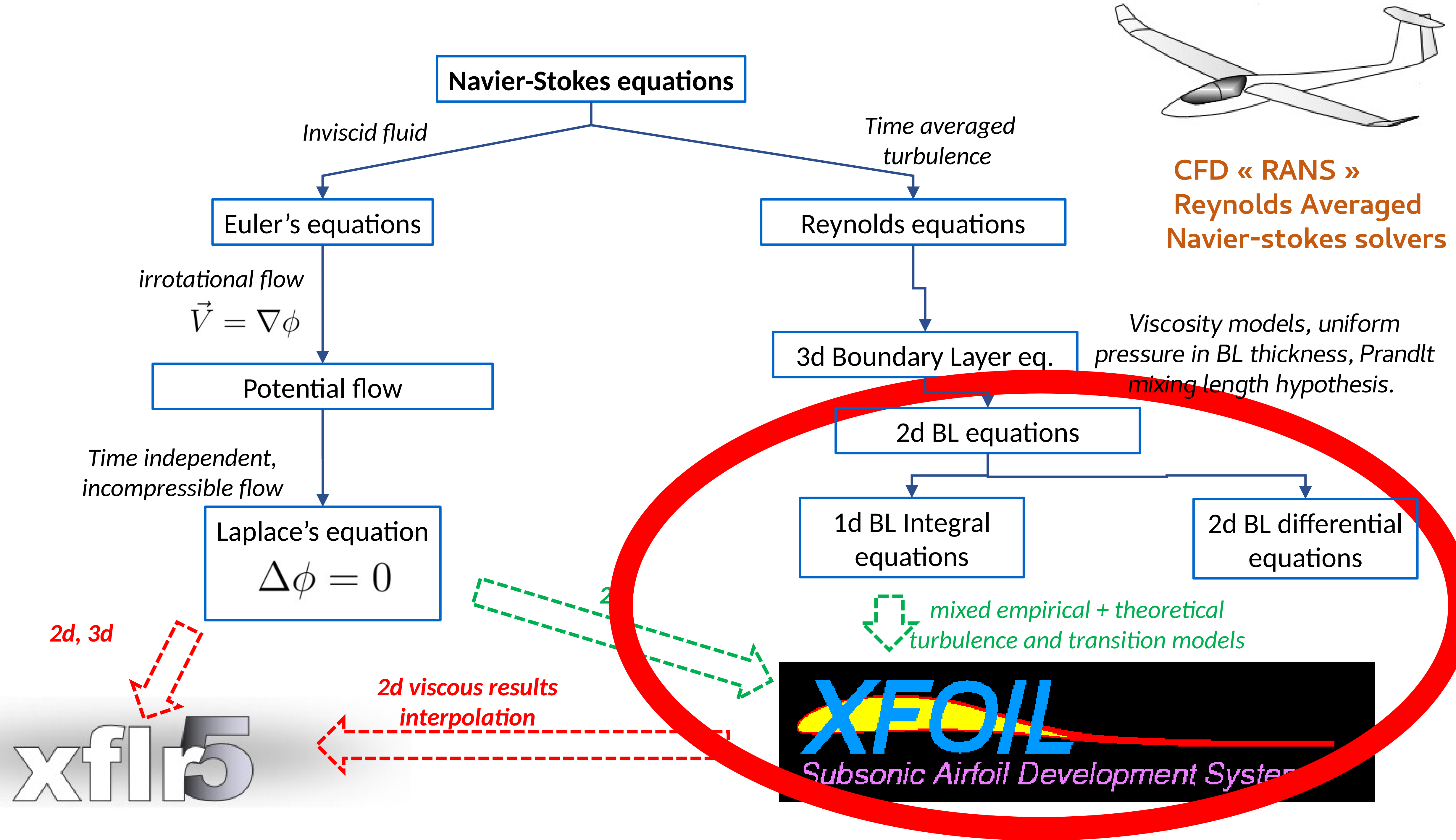


Why does an airfoil drag: the viscous problem

Rev. 1.1 – © André Deperrois – March 2019



Navier-Stokes equations

Inviscid fluid

Euler's equations

irrotational flow

$\vec{V} = \nabla\phi$

Potential flow

Time independent, incompressible flow

Laplace's equation

$$\Delta\phi = 0$$

Time averaged turbulence

Reynolds equations

3d Boundary Layer eq.

Viscosity models, uniform pressure in BL thickness, Prandlt mixing length hypothesis.

2d BL equations

1d BL Integral equations

2d BL differential equations

mixed empirical + theoretical turbulence and transition models

2

2d, 3d

2d viscous results interpolation

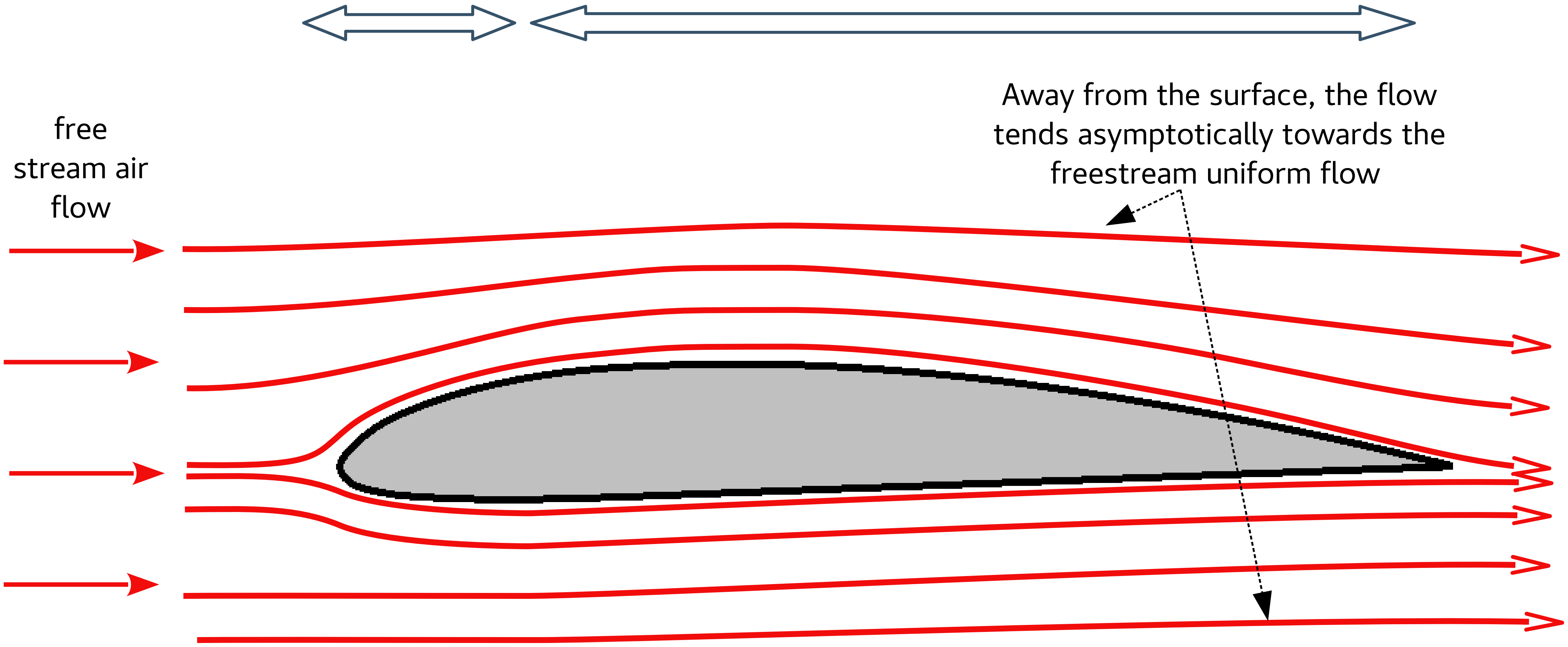
XFOIL

Subsonic Airfoil Development Syste

xflr5

CFD « RANS »
Reynolds Averaged
Navier-stokes solvers

The inviscid flow around an airfoil



Favourable pressure gradient, the flow accelerates from zero at the leading edge's stagnation point.

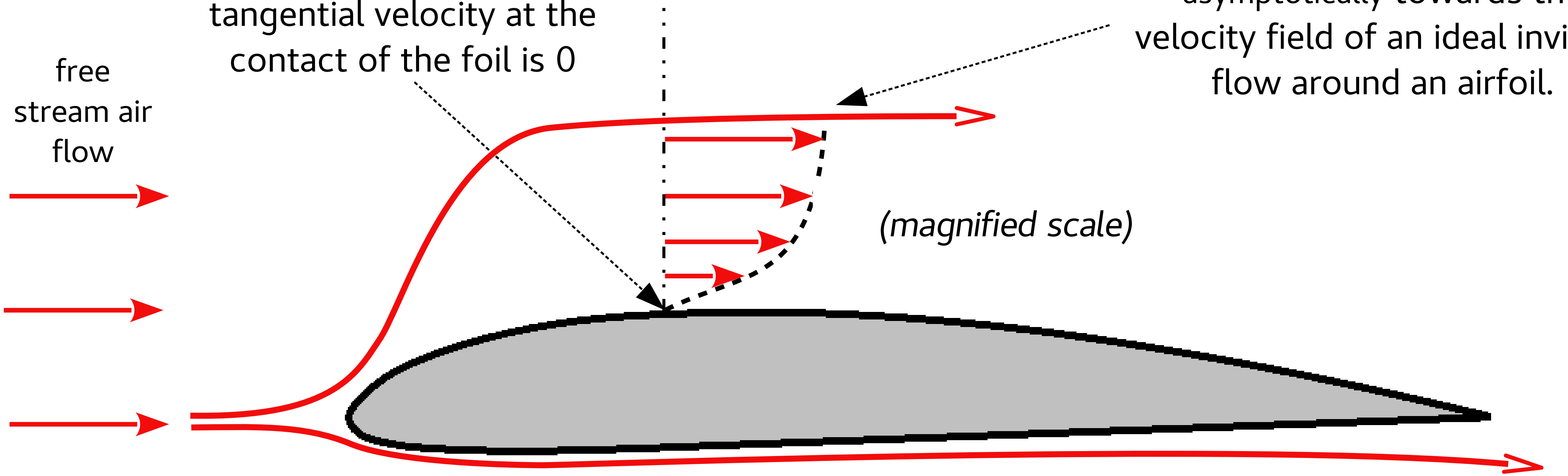
Adverse pressure gradient, the flow decelerates

free stream air flow

Away from the surface, the flow tends asymptotically towards the freestream uniform flow

inviscid ◂—▸ "laminar",

The boundary layer



free
stream air
flow

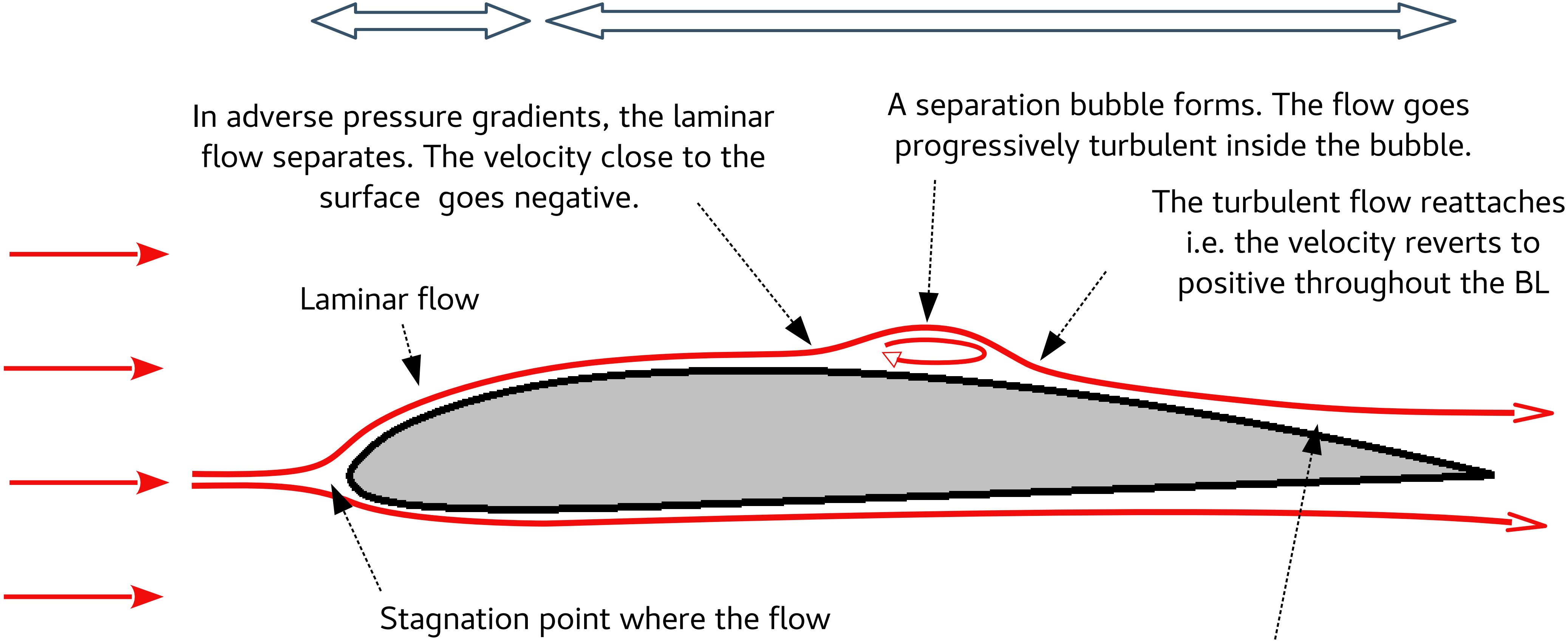
Due to viscosity, the
tangential velocity at the
contact of the foil is 0

Away from the surface, the
fluid’s velocity tends
asymptotically towards the
velocity field of an ideal inviscid
flow around an airfoil.

(magnified scale)

The boundary layer is defined as the flow between the foil’s surface and the thickness where the fluid’s velocity reaches 99% or 99.5% of the inviscid flow’s velocity.

The viscous flow around an airfoil at low Reynolds number



Favourable pressure gradient, the flow accelerates from zero at the leading edge's stagnation point.

Adverse pressure gradient, the flow decelerates

In adverse pressure gradients, the laminar flow separates. The velocity close to the surface goes negative.

A separation bubble forms. The flow goes progressively turbulent inside the bubble.

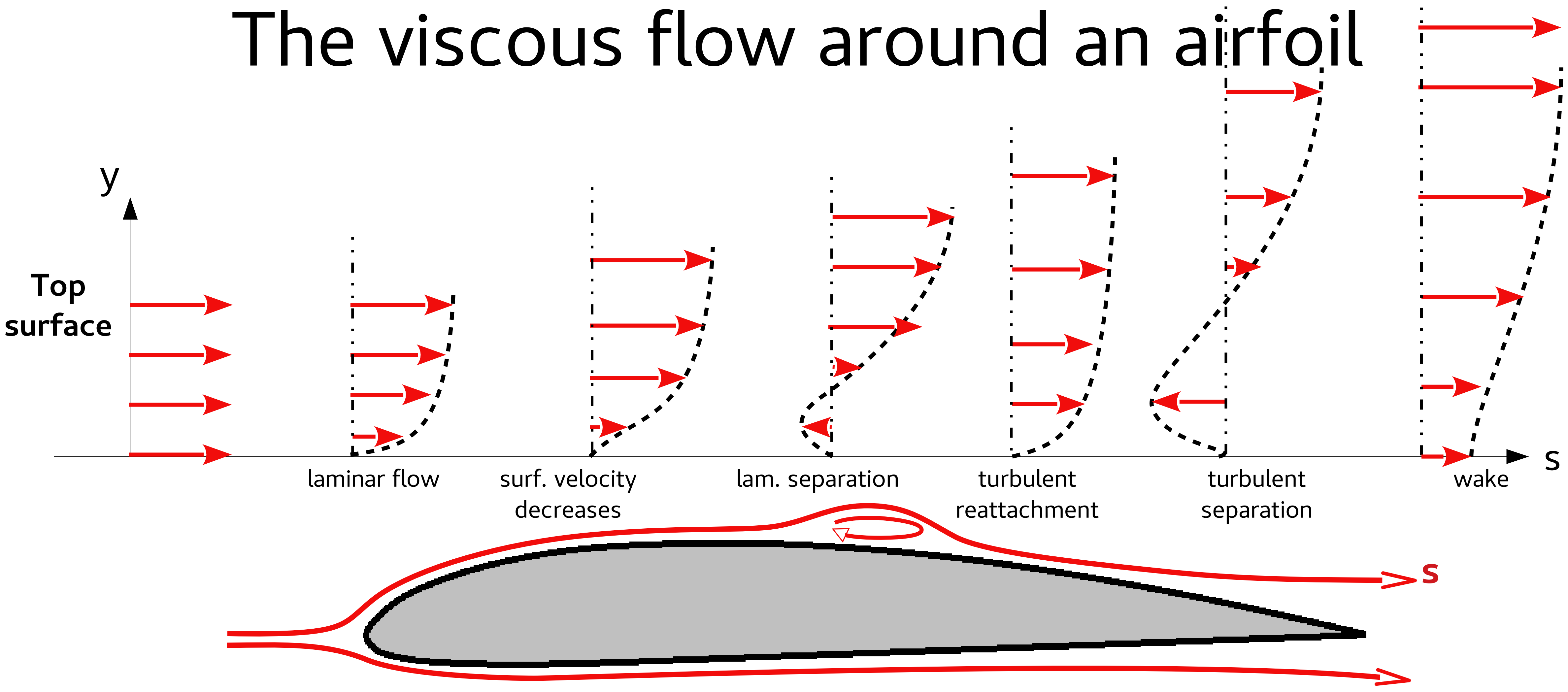
The turbulent flow reattaches, i.e. the velocity reverts to positive throughout the BL

Laminar flow

Stagnation point where the flow separates and the tangential velocity is 0

The turbulent flow separates

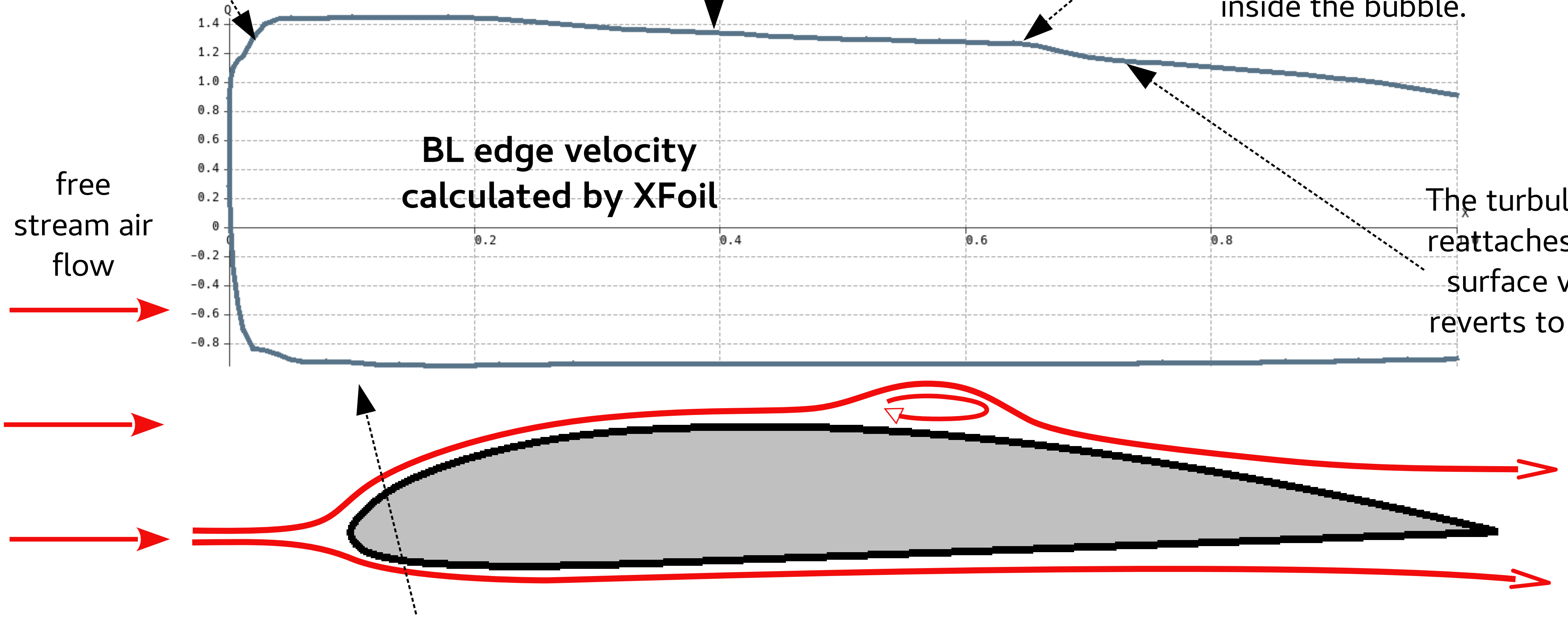
The viscous flow around an airfoil



Things to note

- The BL thickness increases progressively
  No surface slip on the airfoil surface

The viscous flow around an airfoil



Favorable pressure gradient, the flow accelerates.

Adverse pressure gradient, the flow decelerates and separates.

A separation bubble forms. The flow goes progressively turbulent inside the bubble.

BL edge velocity calculated by XFoil

free stream air flow

The turbulent flow reattaches, i.e. the surface velocity reverts to positive

Stagnation point where the flow divides and the tangential velocity is 0

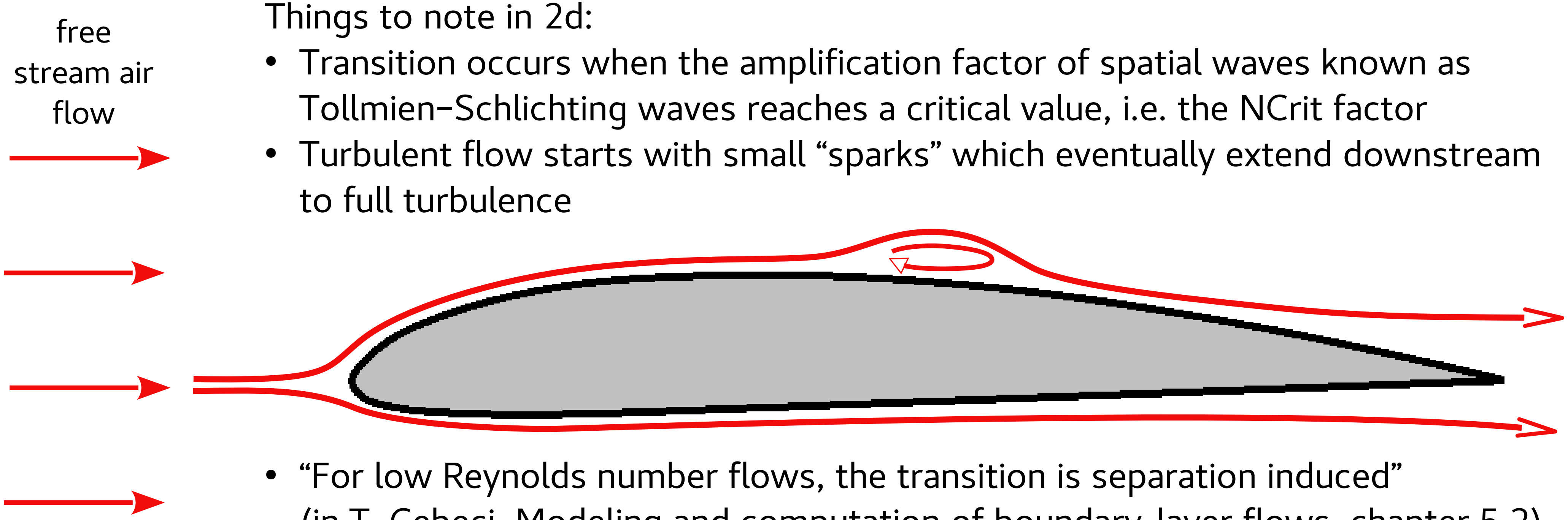
The viscous flow around an airfoil

The transition problem

The transition from laminar to turbulent flow is a complex problem in 2d and even more so in 3d.

Things to note in 2d:

- Transition occurs when the amplification factor of spatial waves known as Tollmien–Schlichting waves reaches a critical value, i.e. the NCrit factor
- Turbulent flow starts with small “sparks” which eventually extend downstream to full turbulence

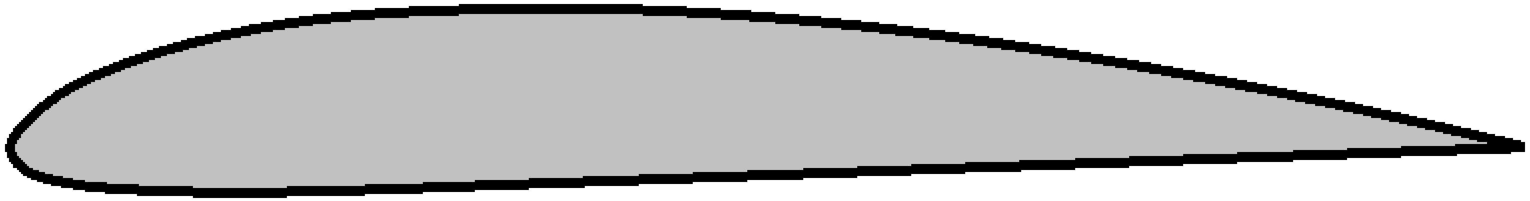


- “For low Reynolds number flows, the transition is separation induced” (in.T. Cebeci, Modeling and computation of boundary-layer flows, chapter.5.2)
  This is also what Xfoil predicts

The 2d problem

The 2d inviscid potential problem can be solved numerically for the velocity field by solving Laplace’s equation

The velocity field is used as an input to solve the BL problem



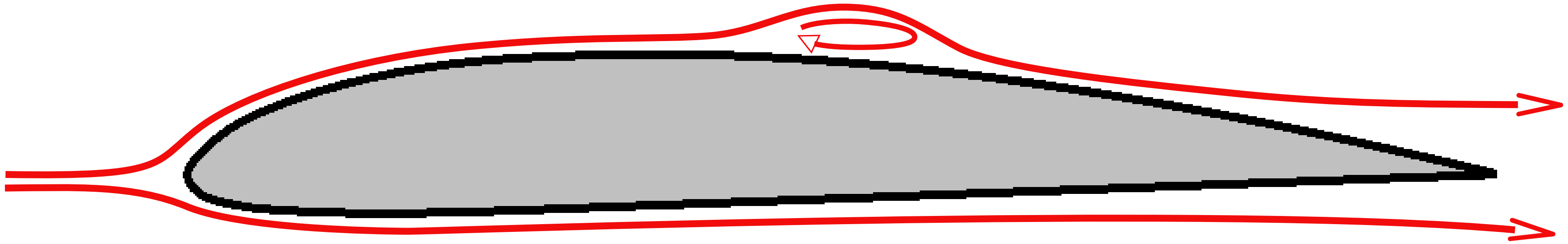
The 2d problem

The 2d inviscid potential problem can be solved numerically for the velocity field

→

The velocity field is used as an input to solve the BL problem

In the 1940s, theoreticians have found that this method does not converge in adverse pressure gradients, e.g. on the upper surface of an airfoil.
This problem is known as the “Goldstein singularity”

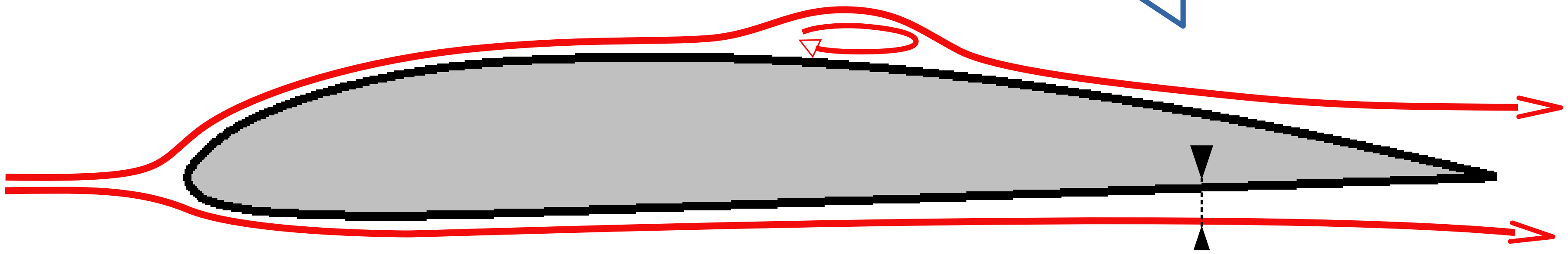


The 2d problem

The 2d inviscid potential problem can be solved numerically for the velocity field

The velocity field is used as an input to solve the BL problem

The reason is that the BL disturbs the inviscid flow: the foil behaves as if it had an additional thickness



The inviscid flow wants to dictate its law to the BL, but the BL does not agree, and vice versa.

This additional thickness is called the “displacement thickness δ*”
Note: not the same thing as the BL thickness

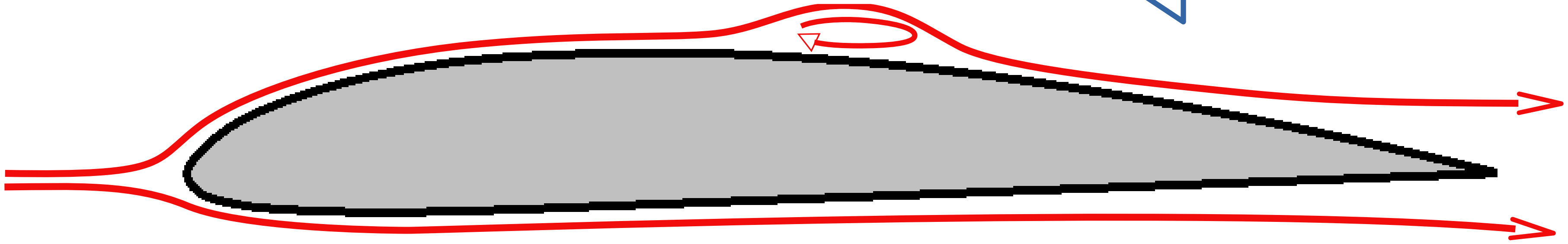
The 2d problem

The 2d inviscid potential problem can be solved numerically for the velocity field

The velocity field is used as an input to solve the BL problem

The reason is that the BL disturbs the inviscid flow: the foil behaves as if it had an additional thickness

The inviscid flow needs to be updated

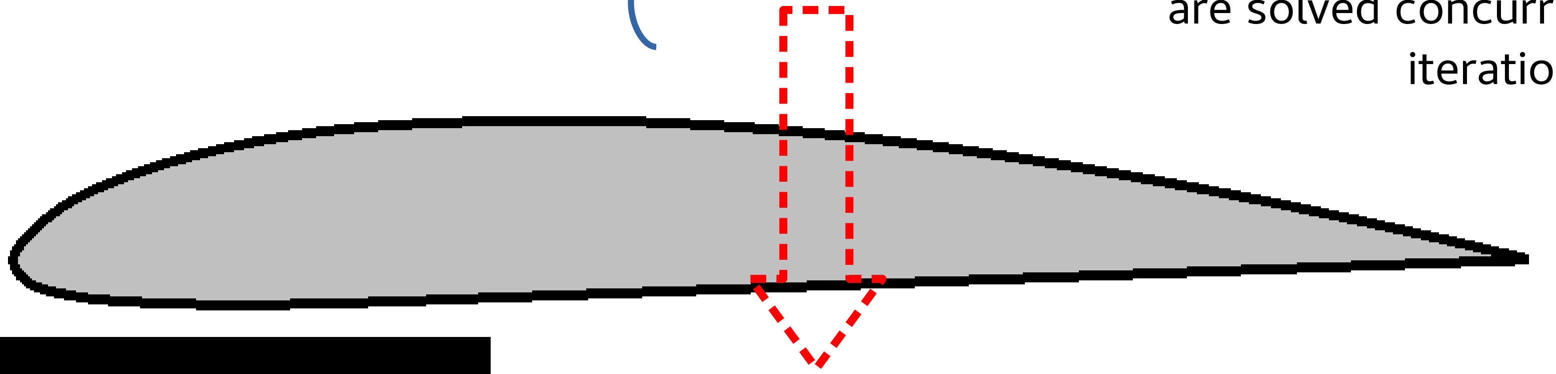


This iterative method is called the “Interactive Boundary Layer”, or IBL

The 2d problem

Many schemes have been proposed for the IBL problem

“Direct” :	The inviscid velocity is used as an input for the BL solver
“Inverse”	The viscous velocity from the BL solution is used as an input for the potential flow solver
“Simultaneous” :	The inviscid and BL equations are solved concurrently at each iteration



XFOIL

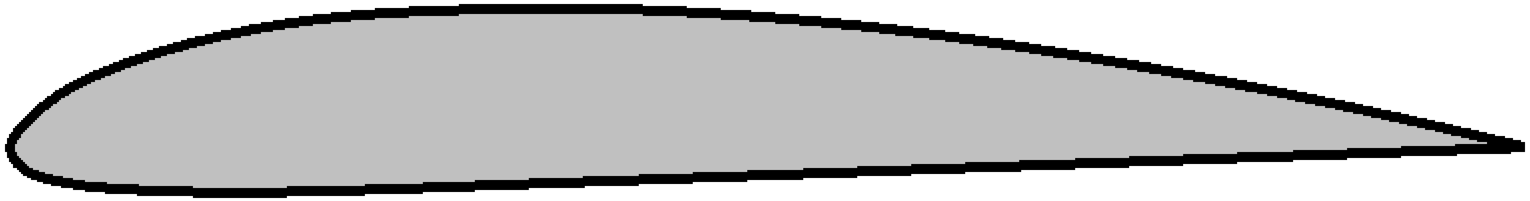
Subsonic Airfoil Development System

Developed by M. Drela and H. Youngren in the 1990s, XFoil is still a (the?) state-of-the-art IBL solver some 30 years later

About XFoil

Three main things which make XFoil outstanding

- A comprehensive set of 2d BL turbulence and transition models
- A full simultaneous IBL solver
- A robust and reliable software package



XFOIL
Subsonic Airfoil Development System

http://web.mit.edu/drela/Public/papers/xfoil_sv.pdf

About XFoil

XFoil's 1D Integral method

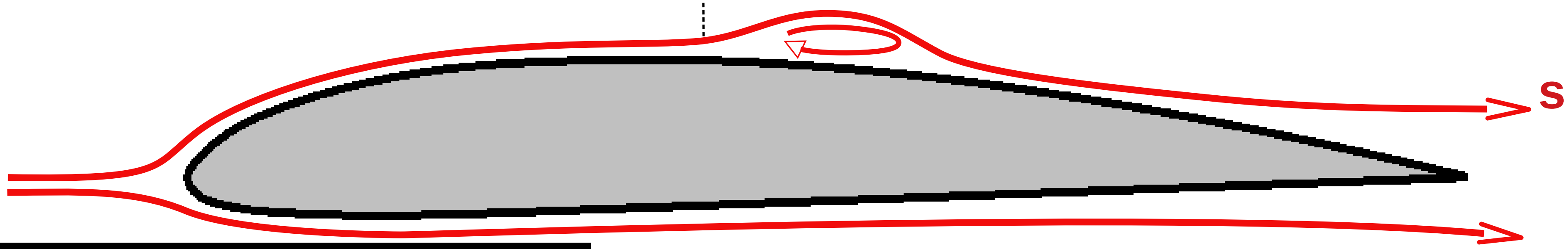
BL equations are integrated in the BL thickness
BL properties are therefore function only of the streamwise position "s"
3 variables, one space dimension

Laminar flow: the BL properties are defined by

- the displacement thickness δ^*
- the momentum thickness θ
- the amplification factor n

Turbulent flow: the BL properties are defined by

- the displacement thickness δ^*
- the momentum thickness θ
- the max. shear stress coeff. C_τ

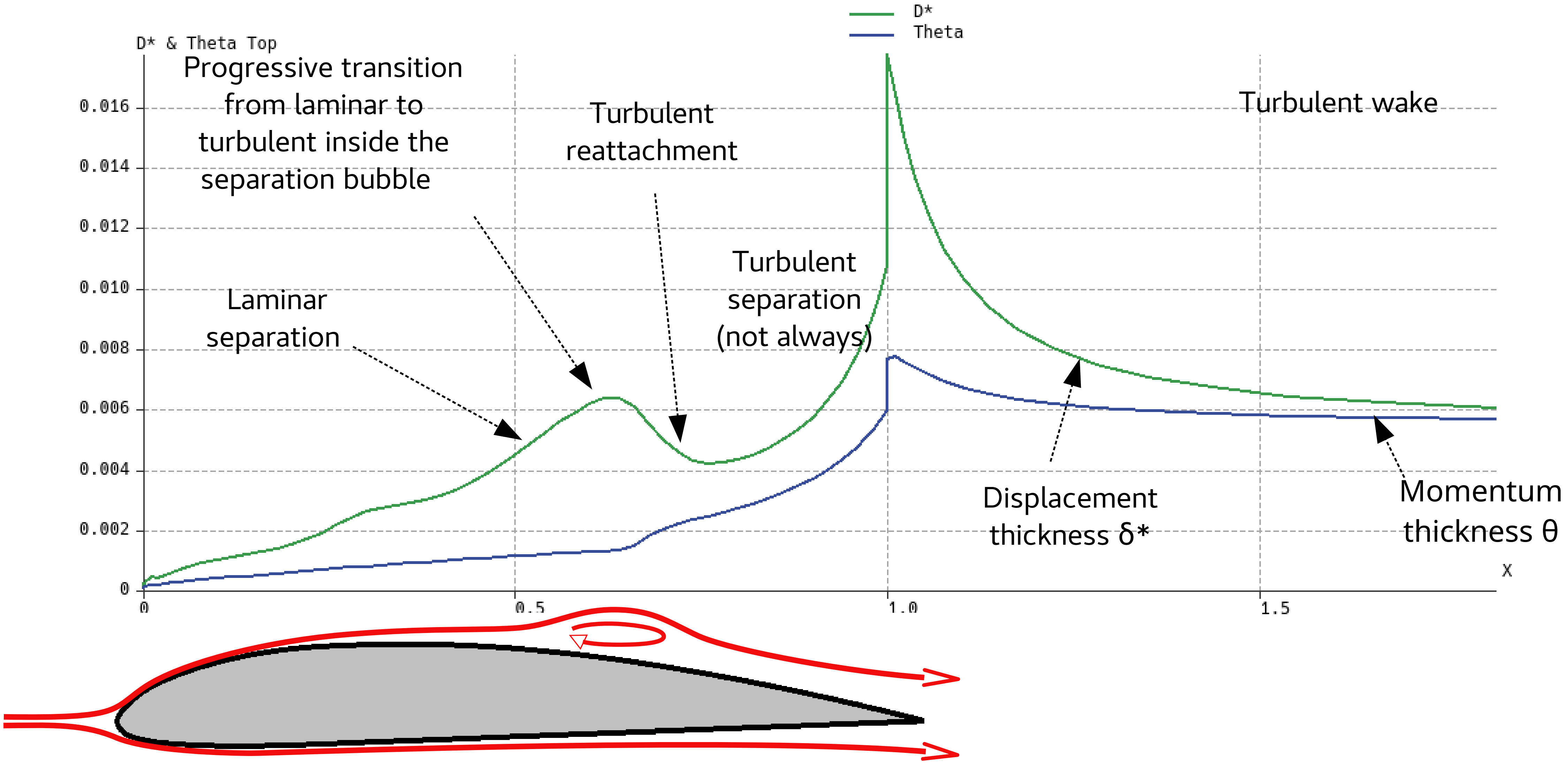


XFOIL
Subsonic Airfoil Development System

http://web.mit.edu/drela/Public/papers/xfoil_sv.pdf

About XFoil

Standard behaviour of a BL at low Re



Progressive transition from laminar to turbulent inside the separation bubble

Turbulent reattachment

Turbulent wake

Turbulent separation (not always)

Laminar separation

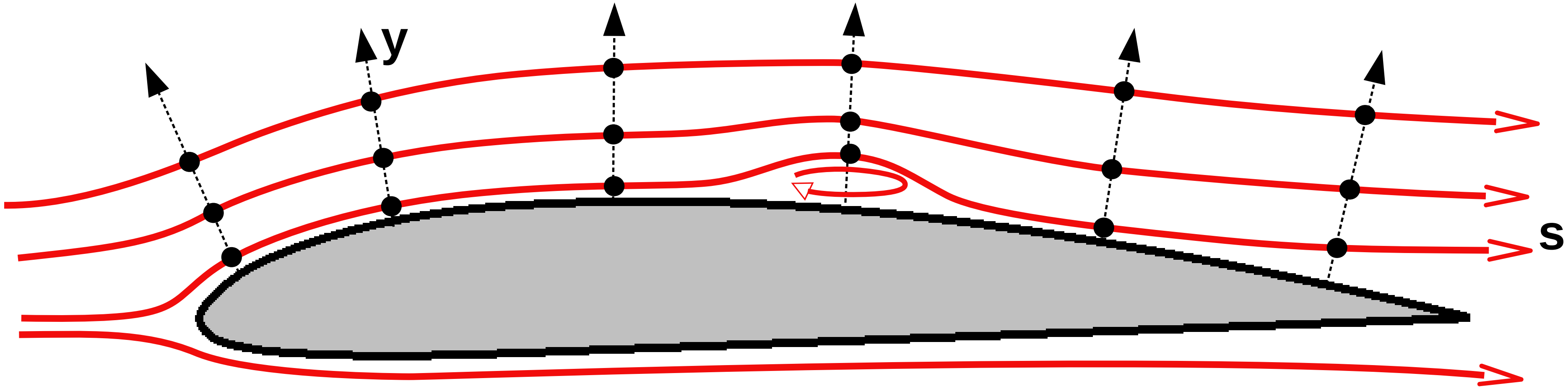
Displacement thickness δ*

Momentum thickness θ

Differential solvers

With the increase of computing power, it has become possible to solve the BL equations without prior integration in the thickness.

BL properties are defined at each position (s, y).

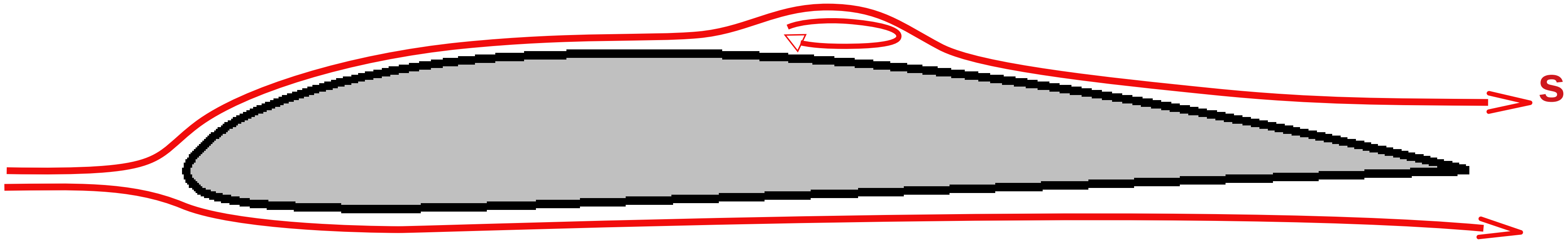


Although they require less empirical assumptions than integral methods, differential solvers still need a turbulence model which is the key building brick of the method.

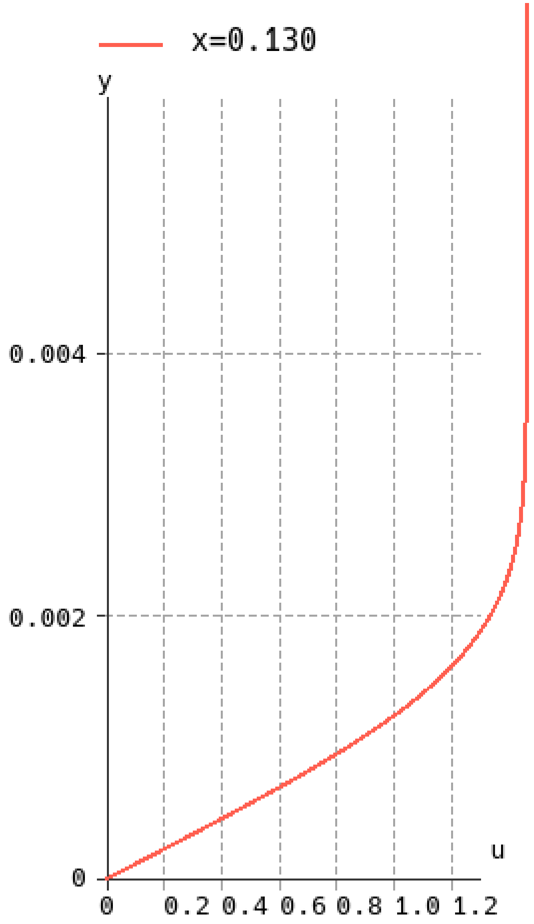
Differential solvers

The results which follow are from a differential solver currently in development.

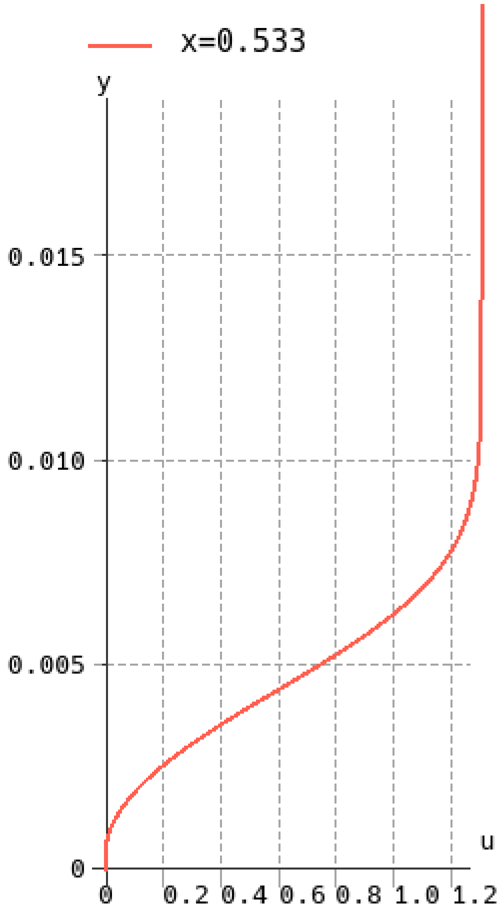
- The solver is based on the methods proposed by T. Cebeci in “Modeling and computation of boundary-layer flows”
- It uses the Cebeci-Smith turbulence model



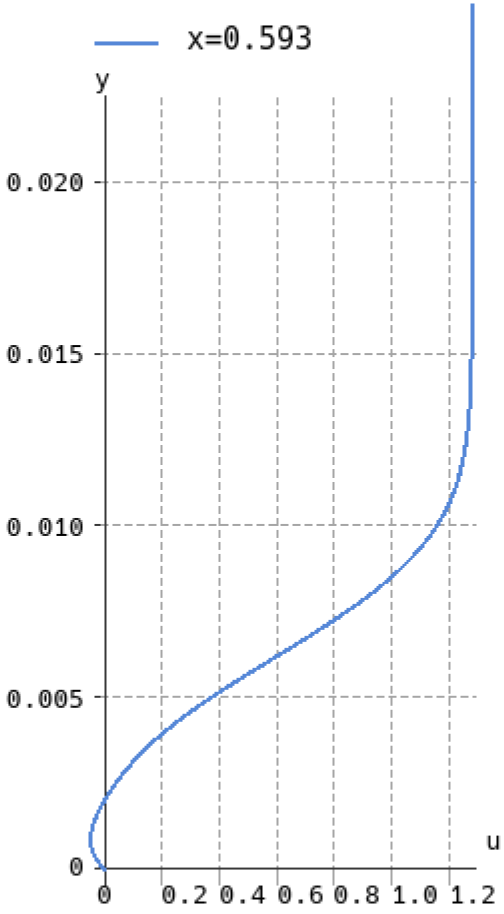
Differential solver



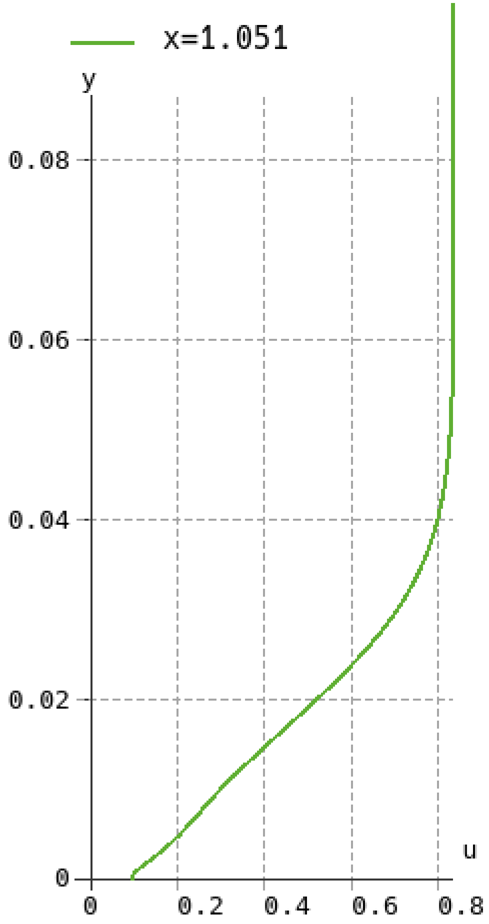
Laminar attached flow
BL thickness ≈ 0.004



Laminar separation
BL thickness ≈ 0.015



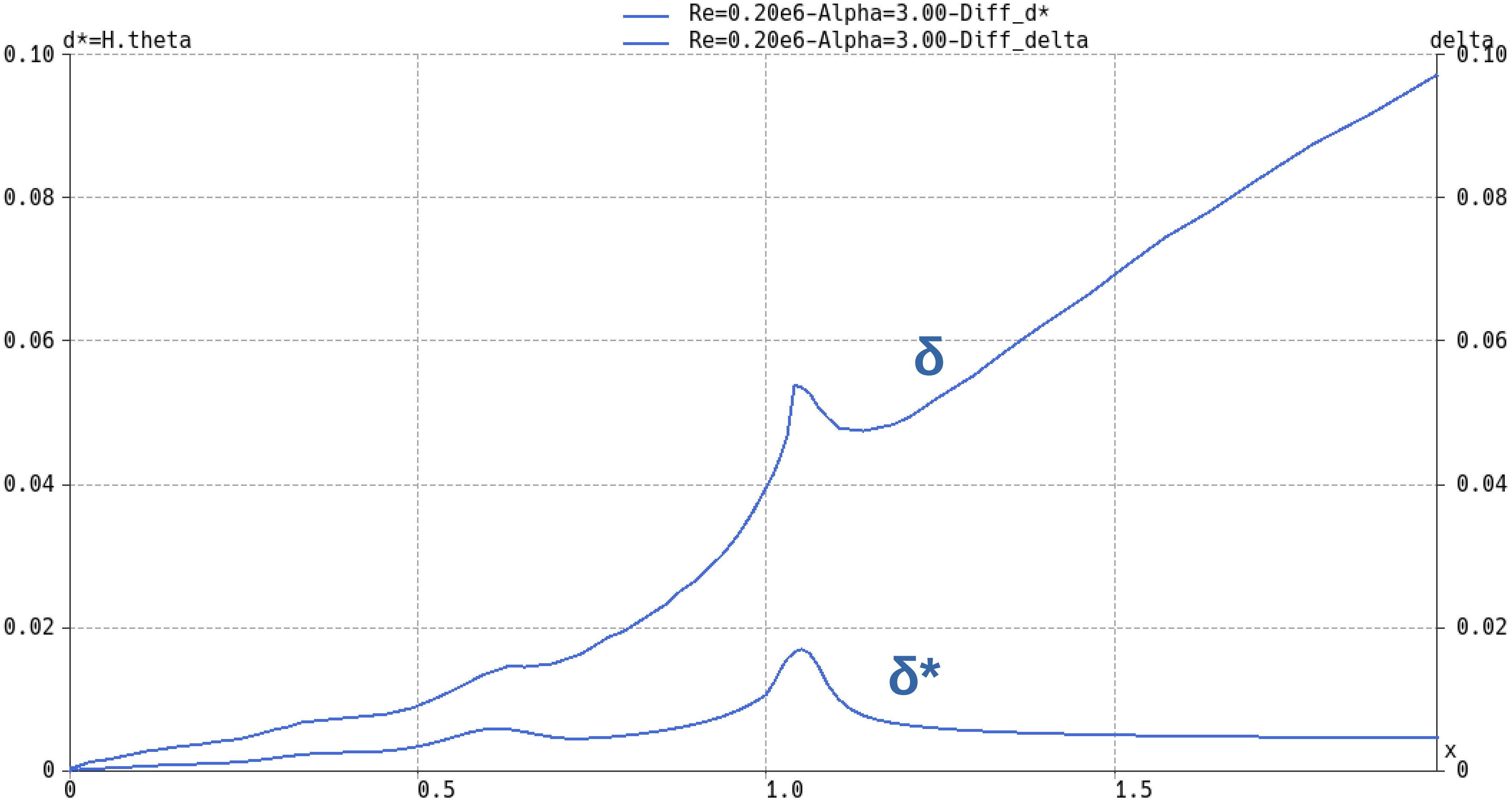
Turbulent separated
BL thickness ≈ 0.020



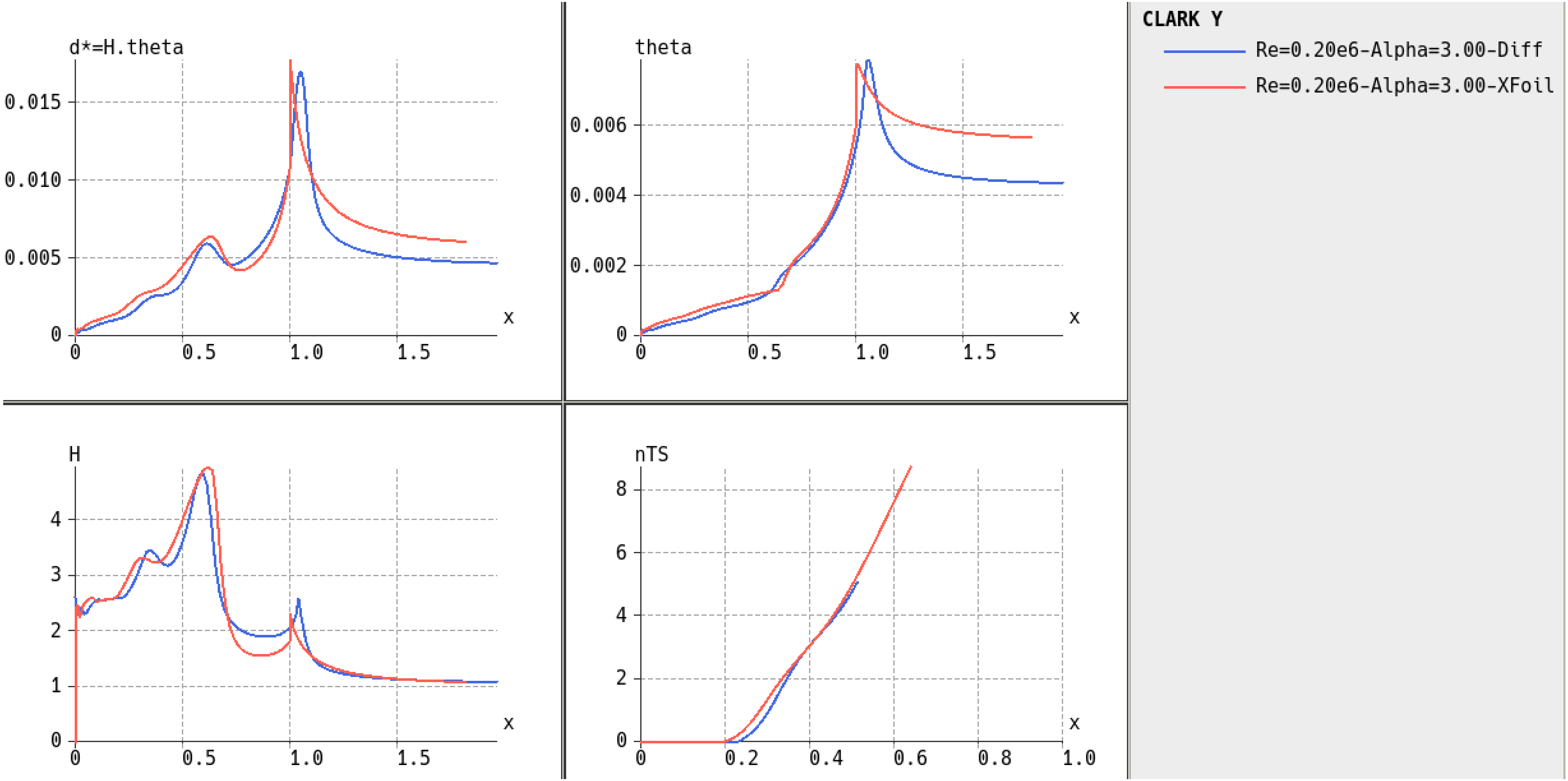
Wake flow
BL thickness ≈ 0.06

Clark Y airfoil, Top surface, Re=200k, aoa=3°, unit chord length

BL thickness vs. Displacement thickness



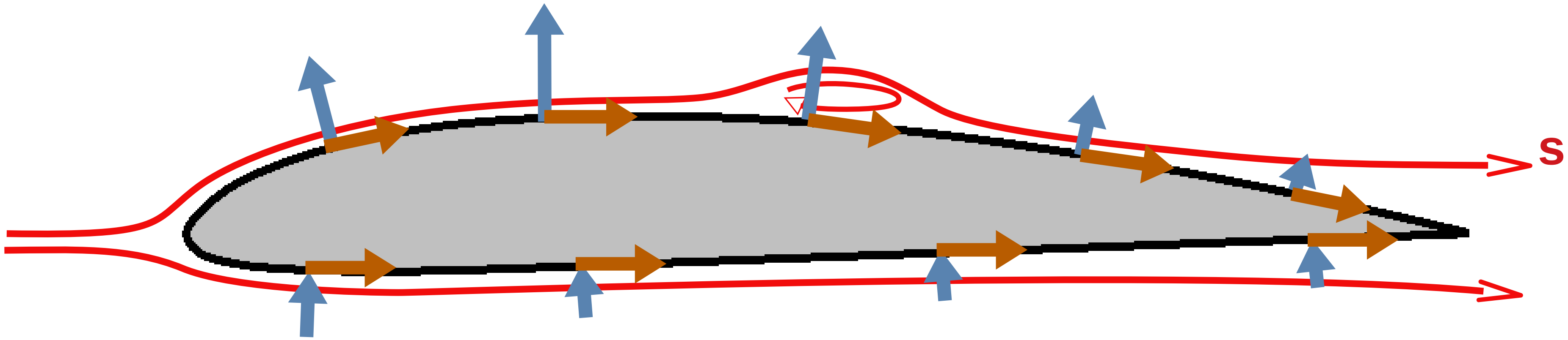
XFoil vs. a differential solver



So why does an airfoil drag?

The viscosity creates drag forces by two effects

- **it creates skin friction forces on the airfoil’s surface** ⇒ **“friction drag”**
- **it creates unbalanced pressure forces on the airfoil’s surface** ⇒ **“pressure drag”**



Note: The induced drag is a 3d effect only, and is not related to viscosity

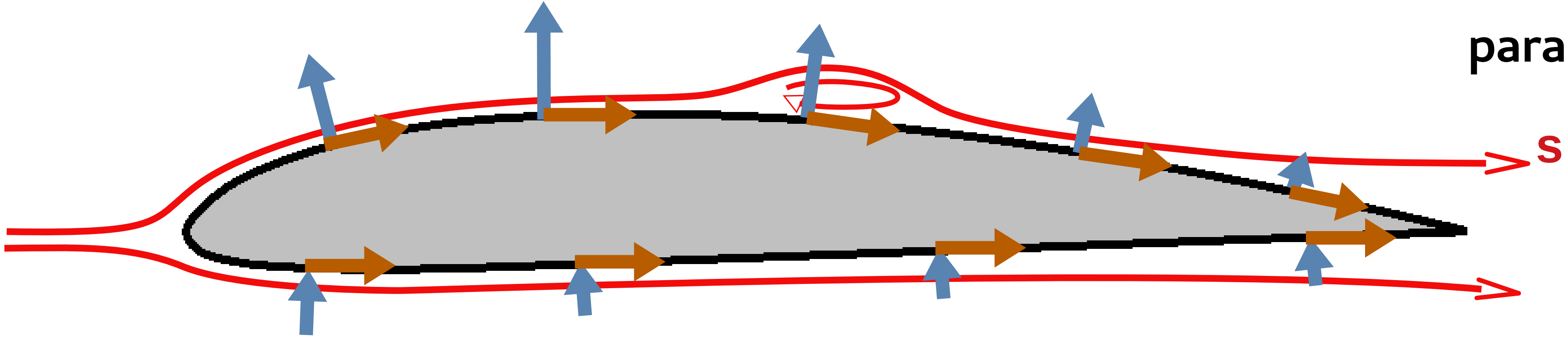
→ pressure forces

→ skin friction forces

So why does an airfoil drag?

The viscosity creates drag forces by two effects

- it creates skin friction forces on the airfoil's surface ⇒ "friction drag" ⇒ =0 in inviscid flow: "no viscosity, no friction"
- it creates unbalanced pressure forces on the airfoil's surface ⇒ "pressure drag" ⇒ =0 in inviscid flow due to d'Alembert's paradox



Note: The induced drag is a 3d effect only, and is not related to viscosity

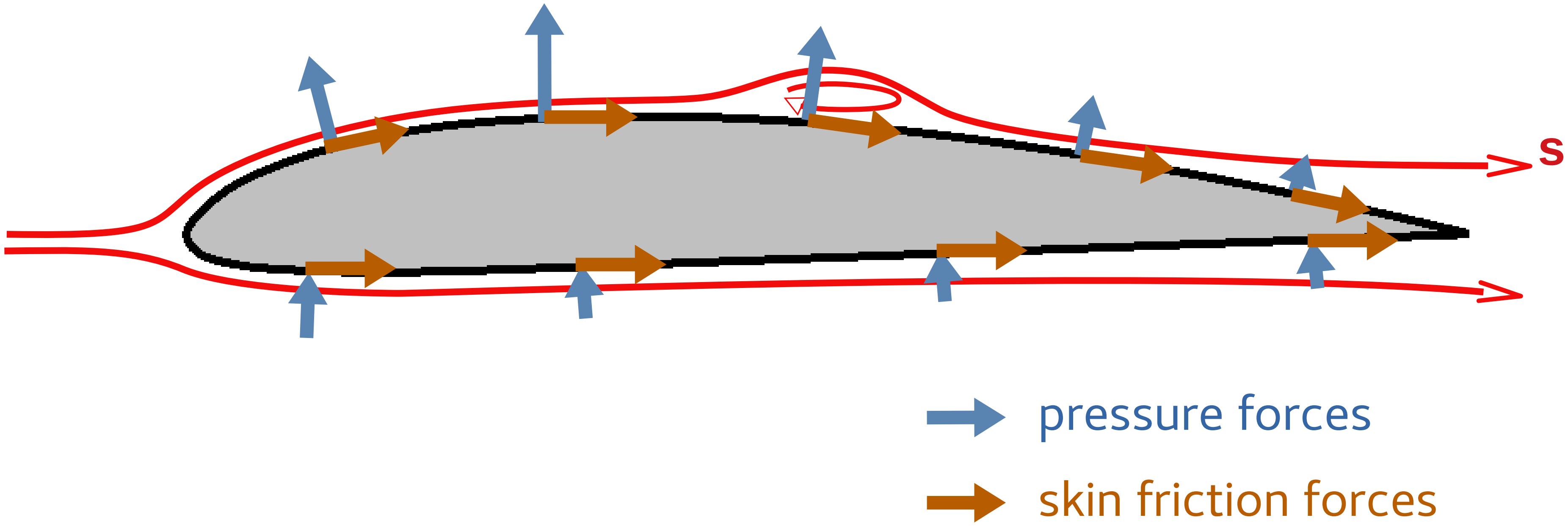
→ pressure forces

→ skin friction forces

So why does an airfoil drag?

“friction drag” + “pressure drag” = “Viscous drag” or “Profile drag”

Both terms are used interchangeably in xflr5



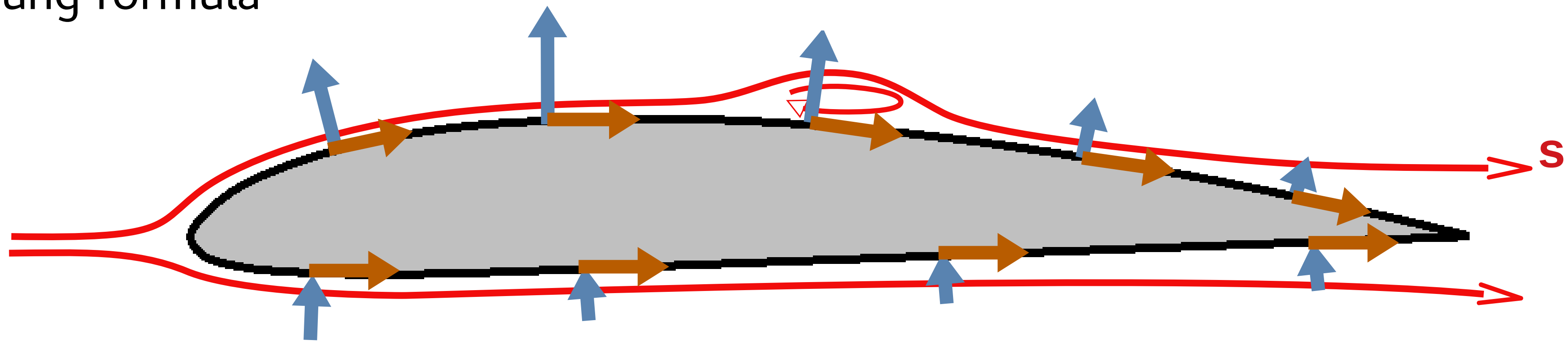
So why does an airfoil drag?

"friction drag" + "pressure drag" = "Viscous drag" or "Profile drag"

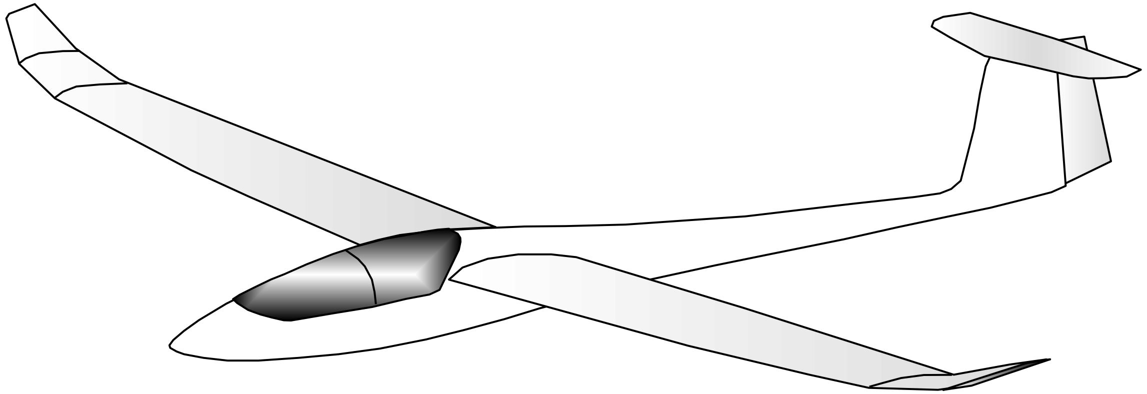
Note: The direct evaluation of friction and pressure forces is numerically unreliable; XFoil's method is to evaluate the total viscous drag in the wake using the Squire-Young formula

$$C_D = D/q = 2\theta_\infty = 2\theta \left(\frac{u}{V_\infty}\right)^{(H+5)/2}$$

where θ and u are evaluated at the end of the wake



- pressure forces
- skin friction forces



-That's it-

In the hope that the concepts, wording, graphs, limitations and possibilities of XFoil and xflr5 are a little more clear now than they were at the start of these presentations.

XFOIL

Subsonic Airfoil Development System

xflr5