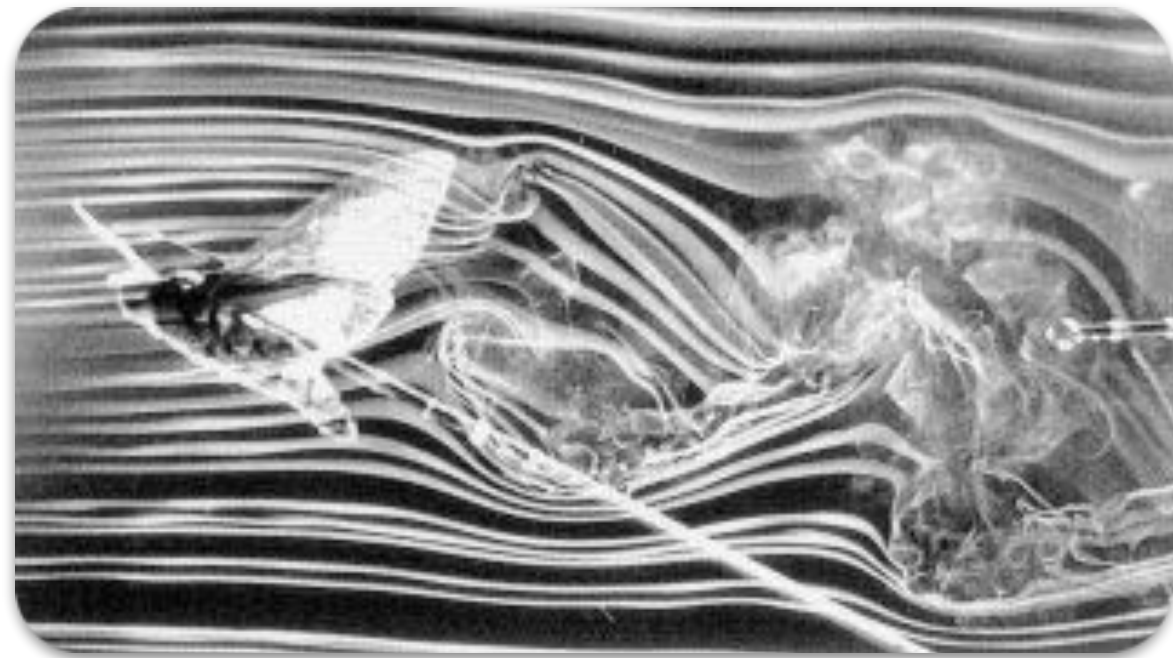# Future Directions in Computational Fluid Dynamics

F.D. Witherden and A. Jameson

Department of Aeronautics & Astronautics
Stanford University
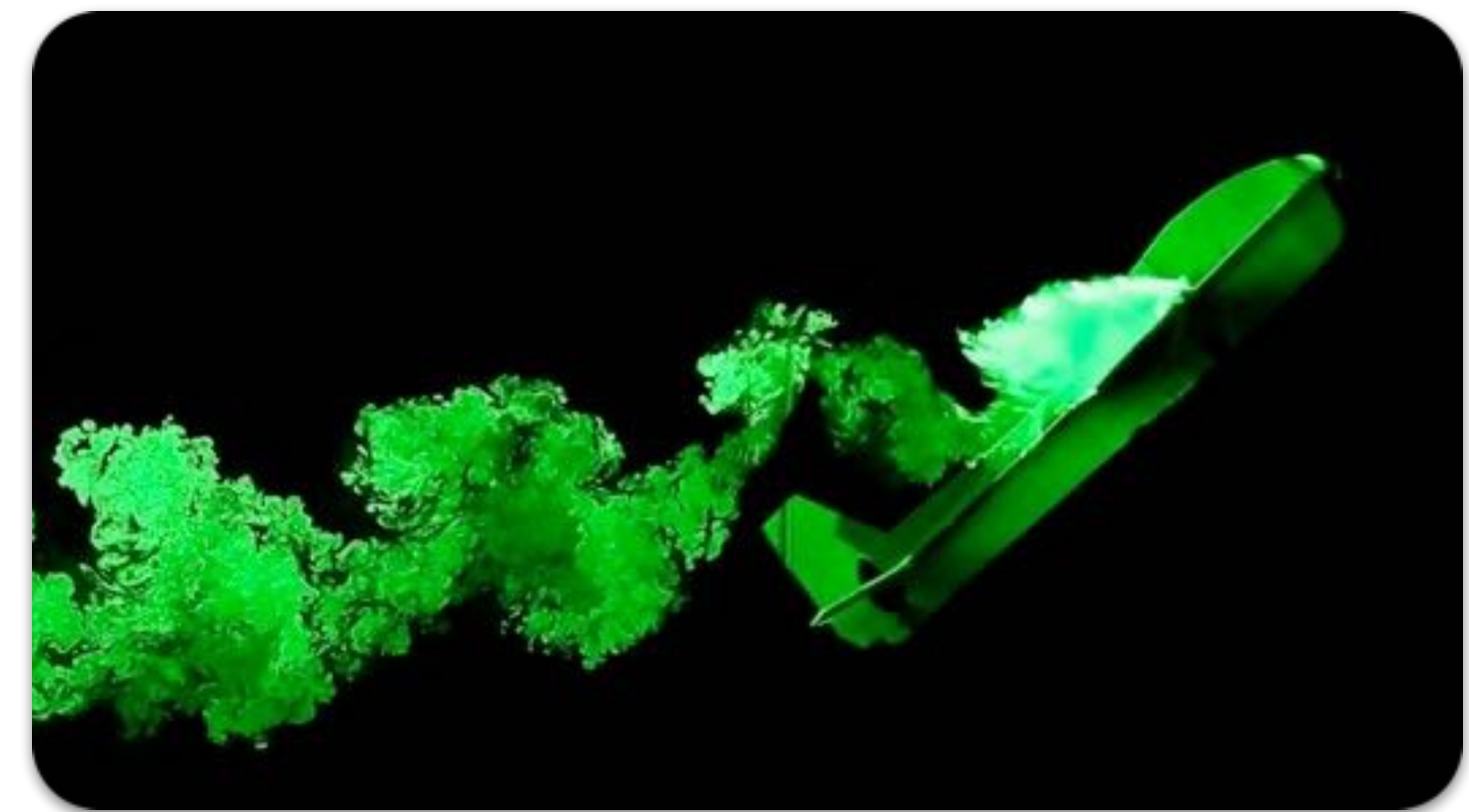
Why CFD?

- Since its inception CFD has been an incubator for the **formulation and development of numerical algorithms**.

Why is CFD Challenging?

- Three words: **Shocks**, **separation**, and **turbulence**.

Brief History of the Evolution of CFD

Van Leer's View

Top level: Jay Boris, Vladimir Kolgan, Bram van Leer, Antony Jameson
Ground level: Richard Courant, Kurt Friedrichs, Hans Lewy, Robert MacCormack, Philip Roe, John von Neumann, Stanley Osher, Amiram Harten, Peter Lax, Sergei Godunov
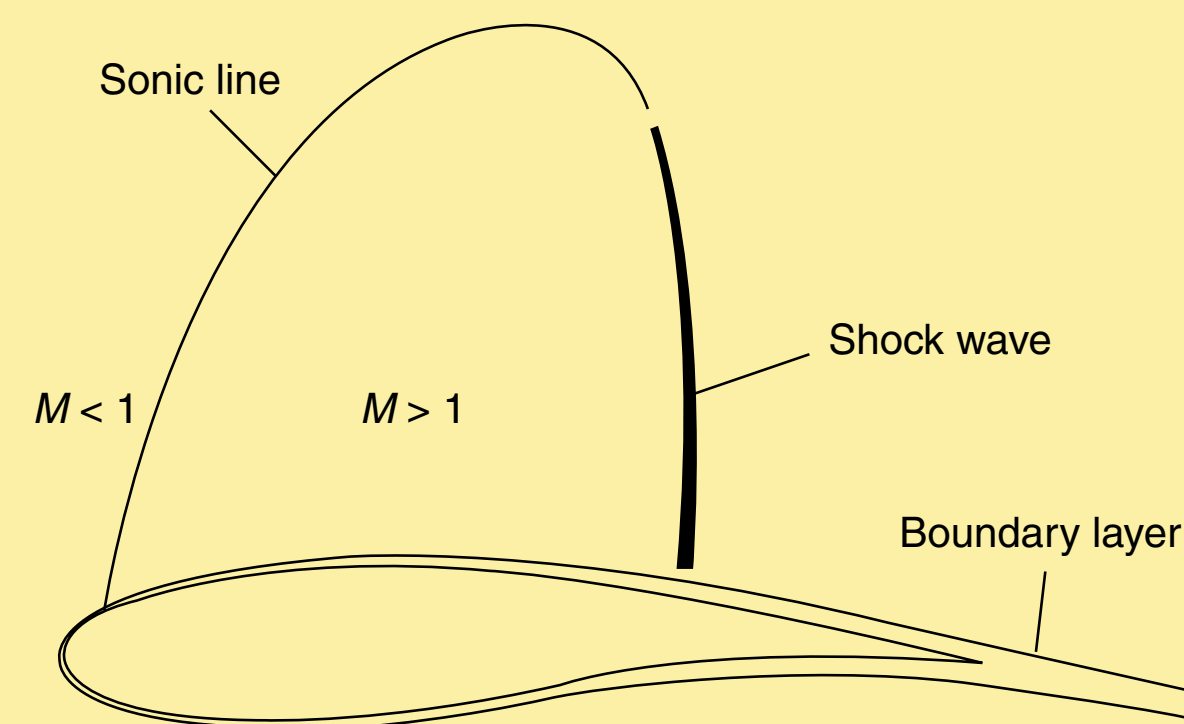
Emergence of CFD

- Driven by advances in computer power and algorithms.

Some significant developments in the '60s:
- birth of commercial jet transport – B707 & DC-8
- intense interest in transonic drag rise phenomena
- lack of analytical treatment of transonic aerodynamics
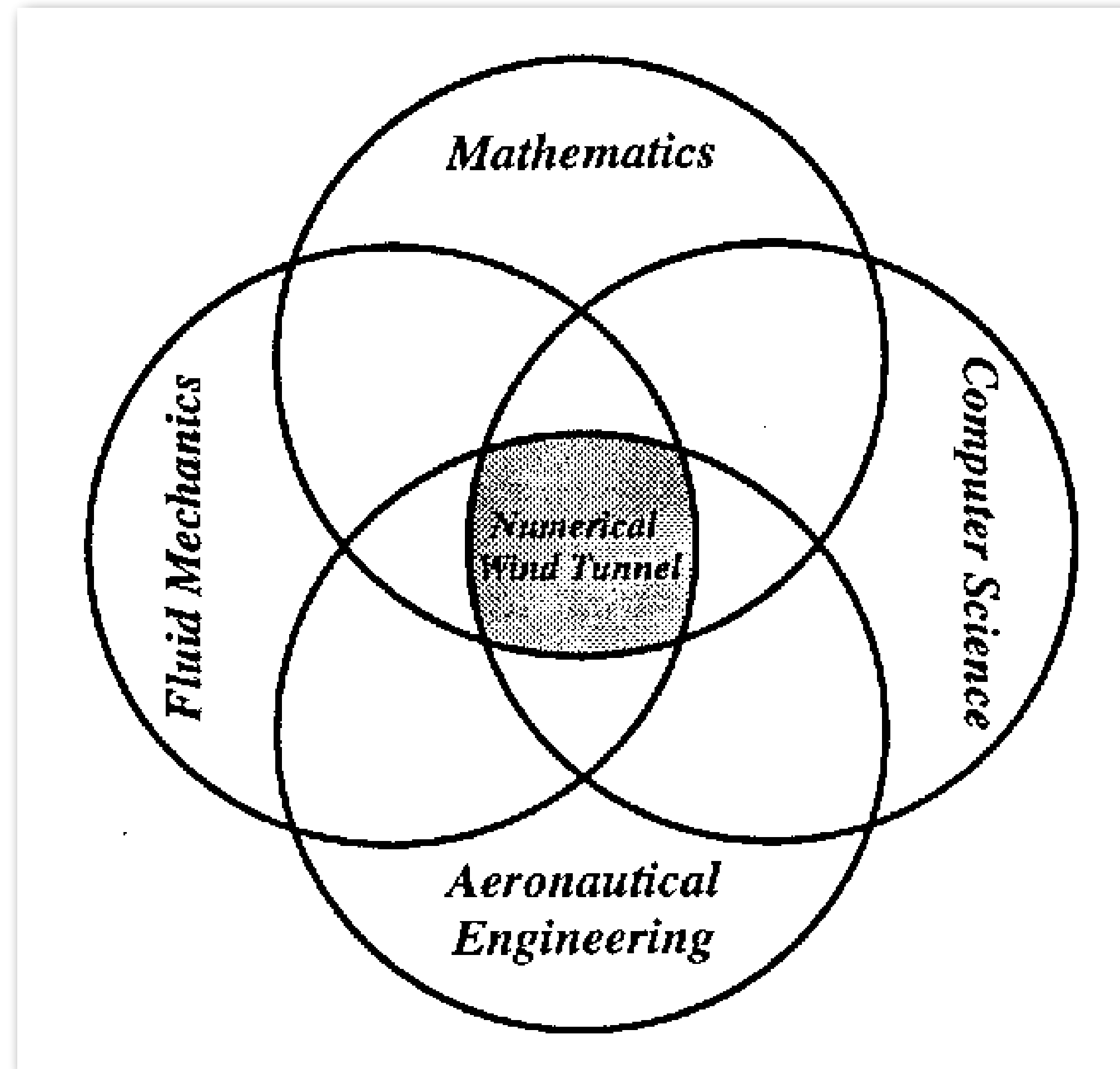- birth of supercomputers – CDC6600

Sonic line

$M < 1$ $M > 1$

Shock wave

Boundary layer

DC-8   **Transonic Flow**   **CDC6600**

Multi-Disciplinary Nature of CFD

Advances in CFD have been paced by advances in computer power
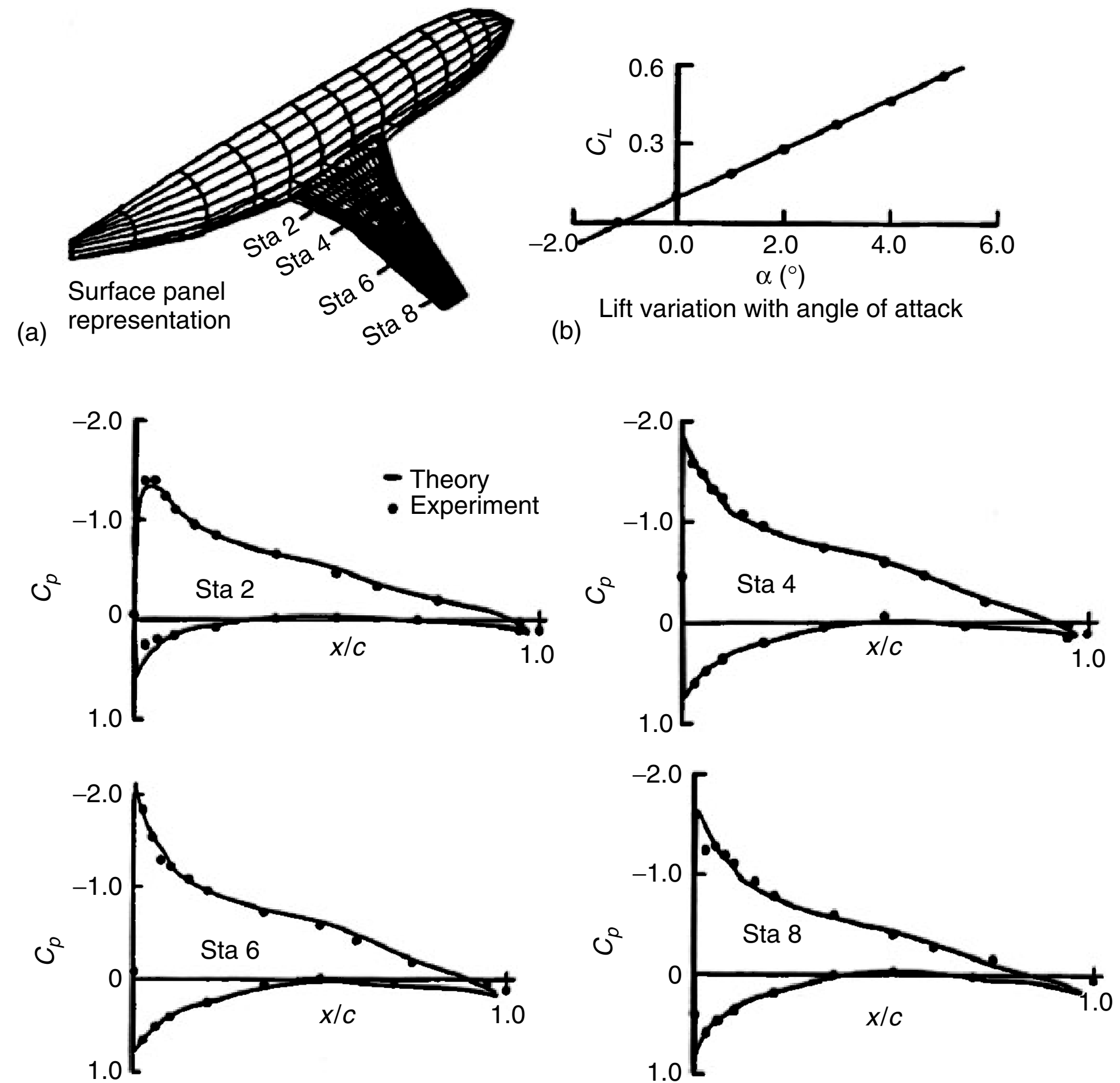
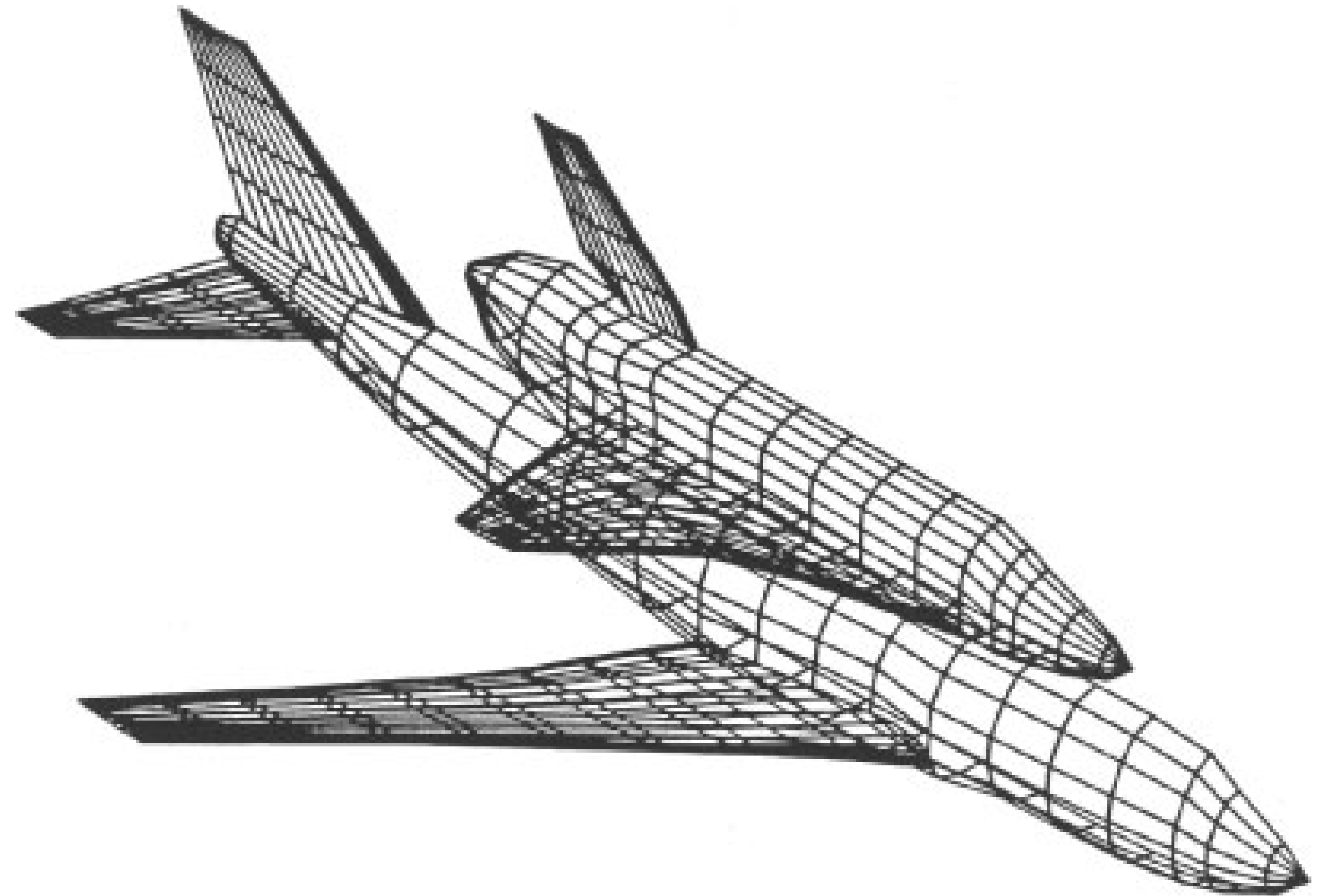| 1970	CDC6600	1 Megaflops	10^6
1980	Cray 1 Vector Computer	100 Megaflops	10^8
1994	IBM SP2 Parallel Computer	10 Gigaflops	10^{10}
2007	Linux Clusters	100 Teraflops	10^{14}
2009	HP Pavilion Quadcore Notebook $1,099	1 Gigaflops	10^9
2011	MacBook Pro Quadcore Laptop $2,099	2.5 Gigaflops	$2.5×10^9$
2012	Titan supercomputer @ ORNL 18,688 × NVIDIA K20 GPUs	20 Petaflops	$2×10^{16}$

Hierarchy of Governing Equations
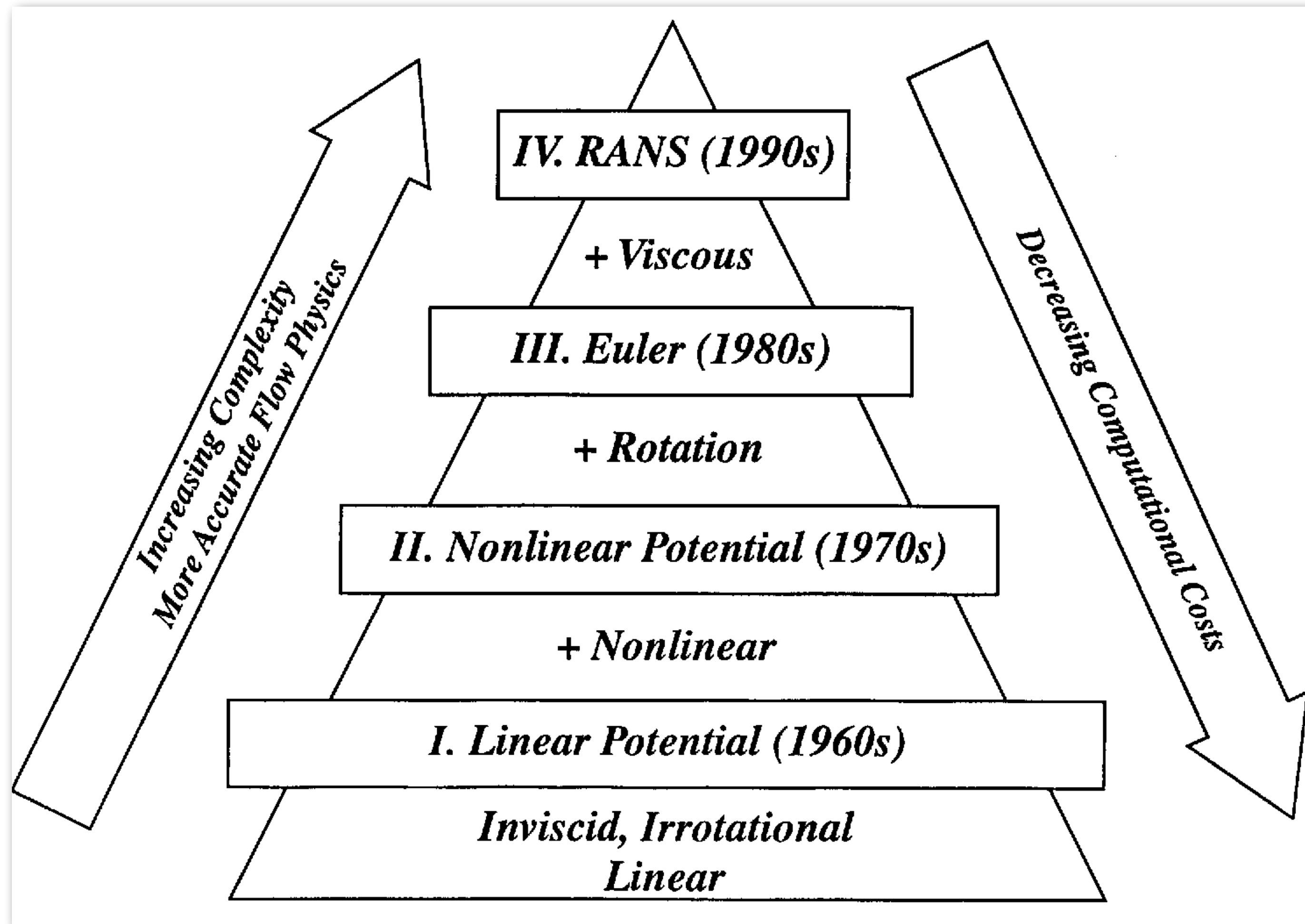
Panel Codes for Potential Flow (Circa 1970)

Panel method applied to a Boeing 747. (Supplied by Paul Rubbert, the Boeing Company.)

(a) Surface panel representation

(b) Lift variation with angle of attack

Sta 2 · Sta 4 · Sta 6 · Sta 8

C_L · α (°)

— Theory
• Experiment

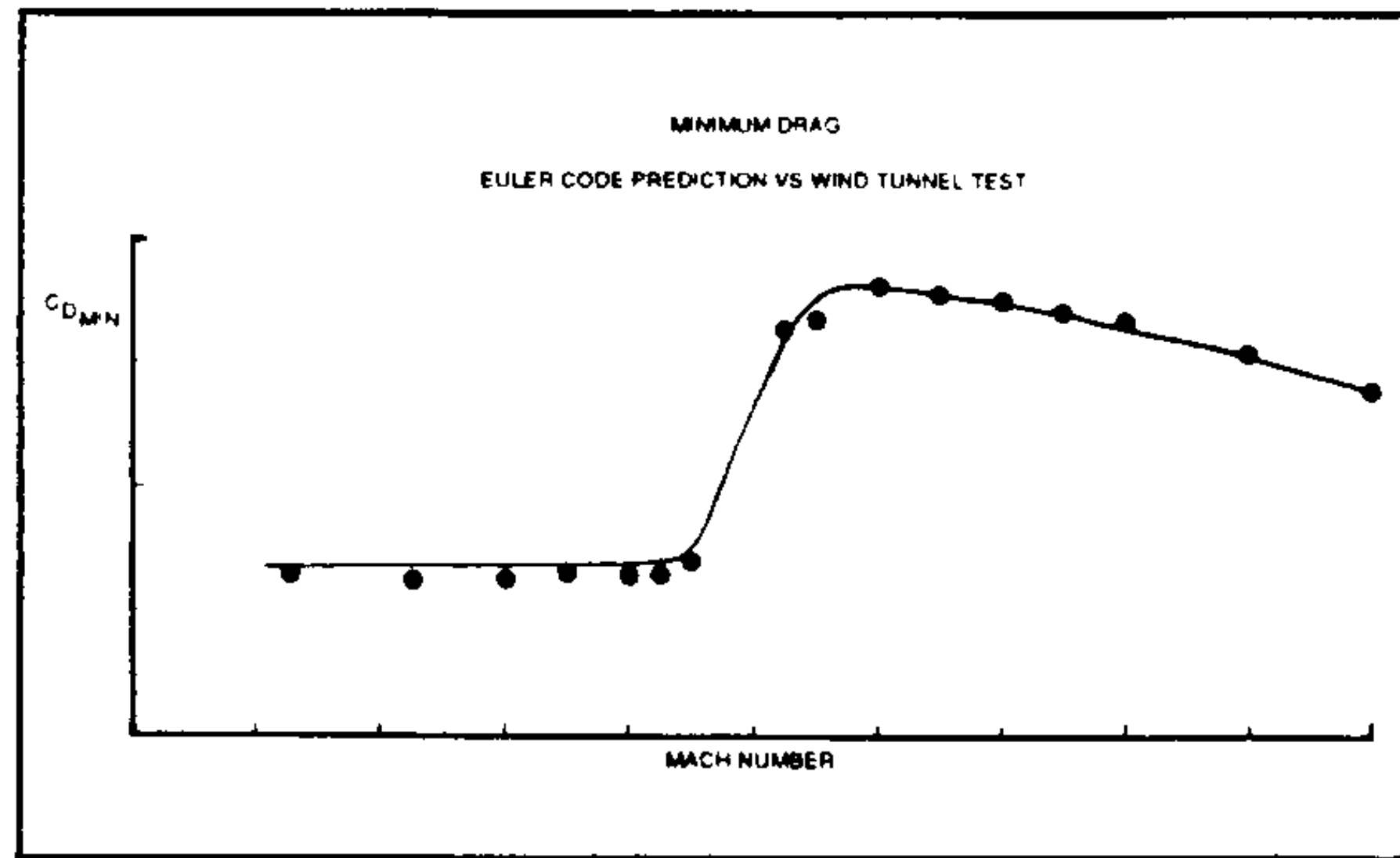Sta 2 · Sta 4 · Sta 6 · Sta 8

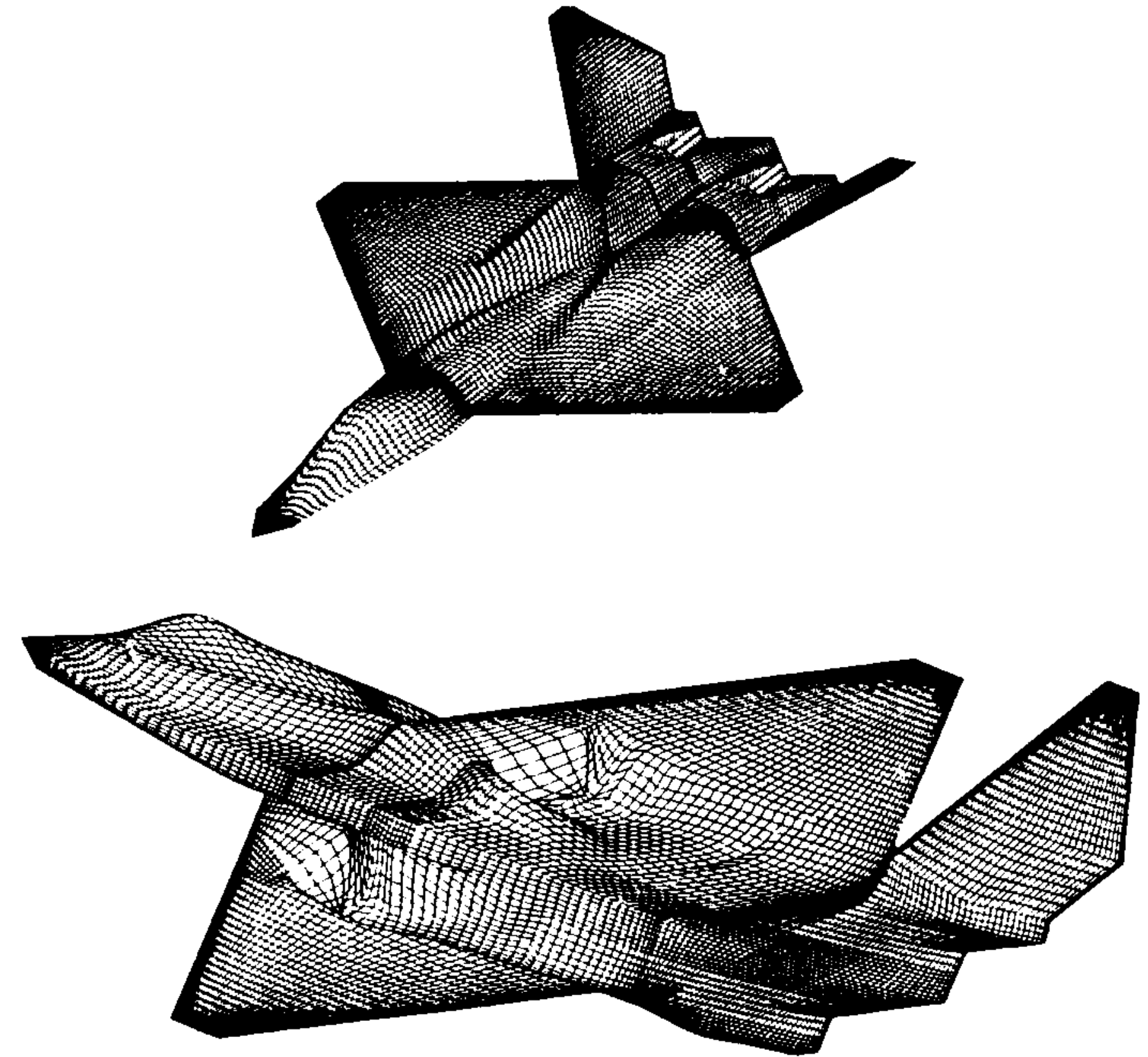C_p · x/c

Panel Codes for Potential Flow (Circa 1970)

Panel method applied to flow around Boeing 747 and space shuttle. Supplied by Allen Chen, the Boeing Company.
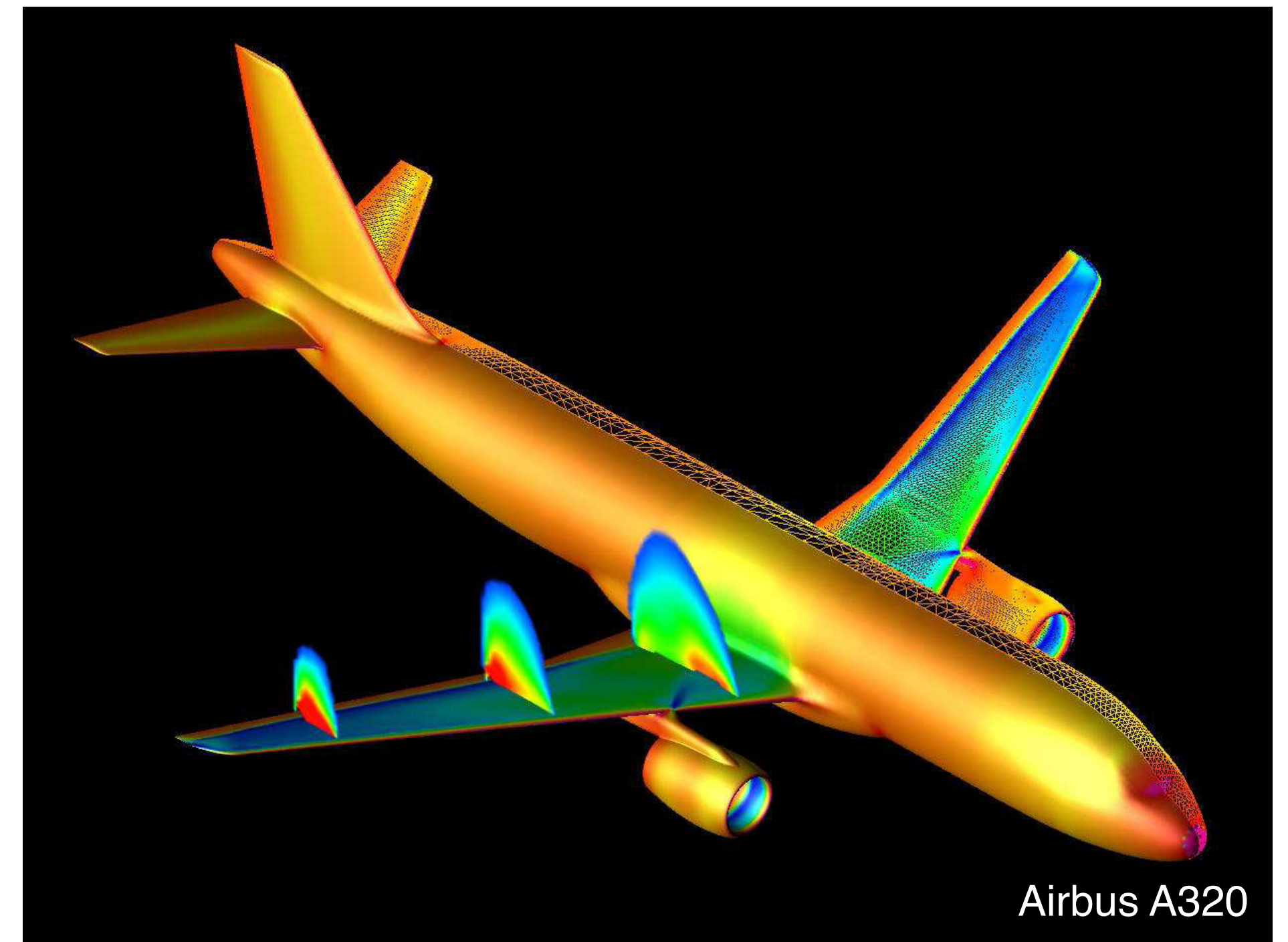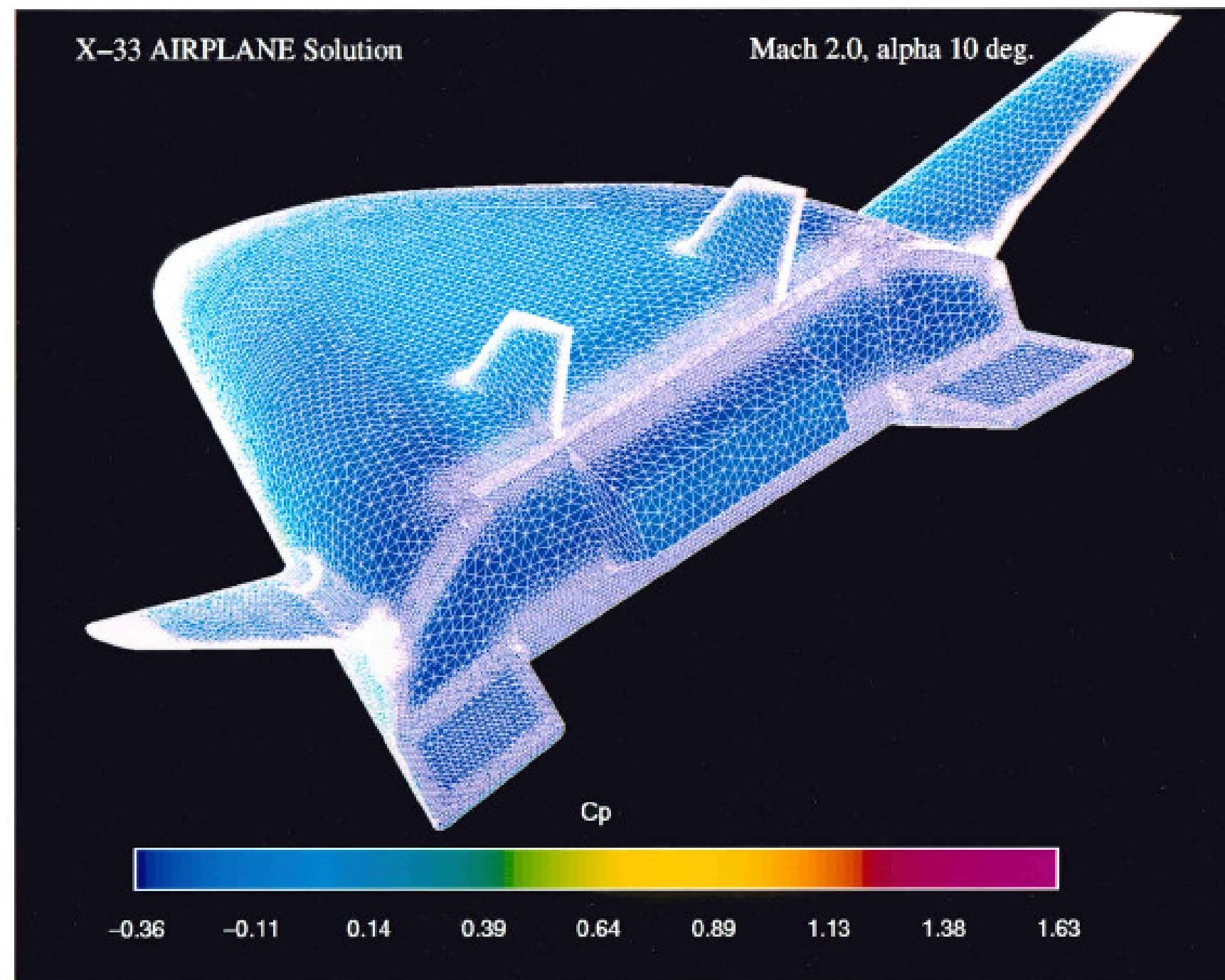
Euler Solutions (1985–1990)

MINIMUM DRAG

EULER CODE PREDICTION VS WIND TUNNEL TEST

$c_{D_{MIN}}$

MACH NUMBER

Northrop YF-23
Extended version of FLO57
by Richard Busch, Jr.

Euler Solutions (1985–1990)

X–33 AIRPLANE Solution   Mach 2.0, alpha 10 deg.

Cp

-0.36 -0.11 0.14 0.39 0.64 0.89 1.13 1.38 1.63

Airbus A320

First and Second Order Accuracy

NACA 0012 : H-CUSP SCHEME
MACH 0.800 ALPHA 1.250
CL 0.3105 CD 0.0298 CM -0.0316
GRID 320X 64 NCYC 100 RES 0.922E-10

NACA 0012 : H-CUSP SCHEME
MACH 0.800 ALPHA 1.250
CL 0.3649 CD 0.0231 CM -0.0406
GRID 320X 64 NCYC 100 RES 0.380E-12
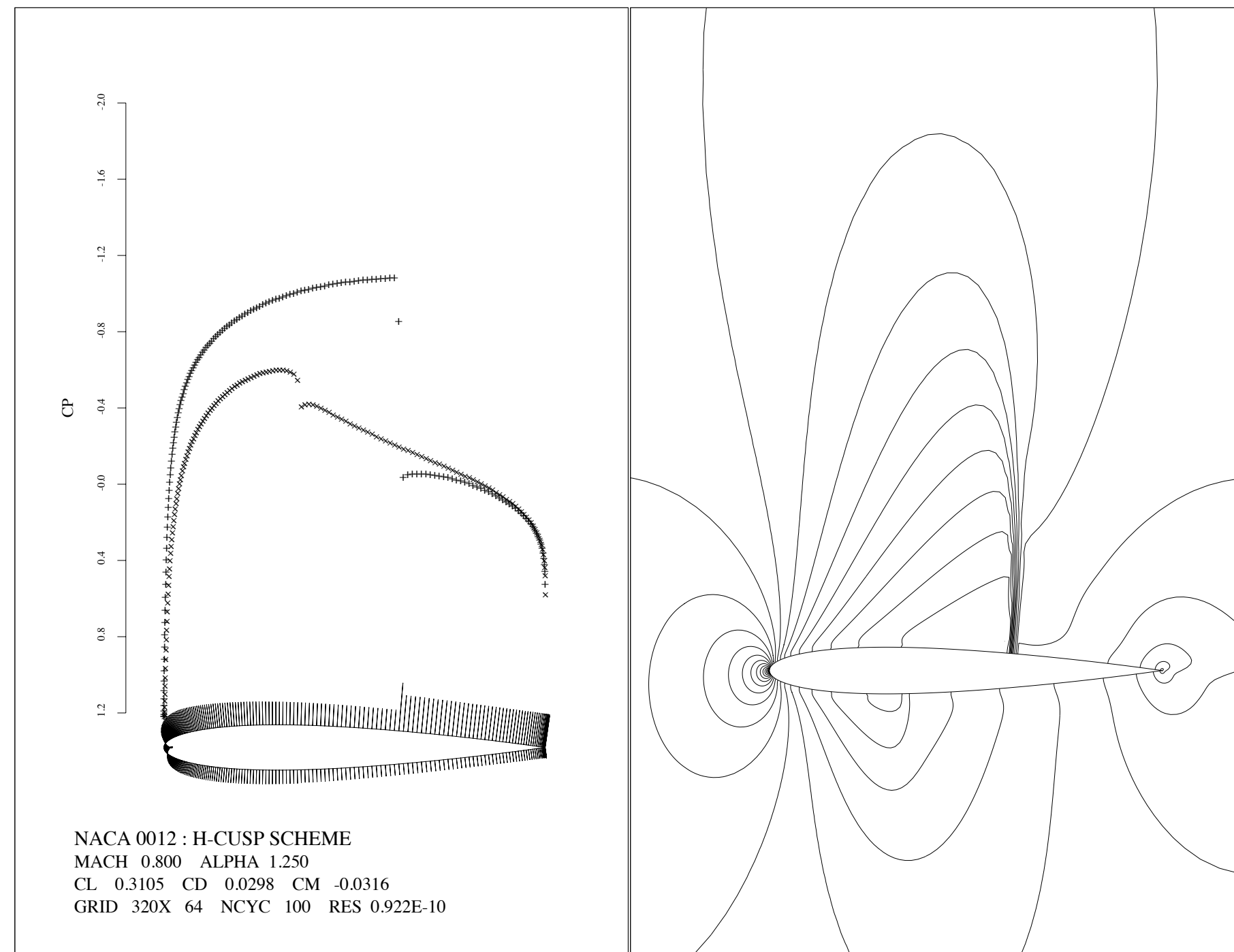
First order
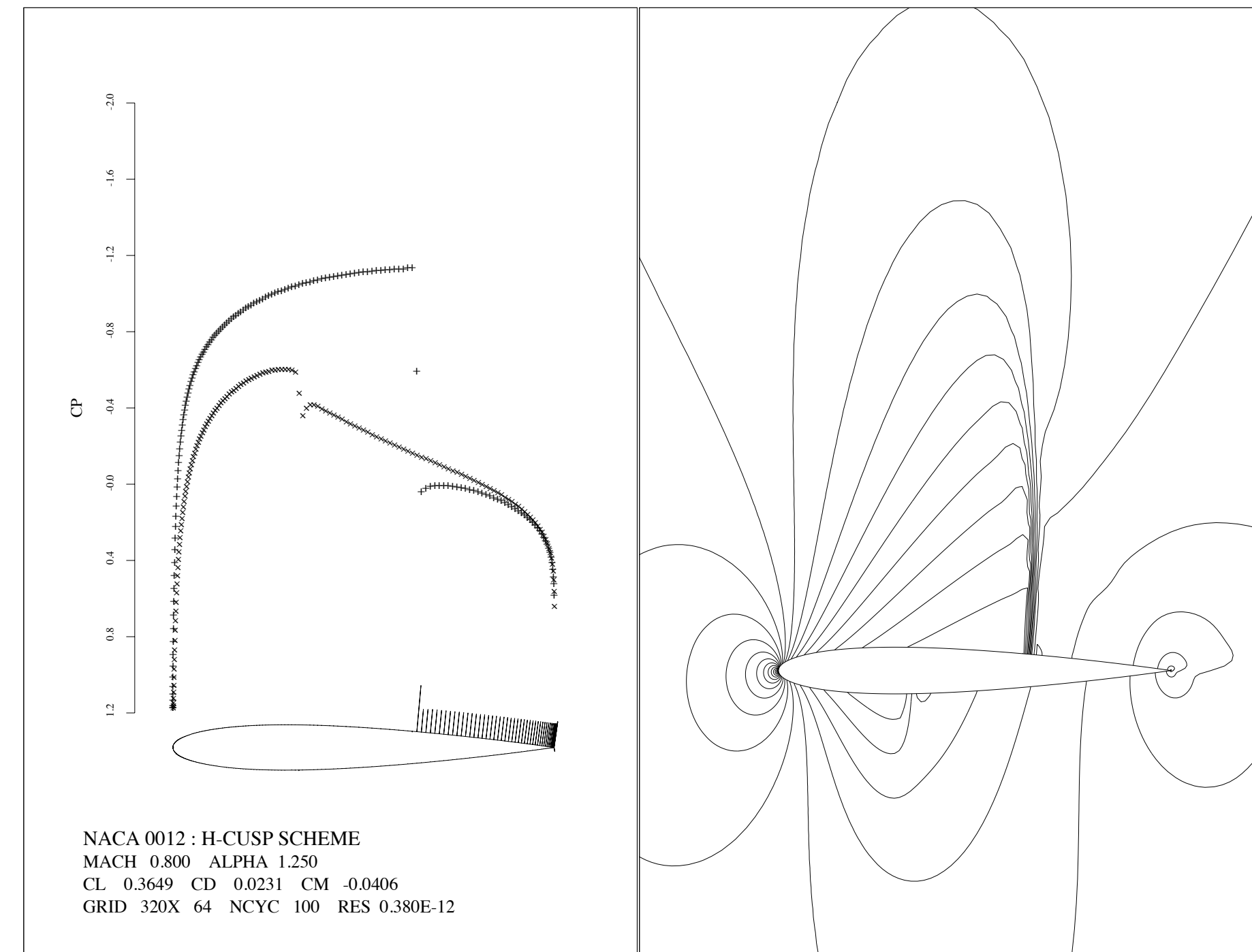
Second order

Industrial Use of CFD
in Aerospace

Impact of CFD at Boeing

NASA Tech	PANAIR	FLO22 A411		Cartesian Grid Tech.		TLNS3D	HSR & IWD	TLNS3D-MB OVERFLOW	CFL3D OVERFLOW
Boeing Tools	A502	A488		TRANAIR			TRANAIR Optimization	TLNS3D-MB/ZEUS	CFL3D/ZEUS OVERFLOW CFD++	Unstructured Adaptive Grid 3-D N-S

Boeing Products

1980   1985   1990   1995   2000   2005

767 757   737-300   777   737NG   787

1980 state of the art 77

Modern close coupled nacelle installation, 0.02 Mach faster than 737-200

21% thicker faster wing than 757, 767 technology

Highly constrained wing design Faster wing than 737-300

Successful multipoint optimization design

Faster and more efficient then previous aircraft

CFD for Loads and Stability and Control

Number of Wings Tested

38

18

11

11

**50% Reduction in Wind Tunnel Testing!**

Uses of CFD for the B787

CFD at Airbus

MEGAFLOW / MEGADESIGN
- National CFD Initiative (since 1995)

Development & validation of a national CFD software for complete aircraft applications which

- ➢ allows computational aerodynamic analysis for 3D complex configurations at cruise, high-lift & off-design conditions
- ➢ builds the basis for shape optimization and multidisciplinary simulation
- ➢ establishes numerical flow simulation as a routinely used tool at DLR and in German aircraft industry
- ➢ serves as a development platform for universities

Airbus

EADS MAS
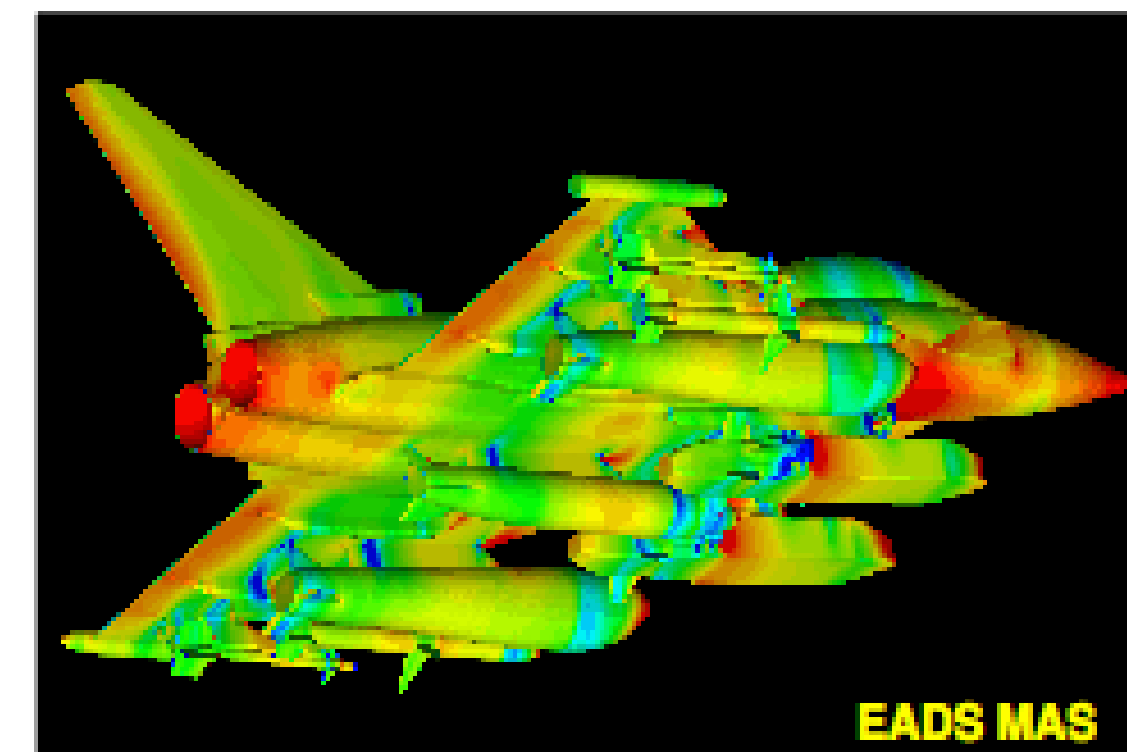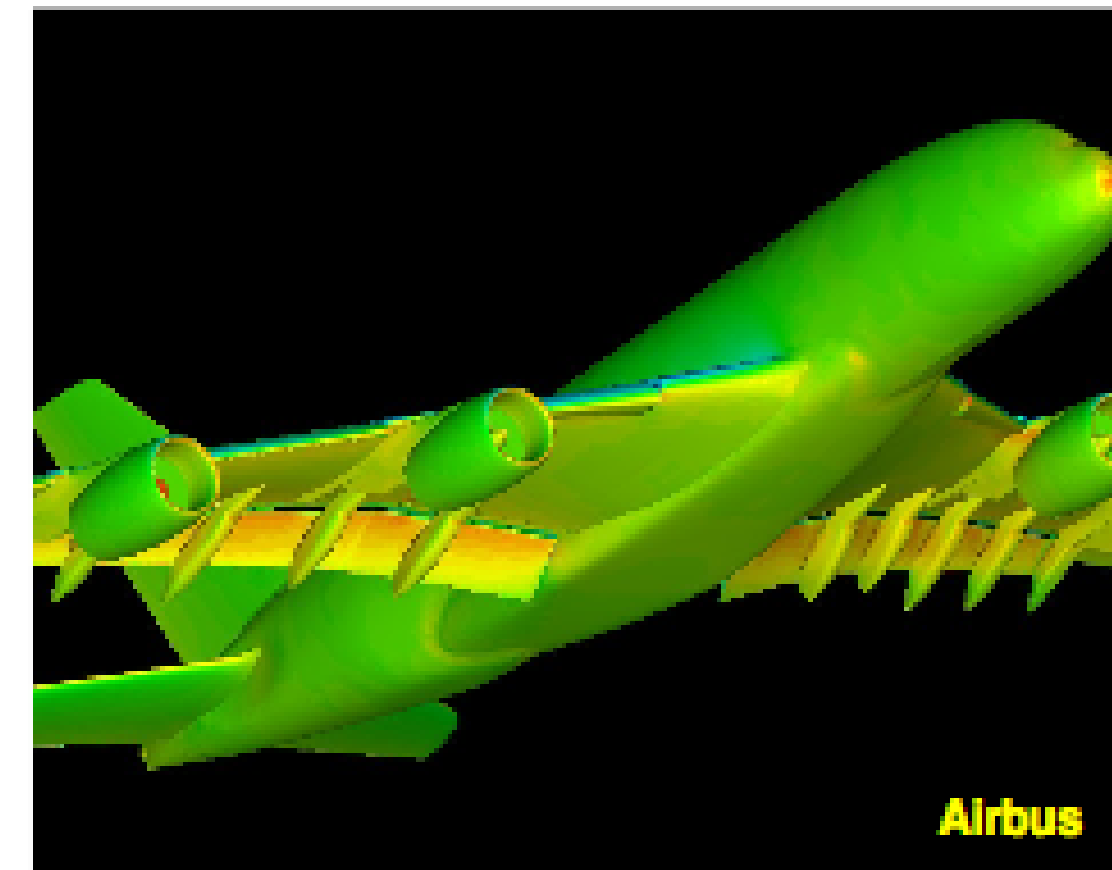
CFD at Airbus

Tool for complex configurations

- hybrid meshes, cell vertex / cell centered
- high-level turbulence & transition models
  (RSM, DES, linear stability methods)
- state-of-the-art algorithms (JST, multigrid, …)
- local mesh adaptation
- chimera technique
- fluid / structure coupling
- continuous/discrete adjoint
- extensions to hypersonic flows
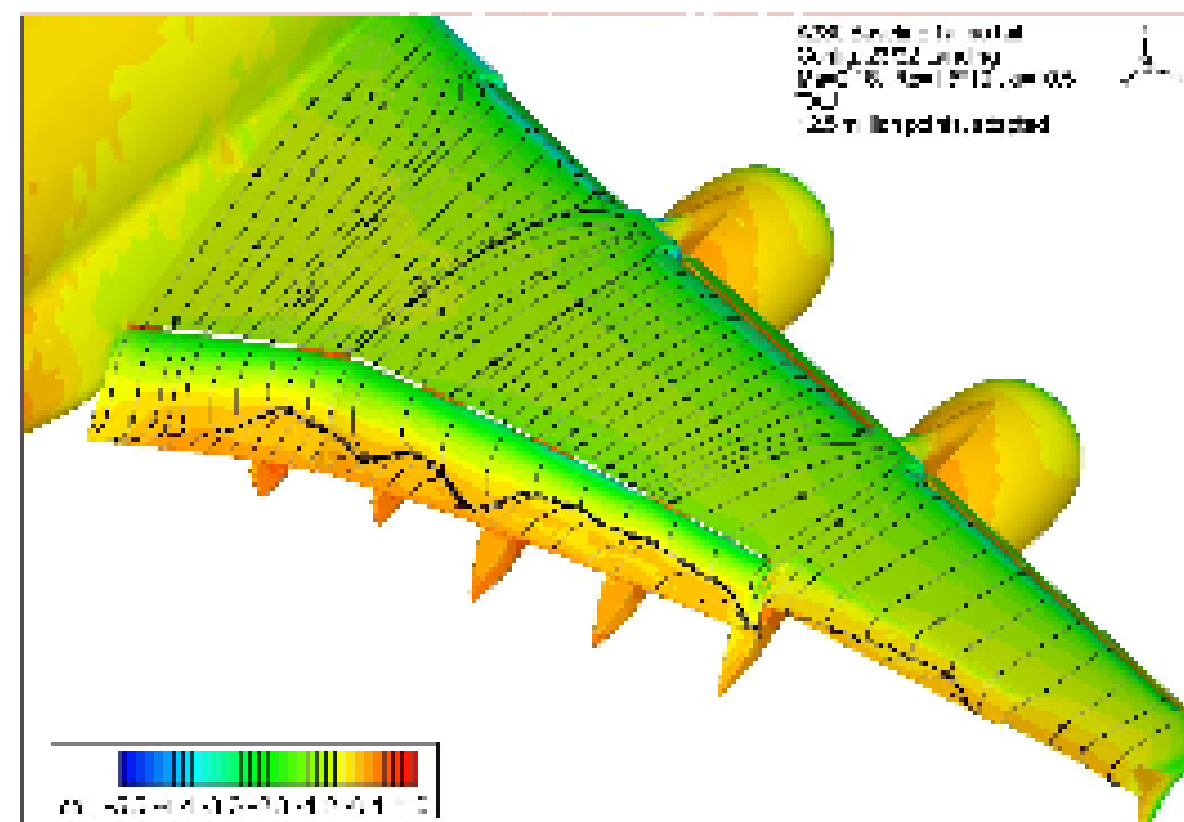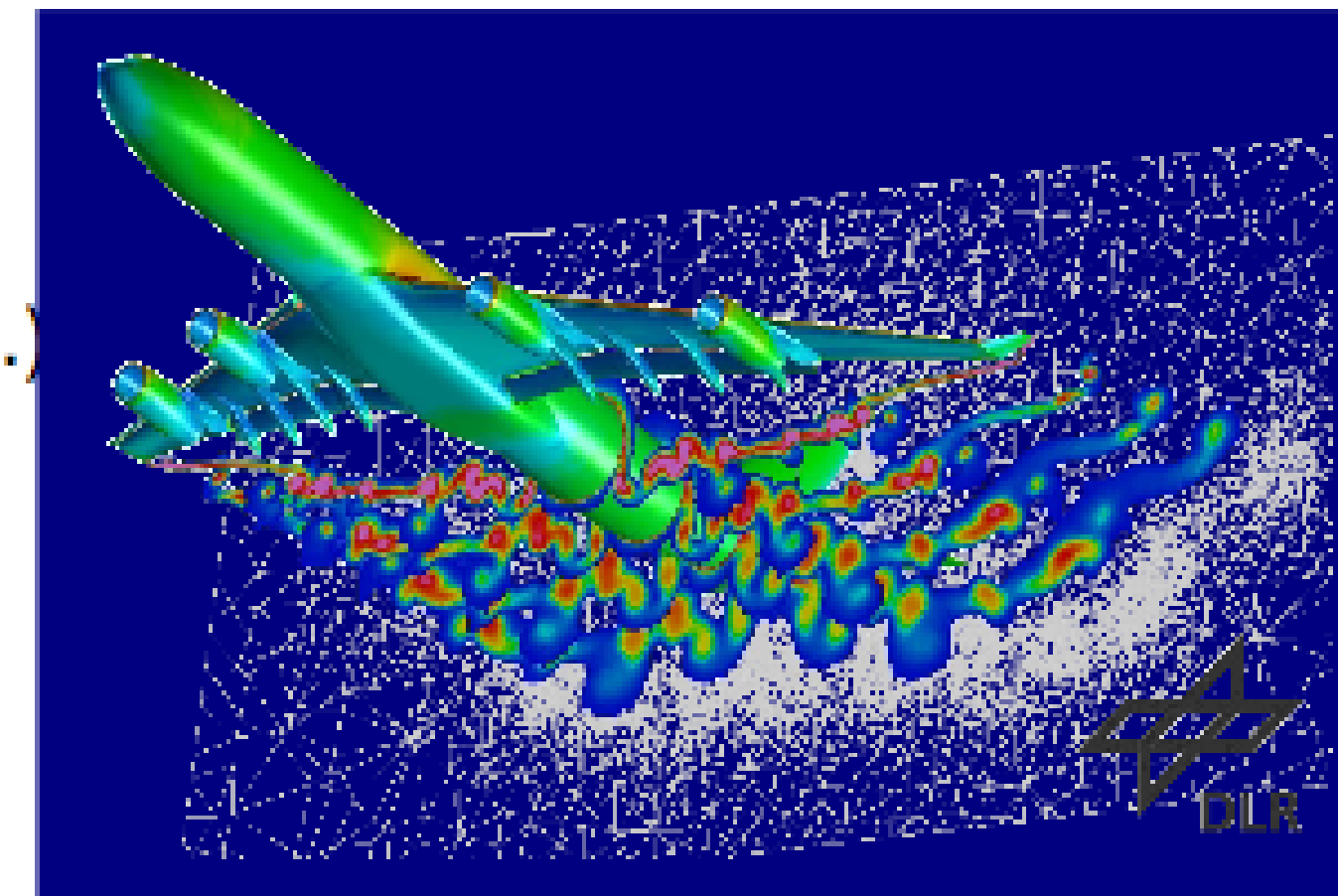
TAU-Code

- unstructured database
- C-code, Python
- portable code,
  optimized for cache hardware
- high performance on
  parallel computer

Uses of CFD for the A380

Current Status of CFD

CFD Today

- Worldwide commercial and government codes are based on algorithms developed in the '80s and '90s

- These codes can handle complex geometry but are generally limited to 2nd order accuracy

- They cannot handle turbulence without modeling

CFD Today

- CFD has been on a plateau for the past 15 years

- The majority of current CFD methods are not adequate for vortex dominated and transitional flows

  - Rotorcraft, High-lift systems, Formation flying, …

CFD Today

"In spite of considerable successes, reliable use of CFD has remained confined to a small but important region of the operating design space due to the inability of current methods to reliably predict turbulent-separated flows"
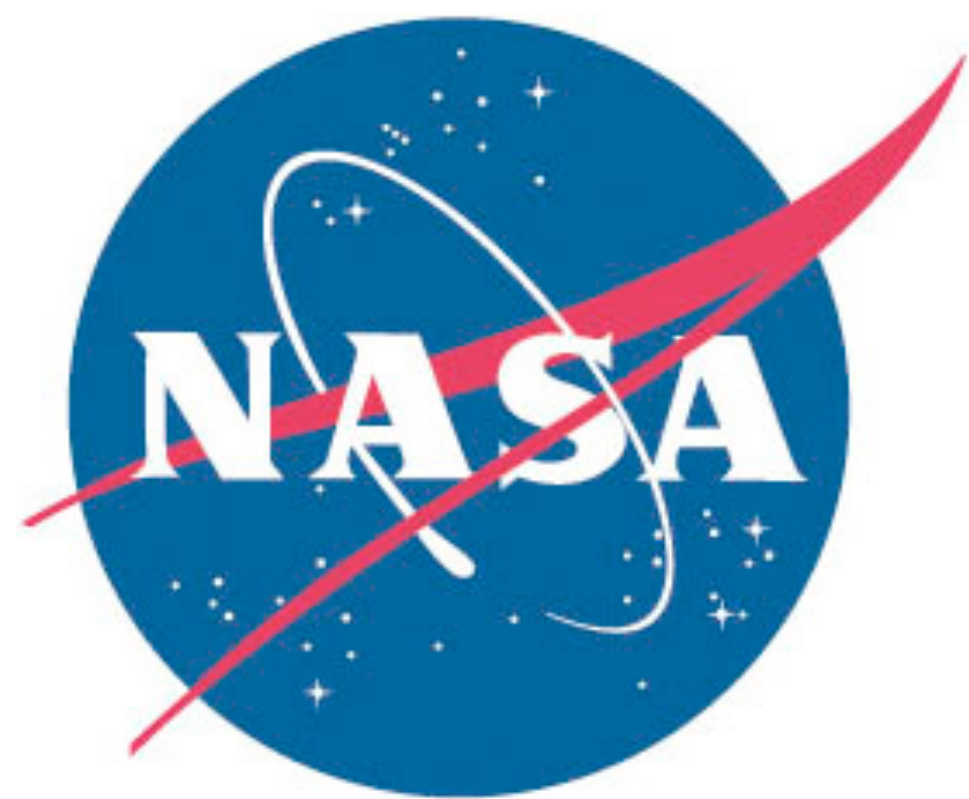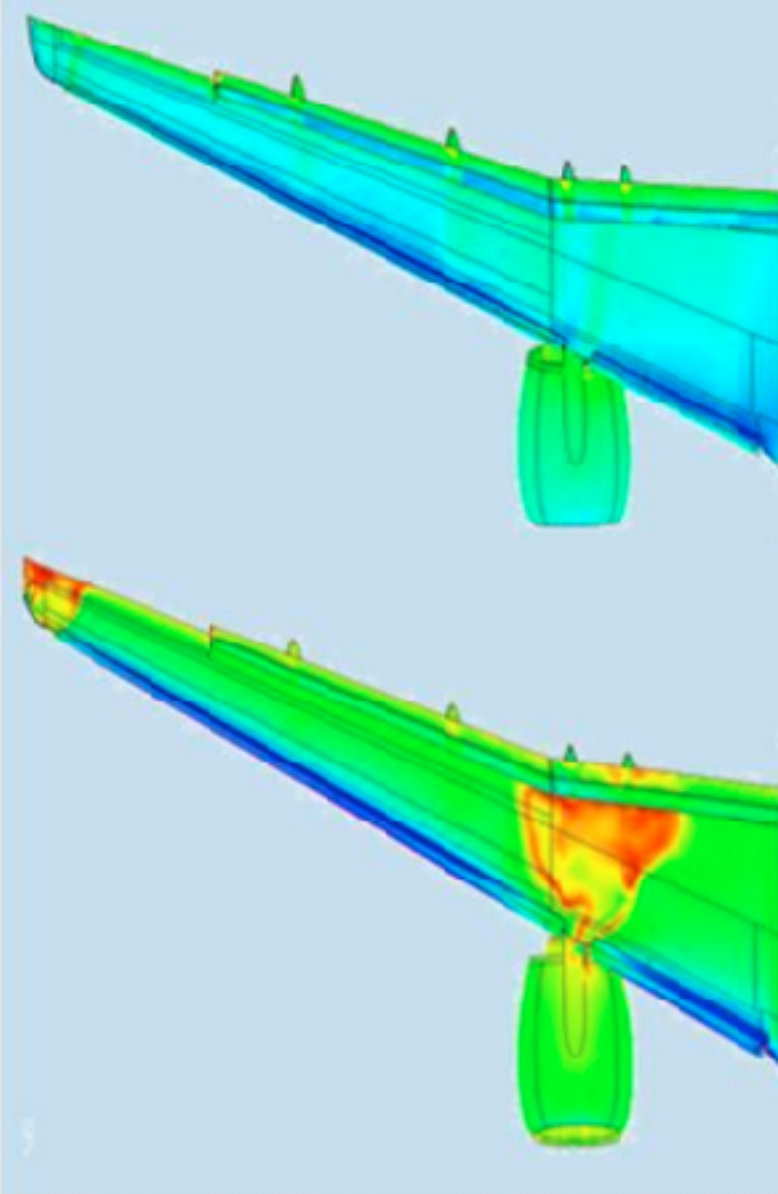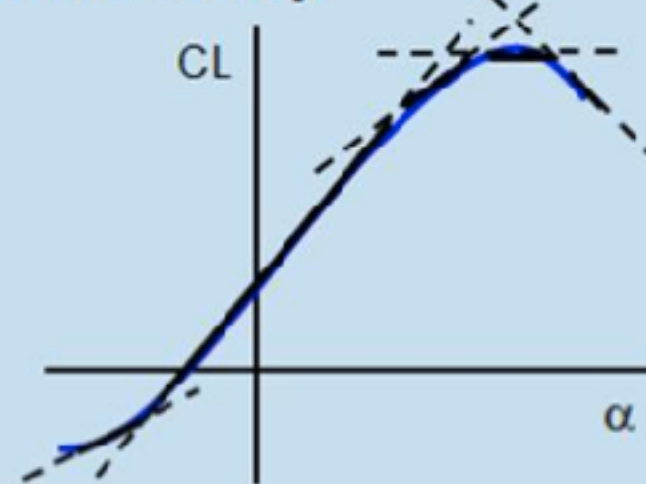
—NASA CFD Vision 2030 Study, 2014.

CFD Today
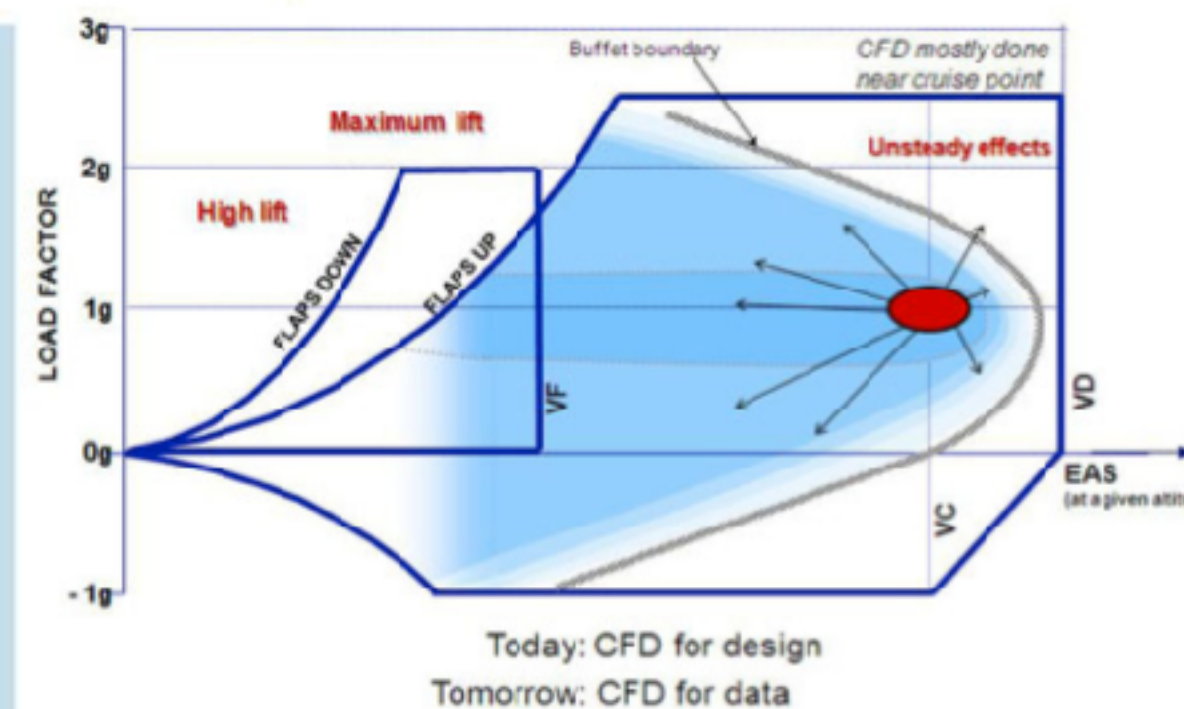
Murray Cross, Airbus, Technology Product Leader — Future Simulations (2012)

CFD in the Future

CFD Tomorrow

- To facilitate a **step-change** in design capabilities we need to move away from RANS simulations to **large eddy simulations** (LES).

- The number of DOFs for an LES of turbulent flow over an airfoil scales as $Re^{1.9\sim2.4}$ (resp. $Re^{0.28\sim0.4}$) if the inner layer is resolved (resp. modeled)
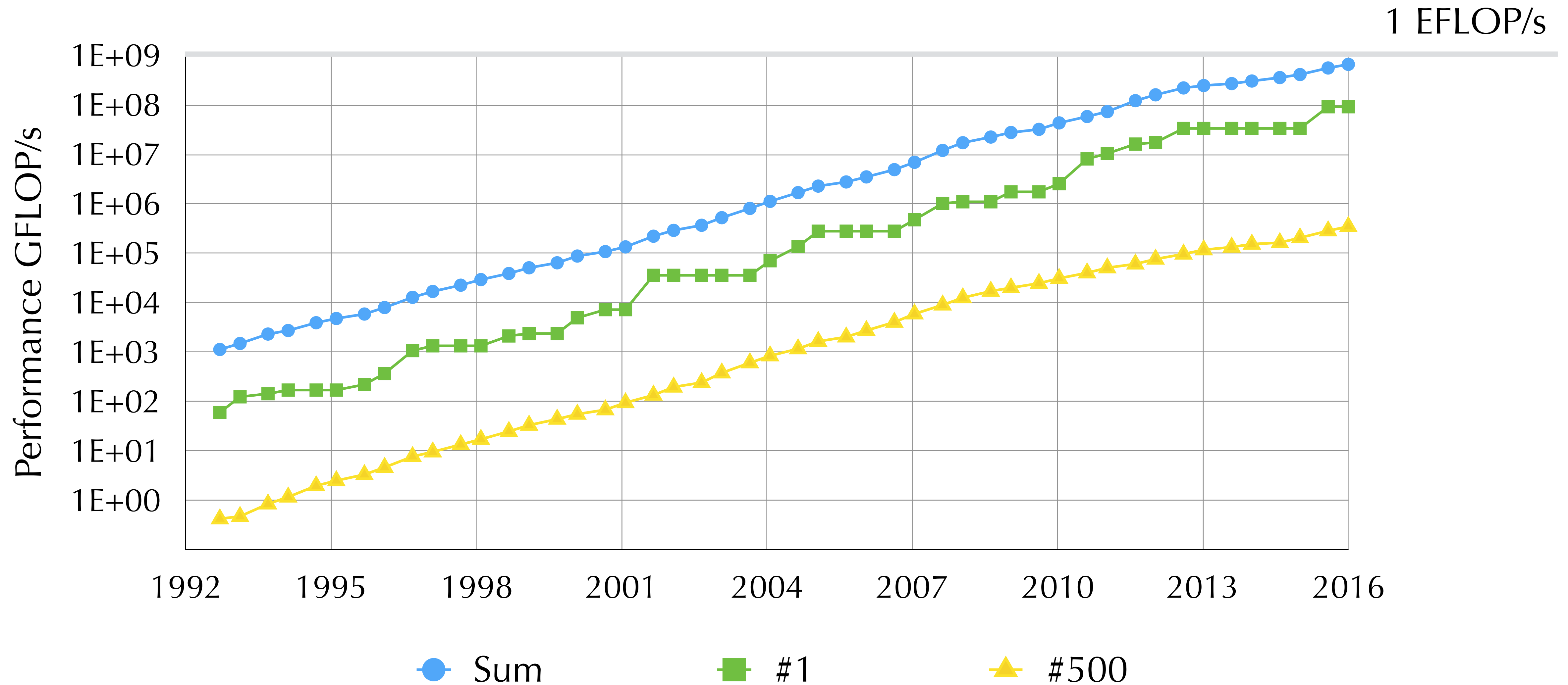
The Cost of LES
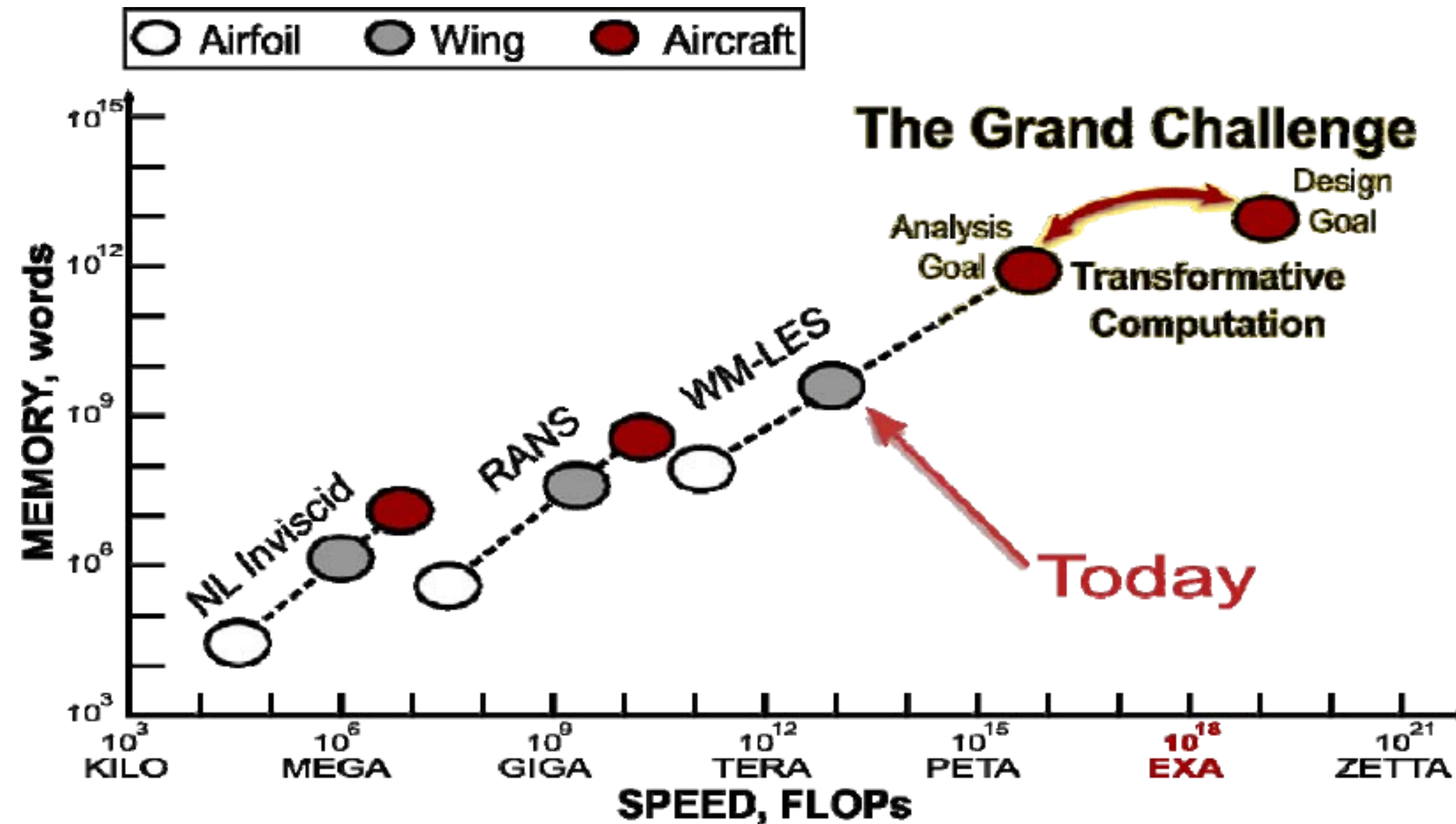
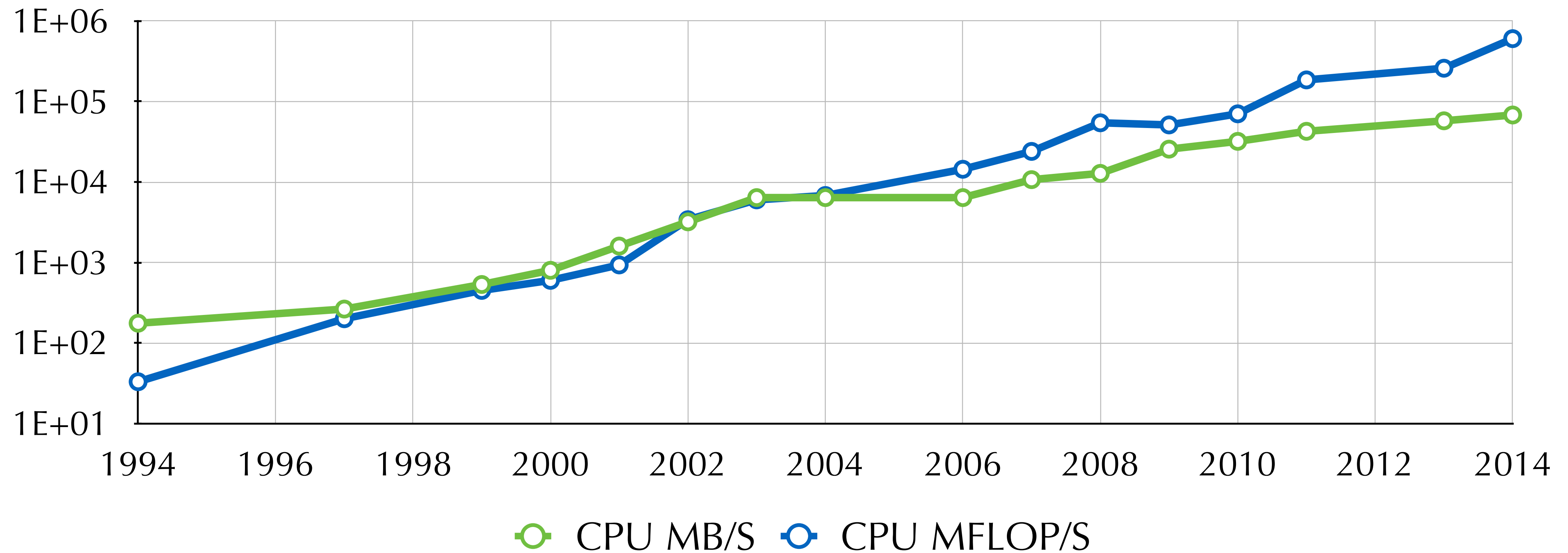From *The Opportunities and Challenges of Exascale Computing*, US DOE, fall 2010.

Hardware Developments

The TOP500 List

FLOP/s and Memory

- Intel server CPUs from 1994–2014…
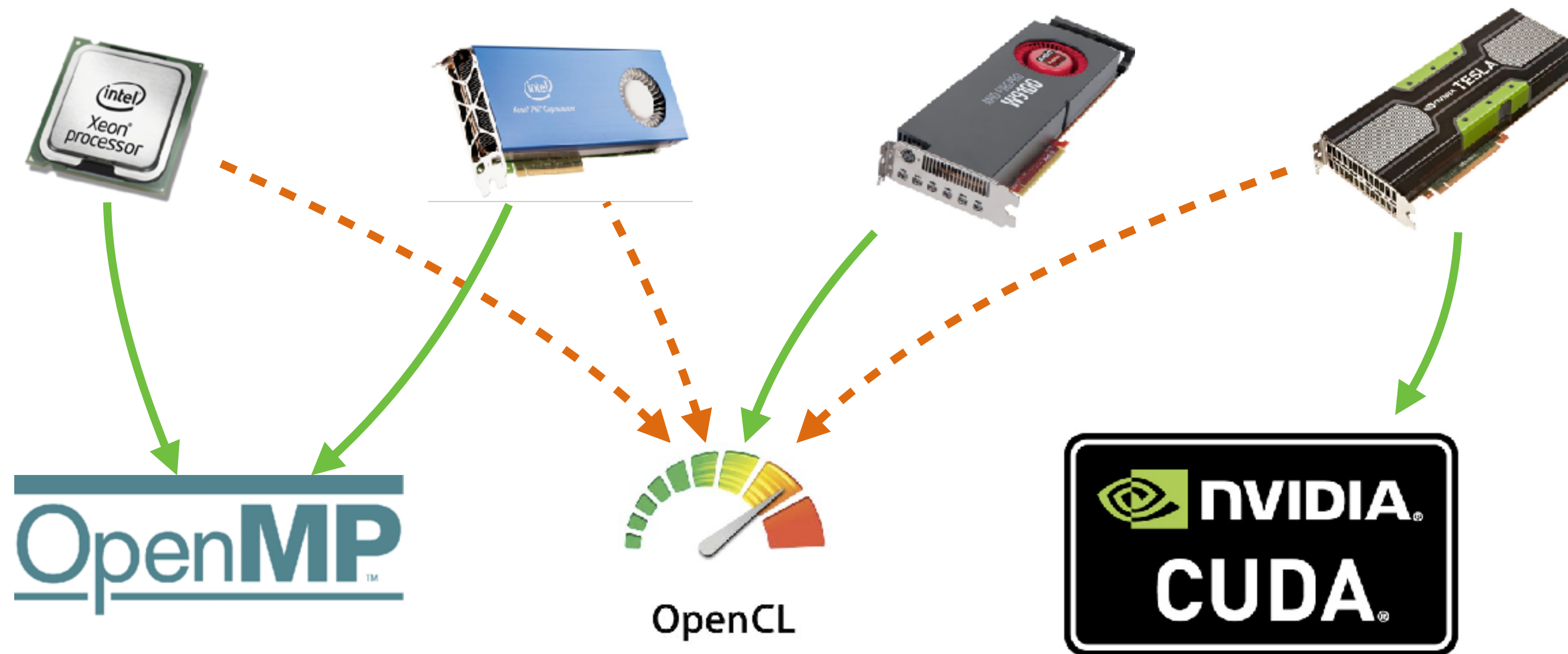
FLOP/s and Memory

- Twenty years of progress.

	1994	2014	Ratio
MFLOP/s	33	604,000	18,303
MB/s	176	68,000	386

FLOP/s and Memory

On account of this **changing landscape** we need to **completely rethink** how we **design methods** now that data movement is expensive and arithmetic is cheap.

Accelerators

- Accelerators complicate the programming environment.

- However, they **do not** change the fundamentals.

Accelerators to the rescue?

- …but they do offer tremendous FLOP rates.

- Titan at ORNL: **17.6 PFLOP/s** with **18,688 K20X** GPUs.

Beyond Hardware: Algorithms

- Our challenges do not stop there…

- Not only are the majority of current numerical methods **ill-suited to modern hardware** they are also **overly dissipative**.

Baseline Requirements

- A good numerical scheme for future CFD needs to:

  - have minimal dissipation

  - conserve memory bandwidth

  - permit complex geometries

High-Order Methods

For turbulent compressible flows the most promising candidates are high-order discontinuous **spectral element schemes**.

- **Reason:** High arithmetic intensity at p = 4 and above.

High-Order Methods

- Paired with **explicit time-stepping** they admit a very efficient implementation.

- Are currently enabling LES of hitherto intractable flow problems.

- However, as a community we are still **far away from LES of a complete air vehicle**.

Challenge I: Time-Stepping

- **Re > 10^6** requires high aspect ratio near-wall grids.

- …which necessitates **implicit time-stepping**.

- Existing approaches are **memory intensive** ($J \sim p^6$) and/or require pre-conditioners which are ill-suited to modern hardware.

Challenge II: Wall and Sub-grid Scale Models

- **Wall** models are still at an early stage.

- High-order sub-grid scale models also lacking.

- Still derived on an 'incompressible first' basis.

- Often introduce extra **free parameters**.

Challenge III: Grid Generation

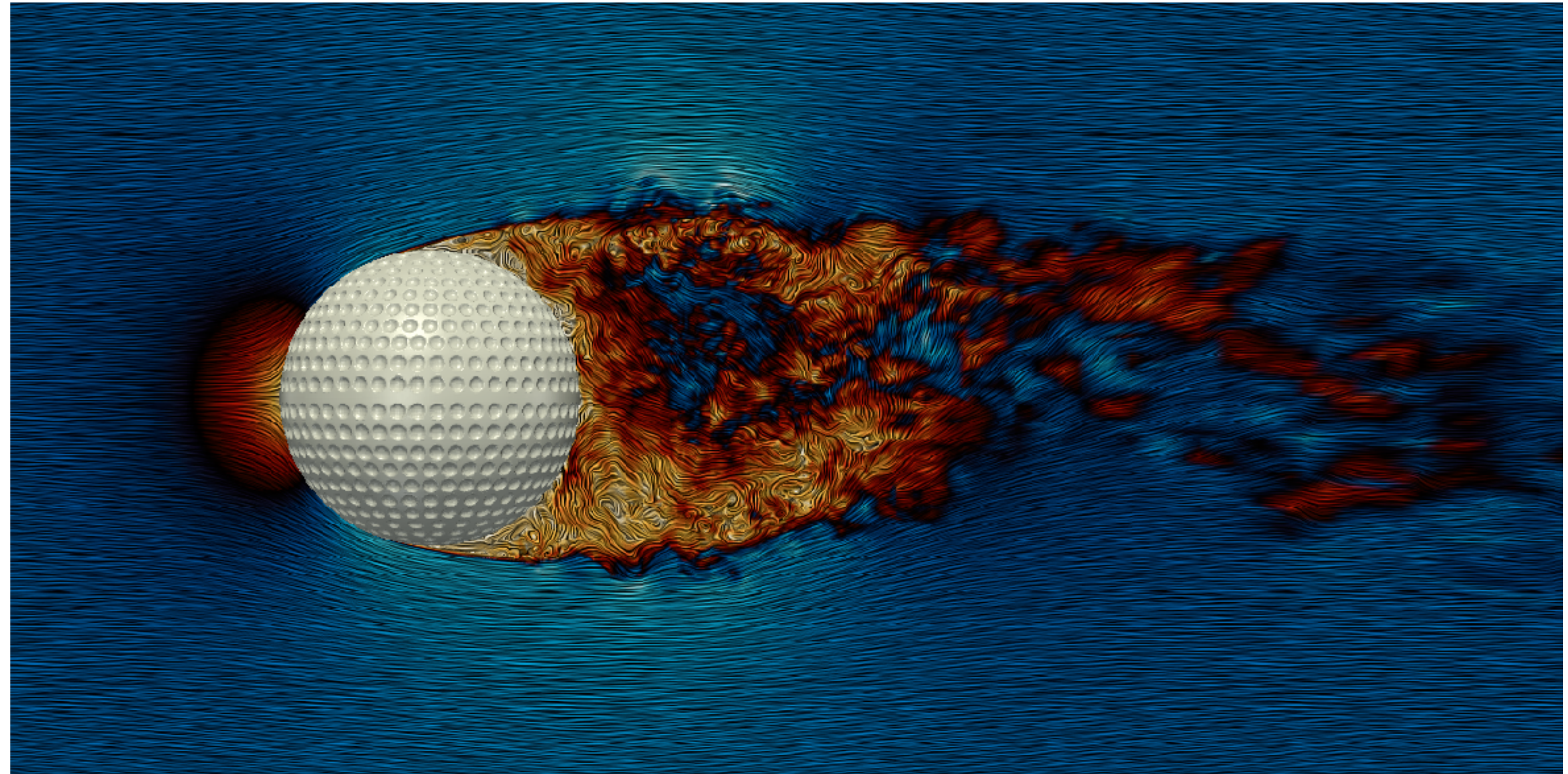- Curved **body fitted** grids are hard to generate.
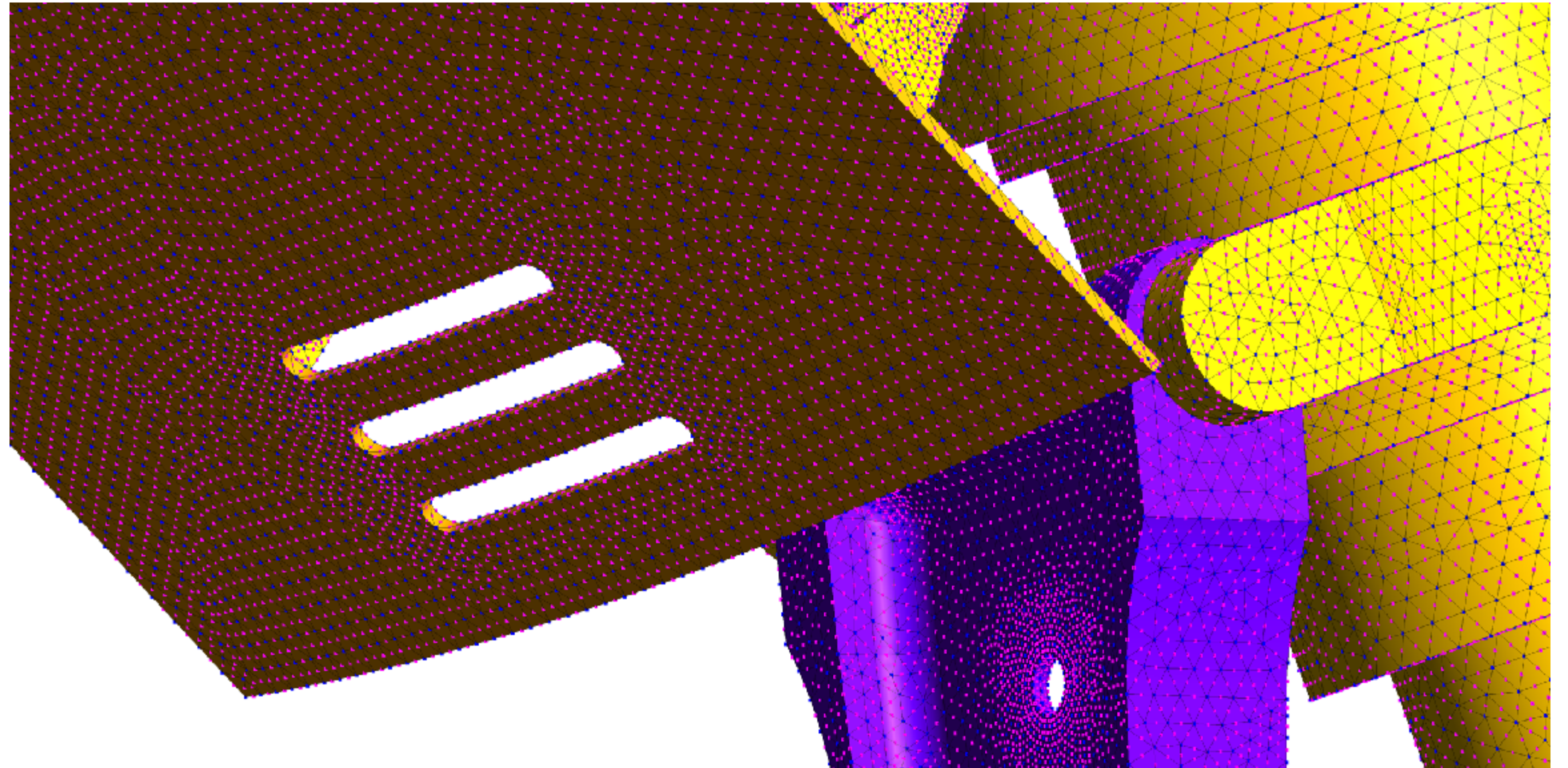
*Courtesy Steve Karman
of Pointwise*

Real World Flows

- LES alone **is not enough**.

LES of a golf ball at Re = 180×10³ using an overset grid to enable the ball to spin

Challenge IV: Dynamic Grids

- Lack **efficient** approaches for **grid deformation**.

- Also need **accurate** methods for **high-order interpolation** in overset settings.
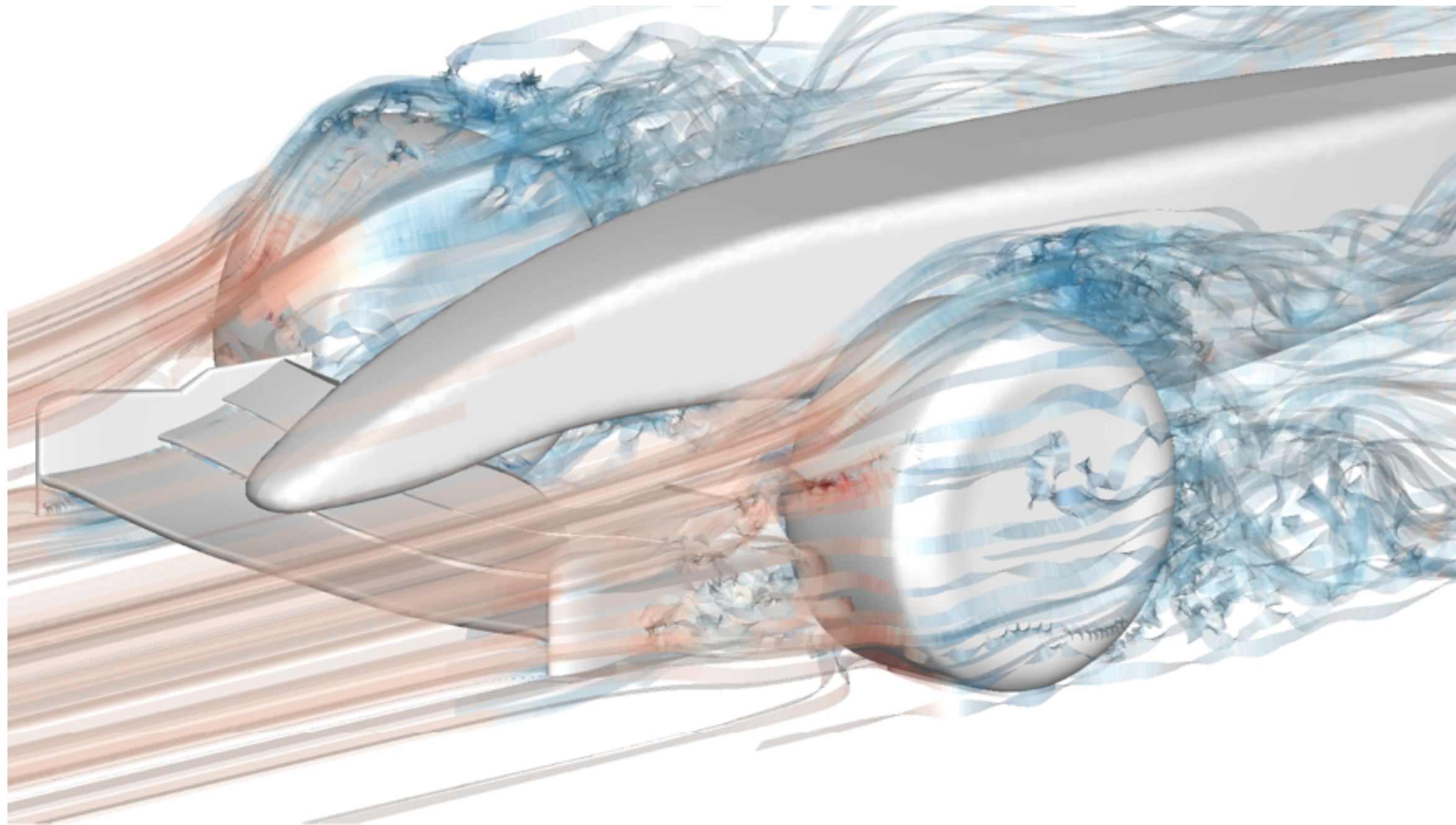
- Some problems also require AMR.

Challenge V: FSI

- Often **Error(RANS) ~ Error(lack of structural effects)**

- Thus need LES + FSI.

- But FSI = Deforming grids + solid mechanics.

Challenge VI: Multiphysics

- Requires complex sub grid scale **chemical models**.

- ΔT(chemistry) $\ll$ ΔT(fluid), truly multi-scale.

- Vital for **hypersonic applications**.

Beyond Aerospace

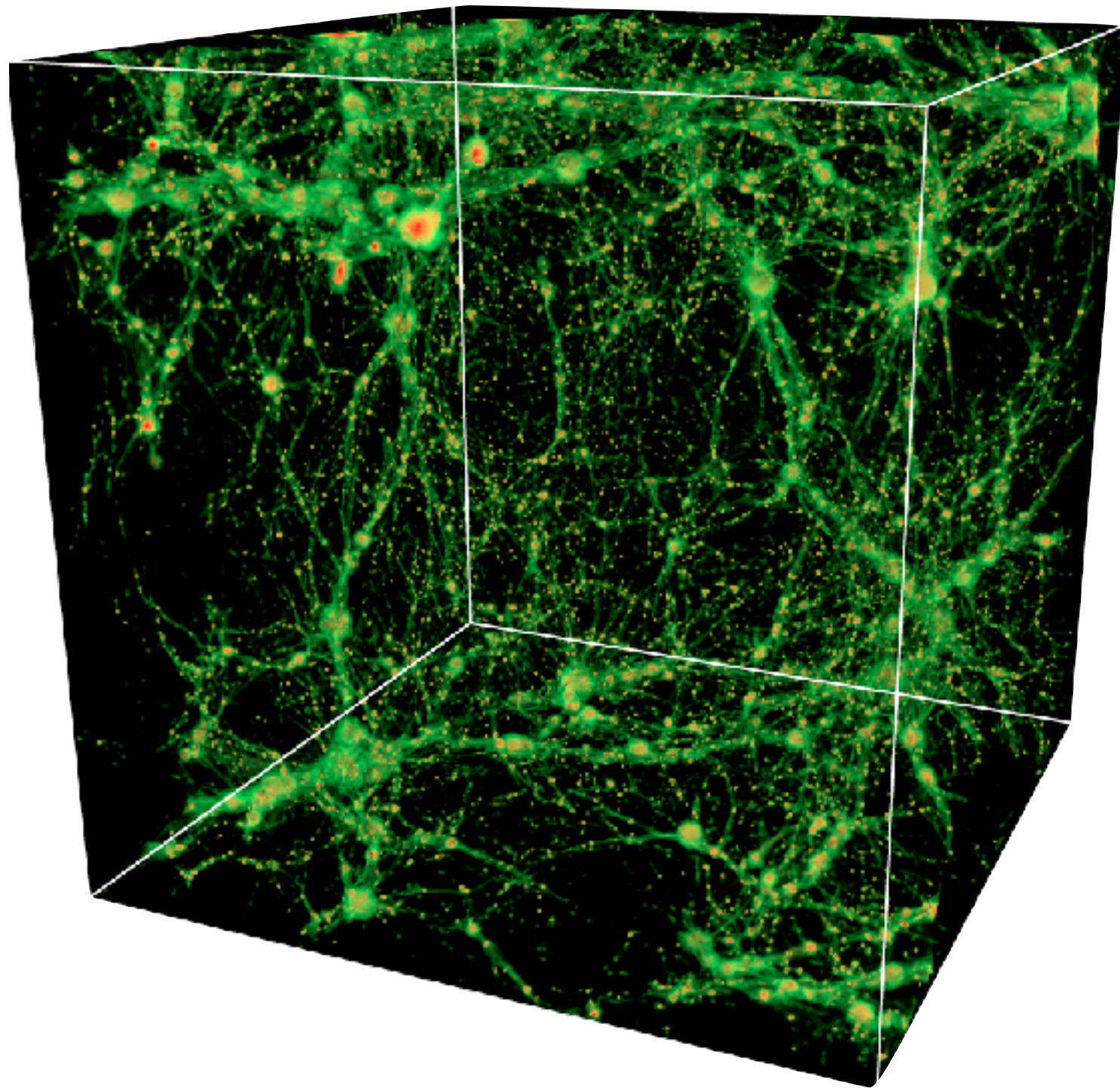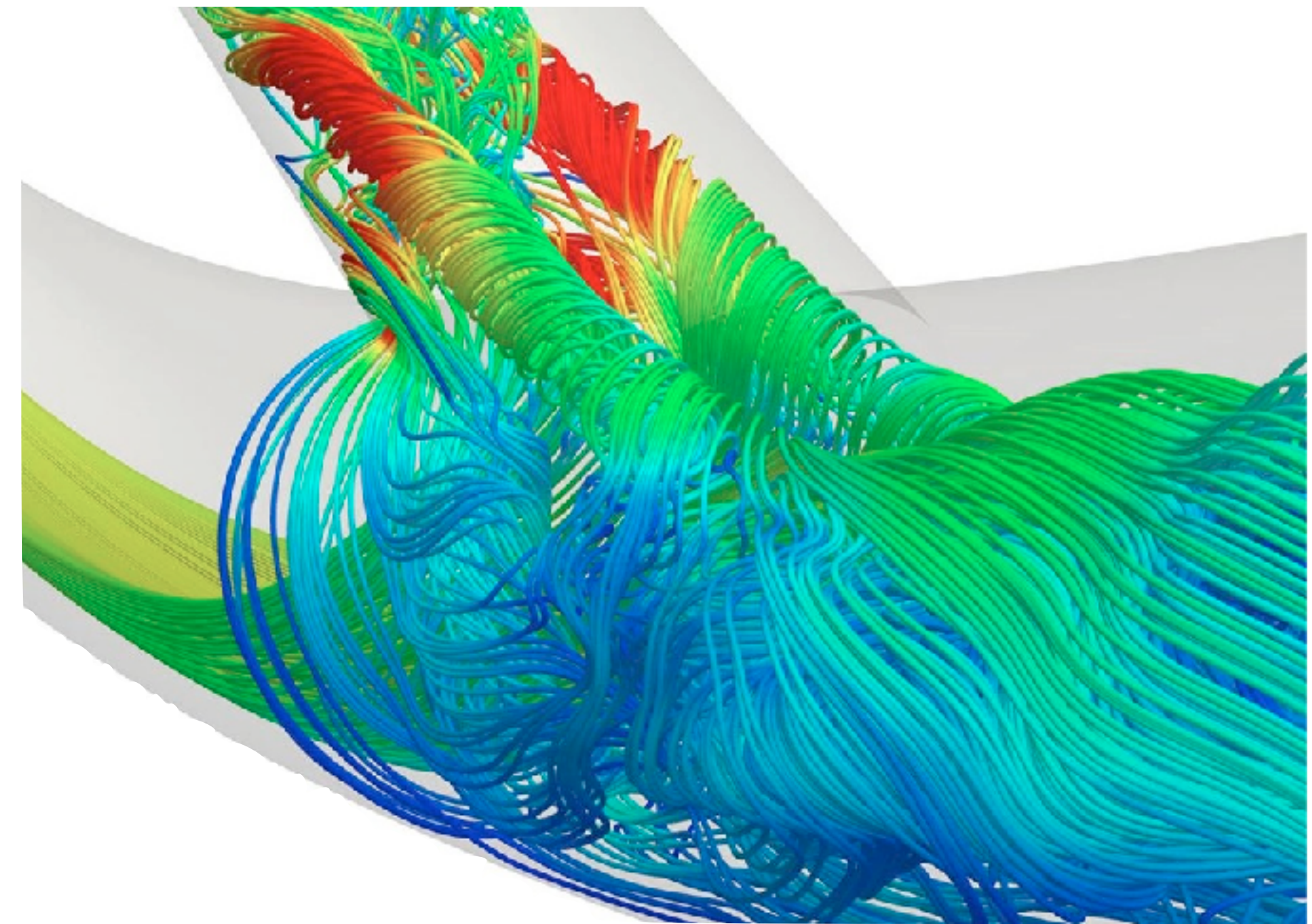Automotive
Courtesy of S. Sherwin

Marine

Beyond Aerospace

Cosmological flows
From SDSC (Tiger simulation)

Bioflows
Courtesy of P. Vincent

What We're Doing

PyFR

- Flux reconstruction code designed from the ground up for **modern hardware**.

- Written in Python — just **8,000 lines of code**.

- Computational kernels specified in a Mako-derived **domain specific language** to enable **heterogeneous computing**.
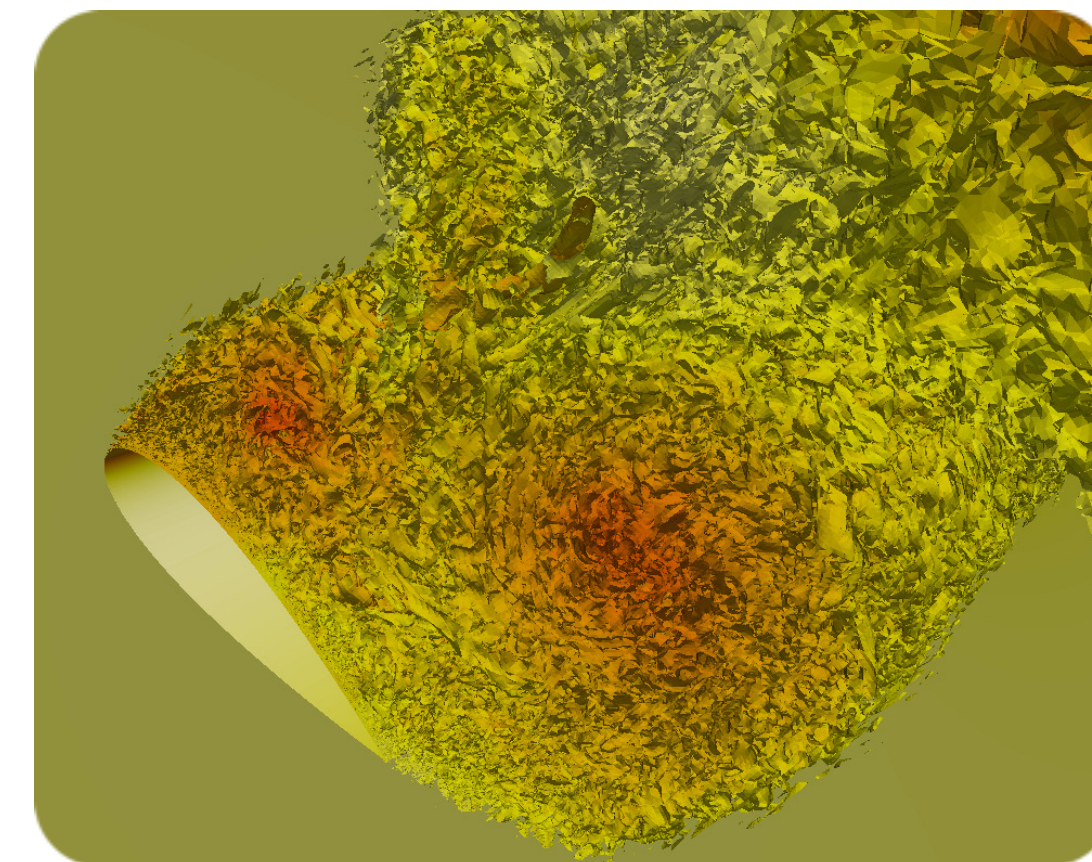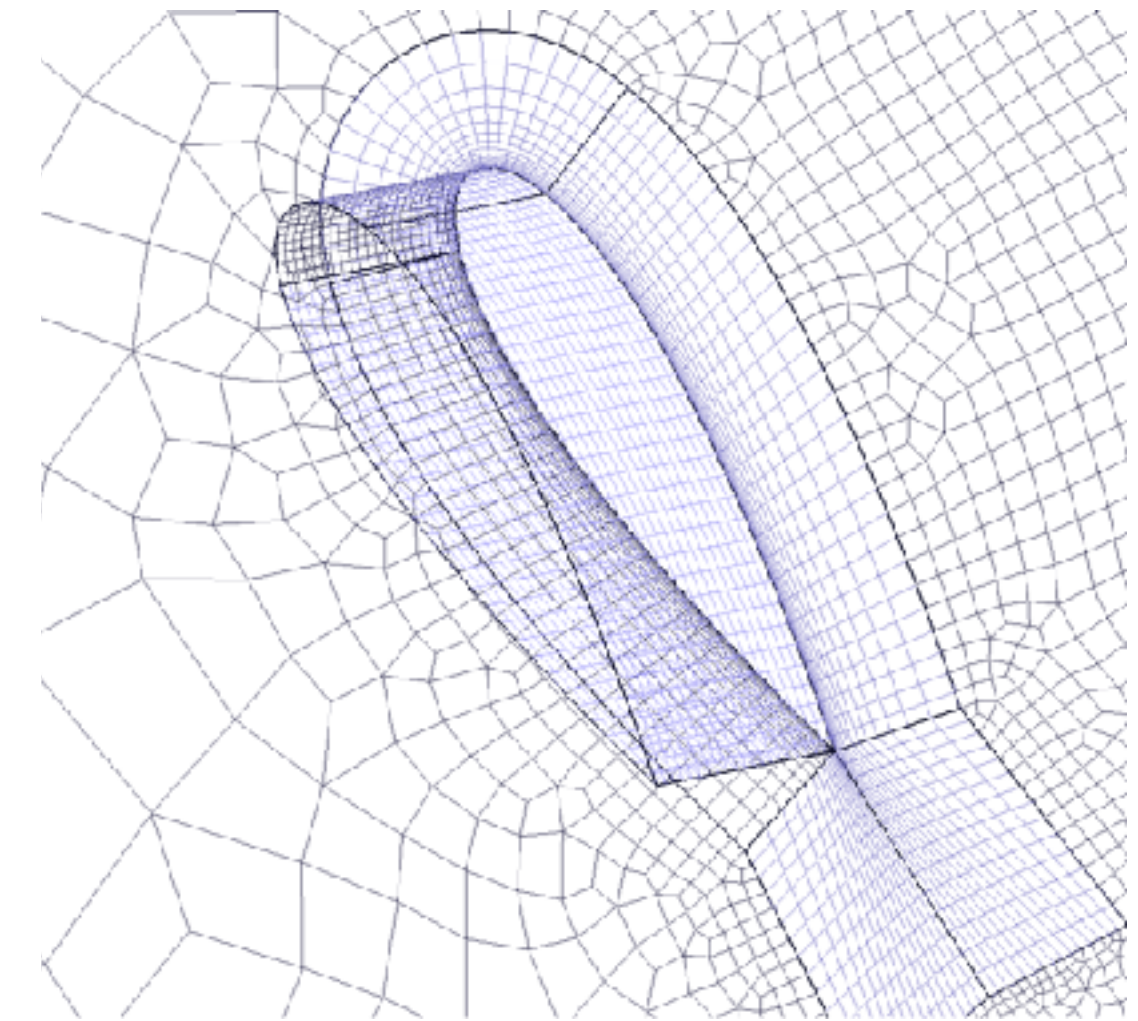
PyFR

- Features.

|	
Governing Equations	Compressible Euler and Navier Stokes
Spatial Discretisation	Arbitrary order Flux Reconstruction on mixed unstructured grids (tris, quads, hexes, tets, prisms, and pyramids)
Temporal Discretisation	Adaptive explicit Runge-Kutta schemes
Precision	single double
Sub-grid scale models	None
Platforms	CPU and Xeon Phi clusters NVIDIA GPU clusters AMD GPU clusters

PyFR: NACA 0021

- Flow over a NACA 0021 at 60 degree AoA

- Re = 270,000 and Ma = 0.1

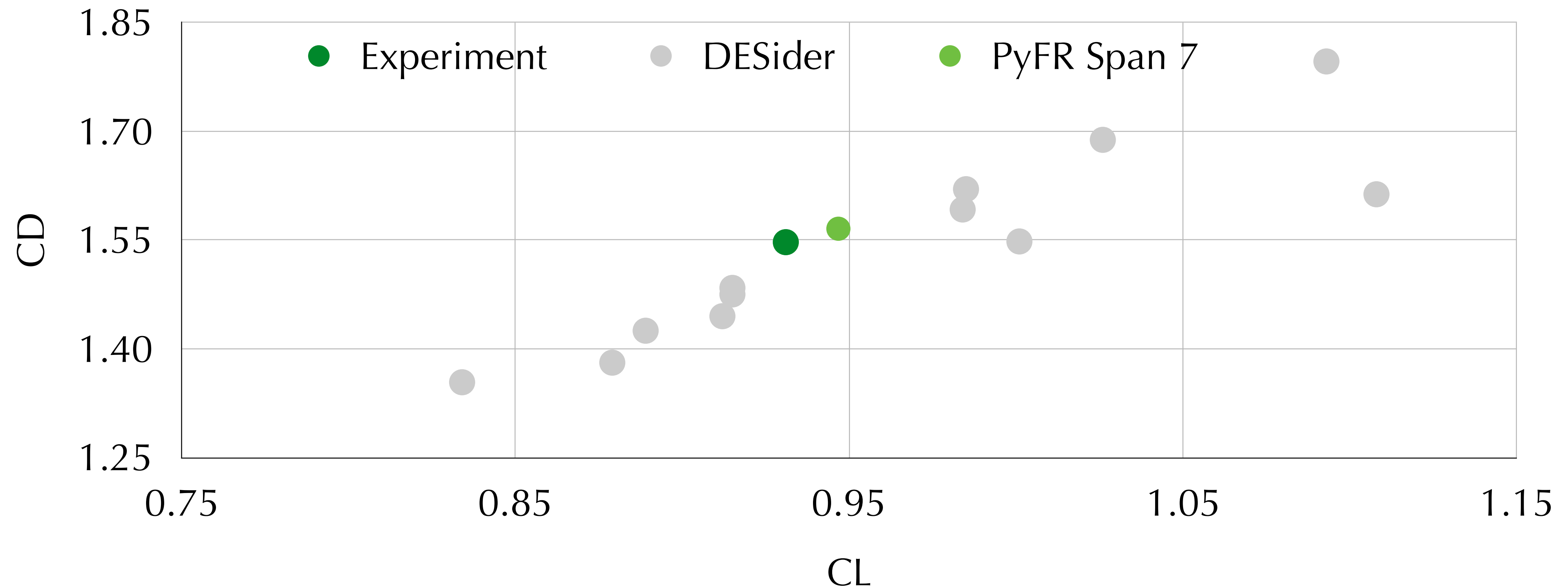- Compare with Swalwell and DESider
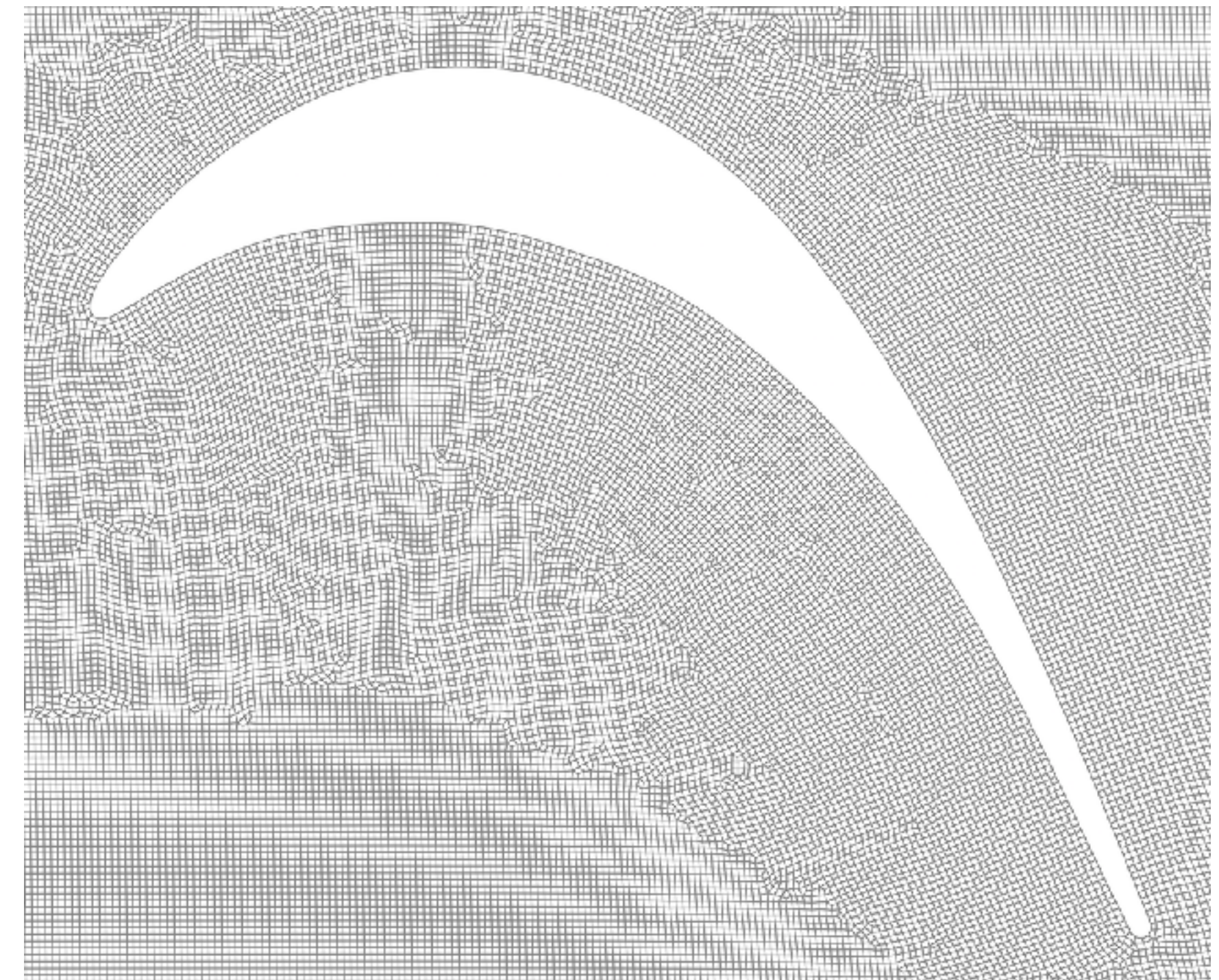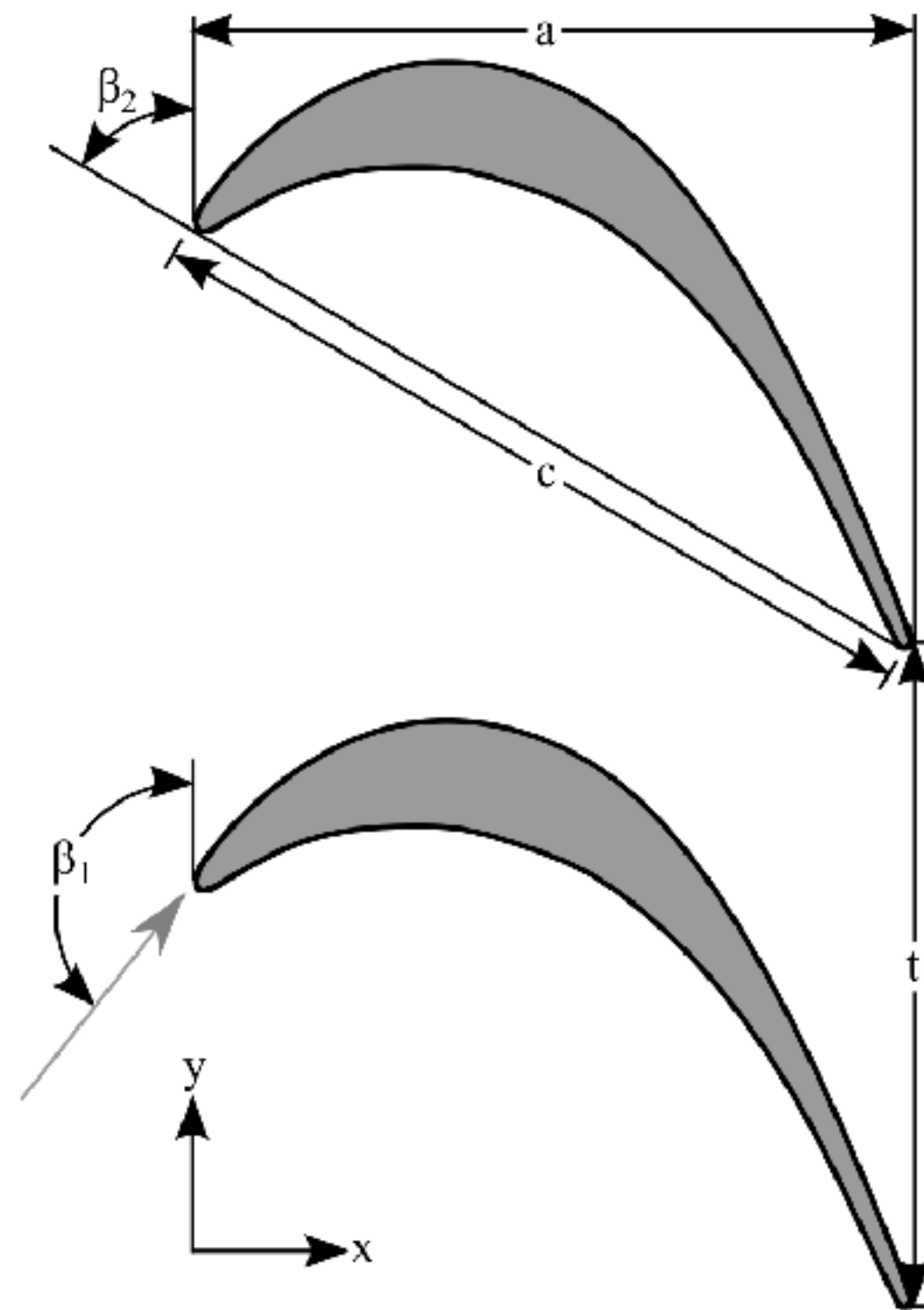
PyFR: NACA 0021

- Time-span averaged surface pressure.
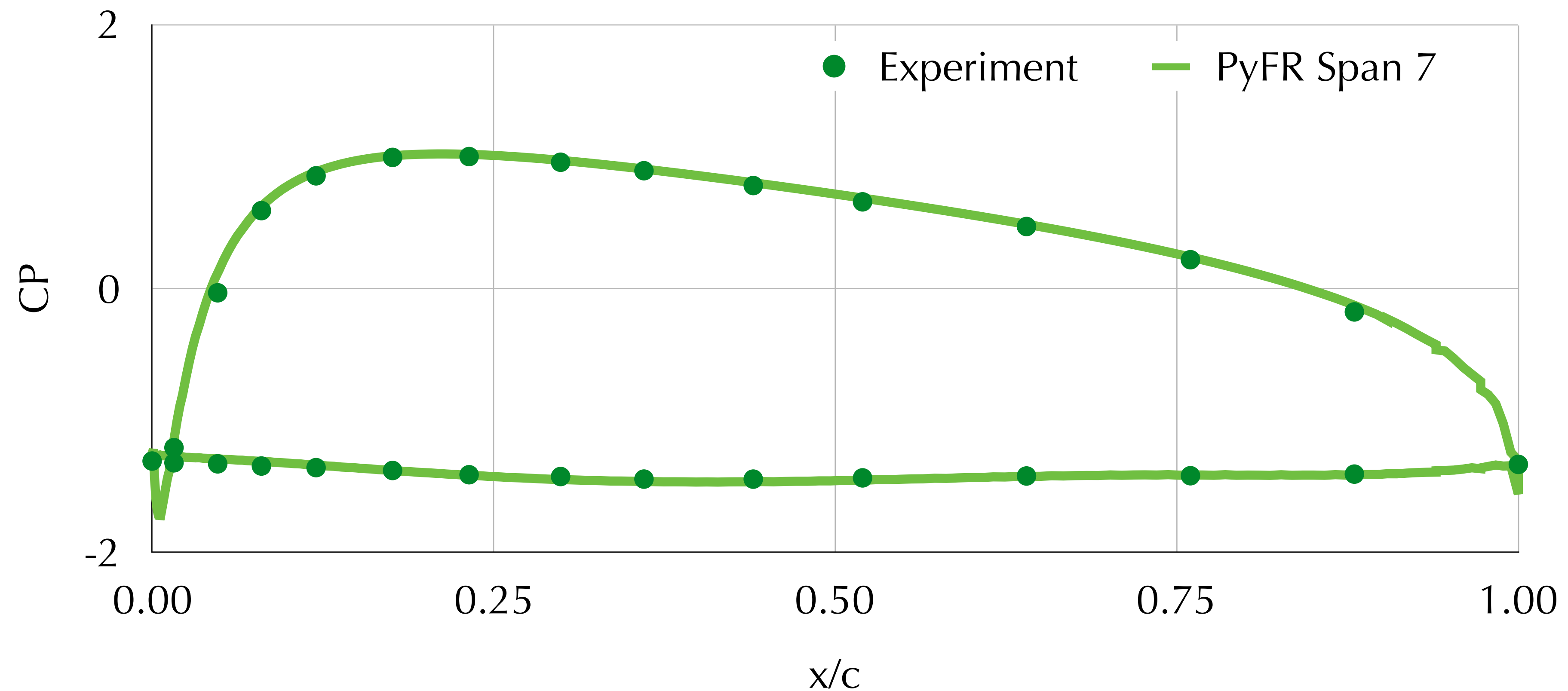
PyFR: NACA 0021

- Time-averaged lift and drag coefficients

PyFR: T106D

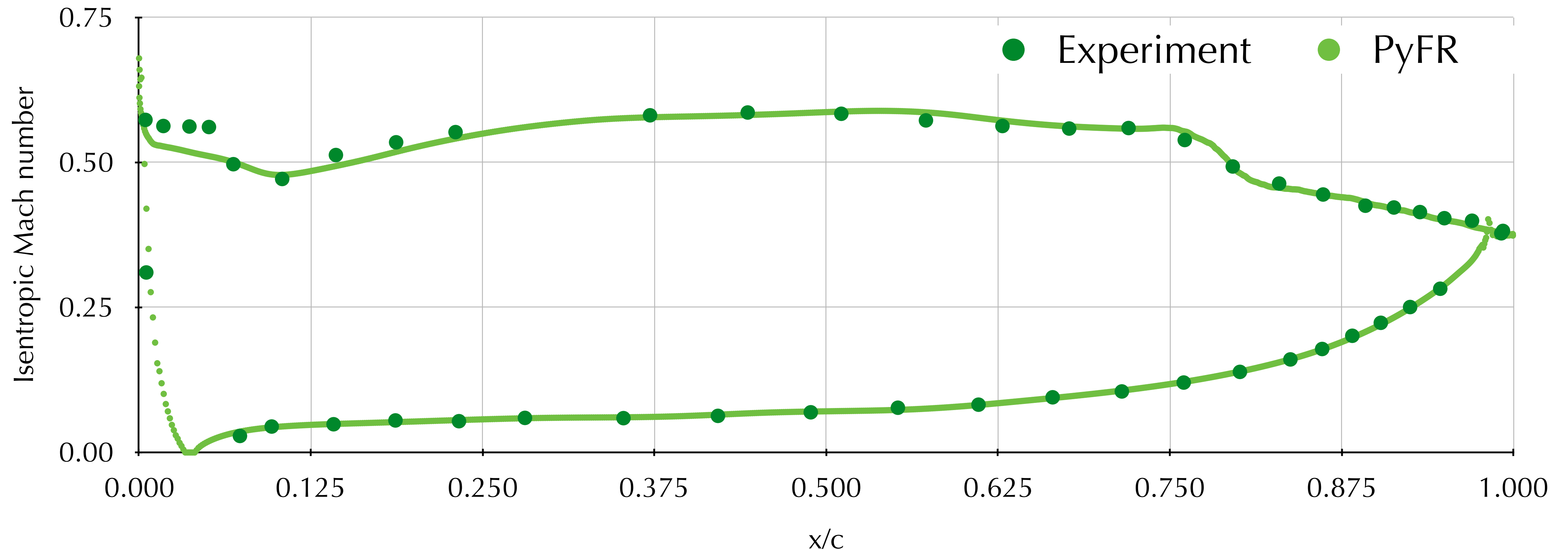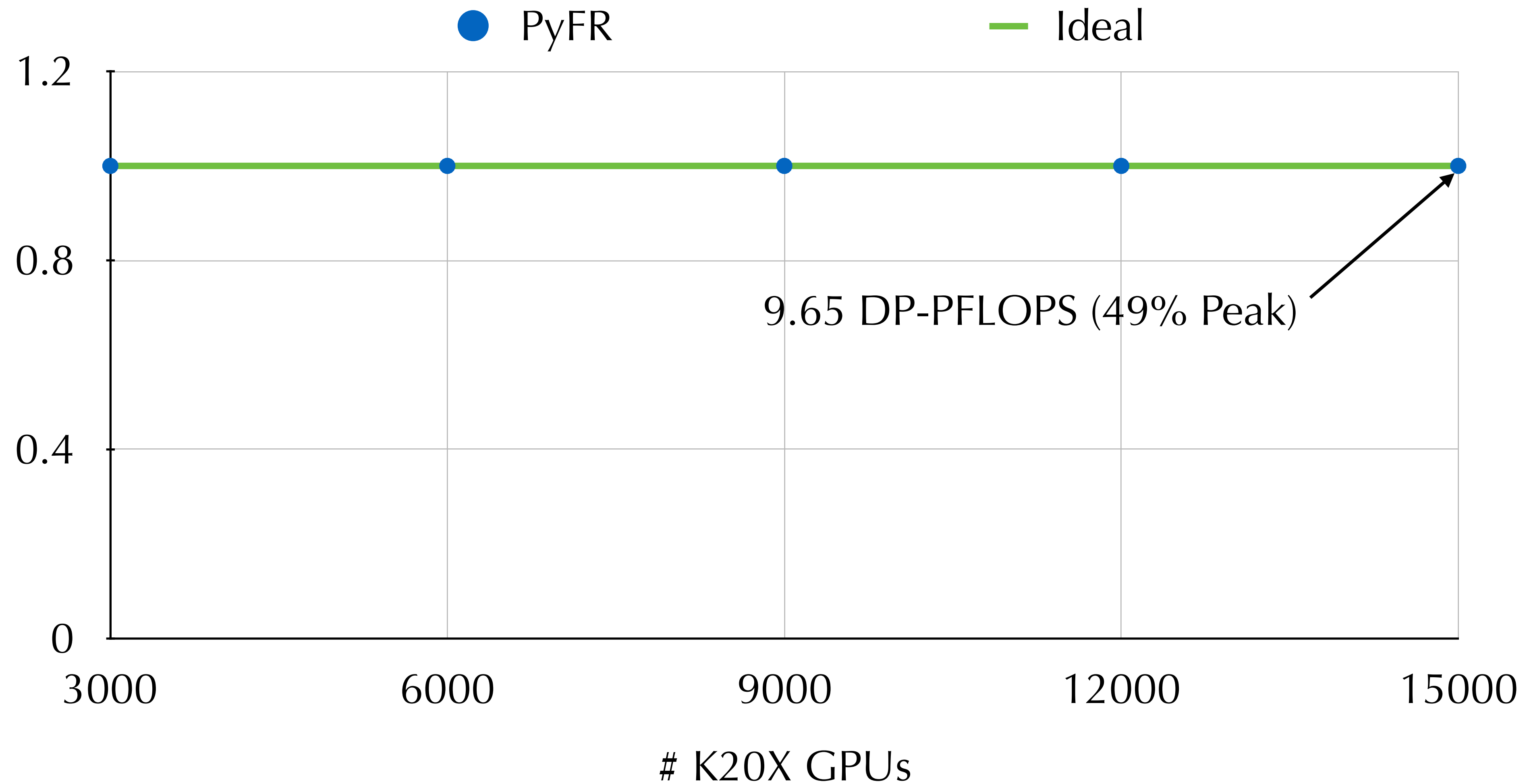- T106D low pressure turbine cascade at **Re = 80,000** and **Ma = 0.4**.

PyFR: T106D

PyFR: T106D

- Comparison with experimental data of P. Stadtmüller et al.

PyFR: Weak Scaling

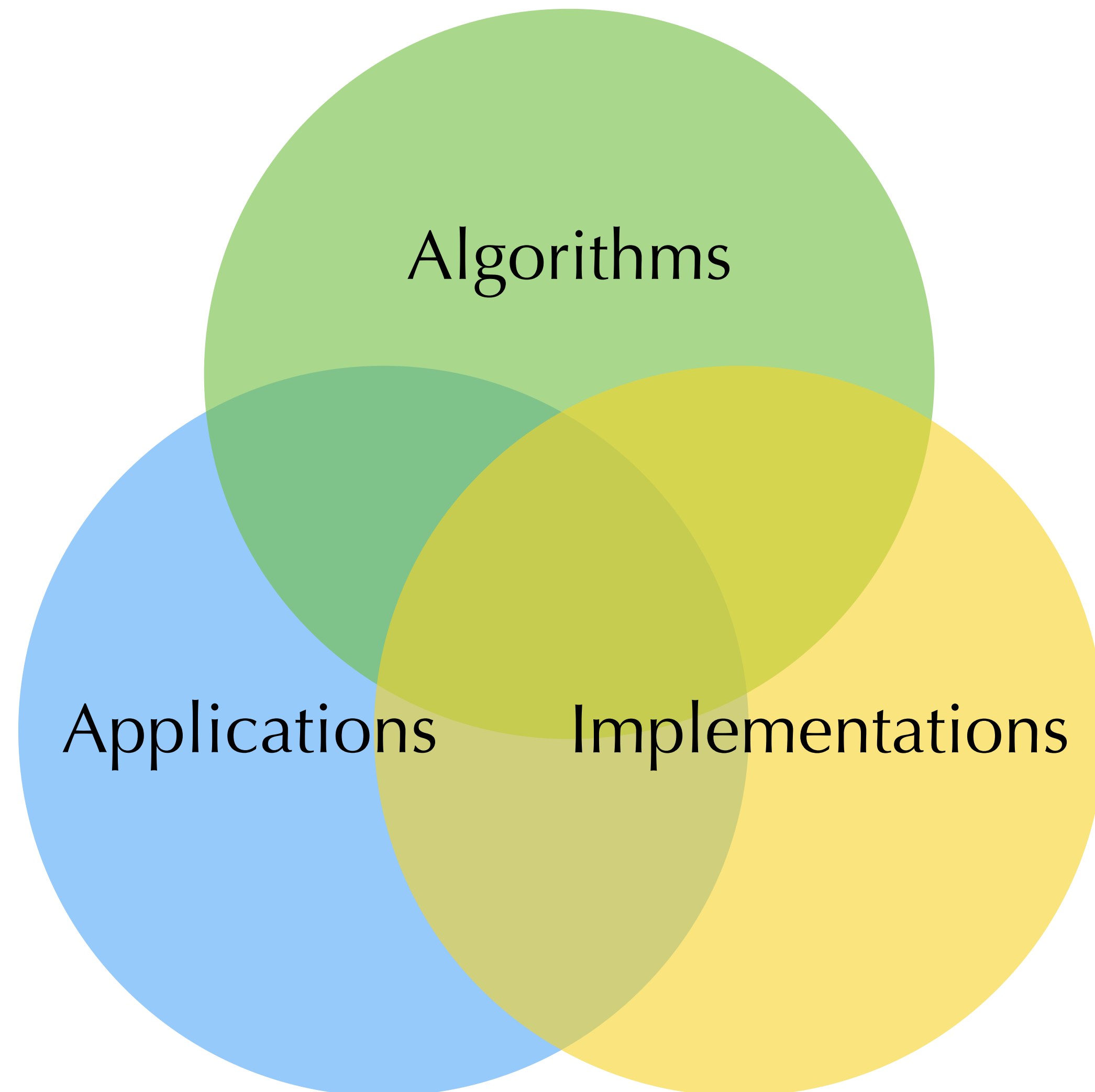PyFR ●   Ideal —

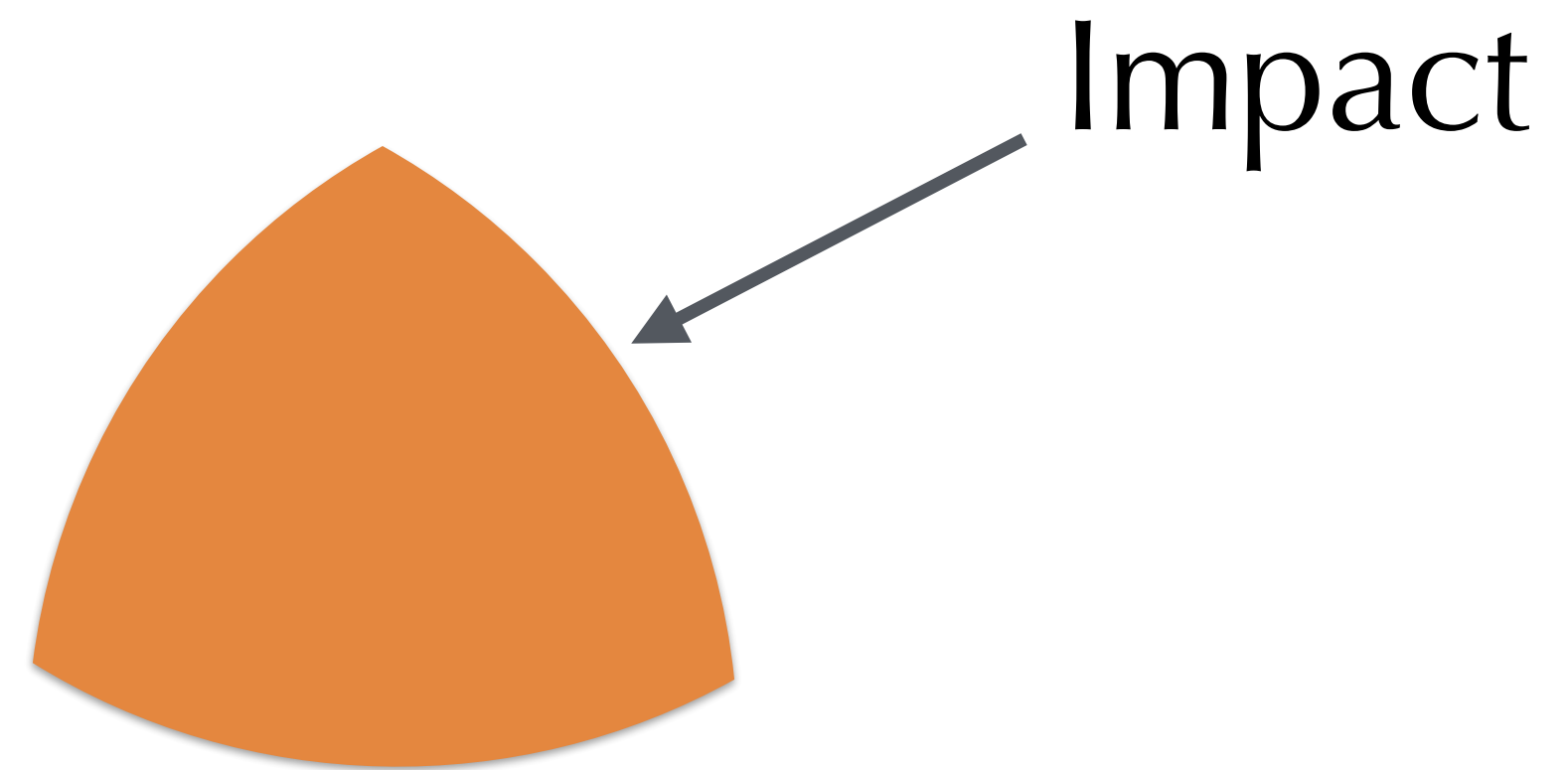9.65 DP-PFLOPS (49% Peak)

K20X GPUs

Future Directions

Future Directions

- Numerical methods alone **are not enough**.

- If we want **impact** we need to

- …take ownership of **implementing** these methods

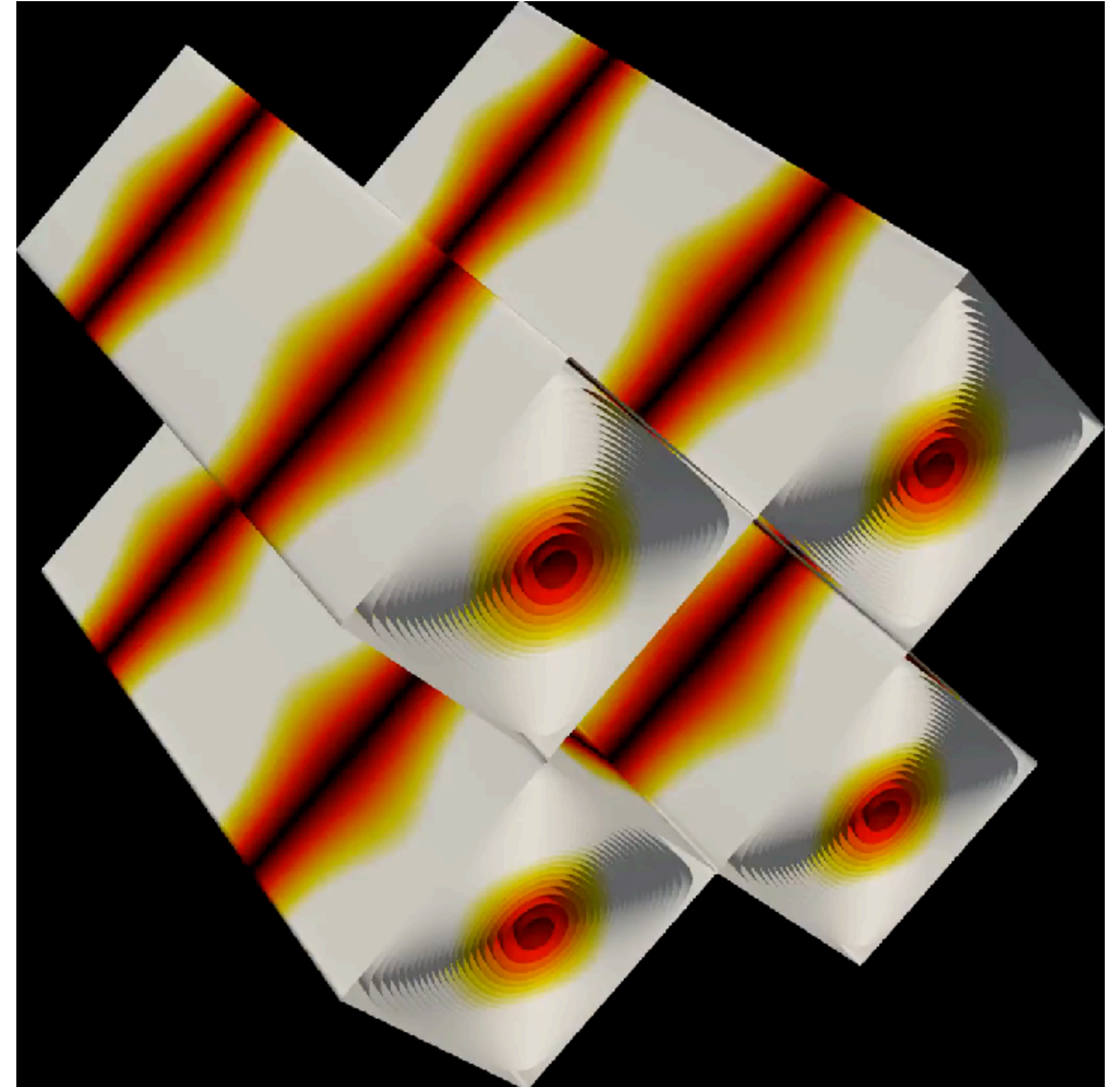- …and **applying** them to real problems.

Future Directions

Future Directions

Impact

Future Directions

- We should thus look to define **challenge problems** that are **relevant to industry**.

- Existing test cases are typically far removed from real-world problems.

Evolution of a Taylor–Green vortex

Future Directions

- Real-world problems are **large**…typically north of **one billion DOFs**.

- Thus it is vital that we have implementations that are:

- …**efficient** on leadership-class DOE systems.

- …**maintainable**.

Future Directions

- Developing test cases is also far from trivial.

- Industrial **geometries** and **validation data** are very often **proprietary**.

- Here, collaborations are critical.

Conclusions

Conclusions

- CFD is still a exciting discipline.

- By addressing the challenges herein we can **facilitate a step-change** in several key fields.

Conclusions

- Predicting the future is general ill-advised.

- What follows are the authors' opinions.

Conclusions

- The early development of CFD in the Aerospace Industry was primarily driven by the need to calculate steady transonic flows: **this problem is quite well solved**.

- CFD has been **on a plateau** for the past 15 years.

- Advances in numerics and hardware **should enable LES for industrial applications** in the foreseeable future.

Conclusions

- Industrial LES research should focus on **high-order methods for unstructured grids**.

- Open issues include: implicit time-stepping, wall and sub-grid scale models, curved grid generation, treatment of dynamical grids, fluid structure interaction, and multiphysics.

Conclusions

Eventually DNS may become feasible for high Reynolds number flows.

Hopefully with a smaller power requirement than a wind tunnel.

Acknowledgements