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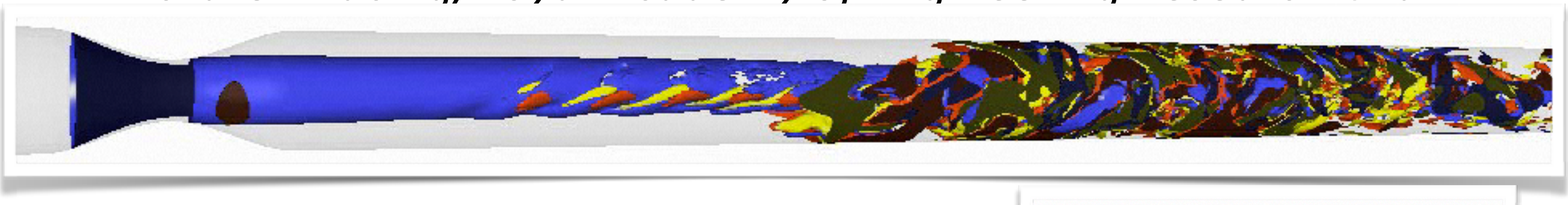
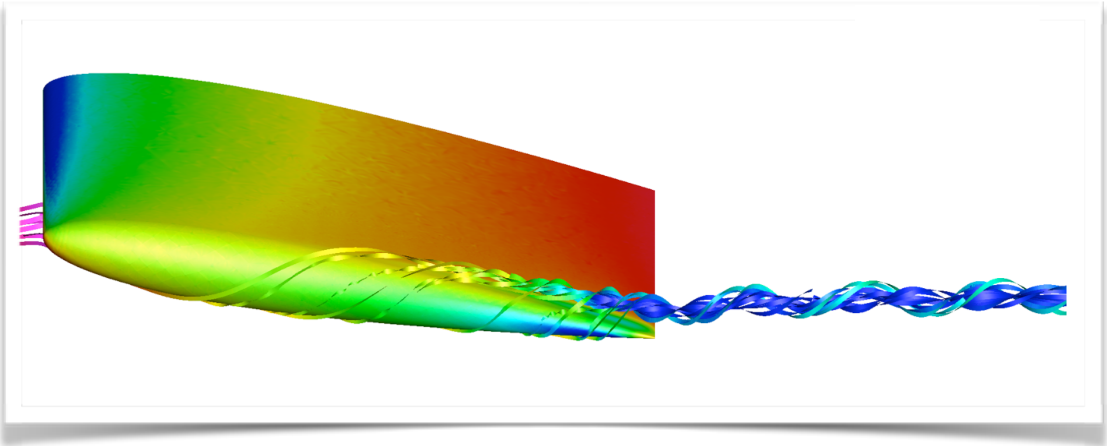
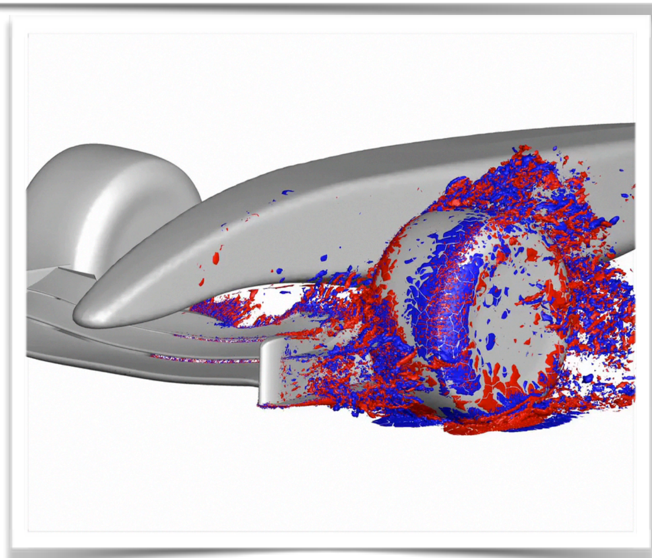
Spectral/hp element, scale resolving modelling for high Reynolds number F1 Aerodynamics

Spencer Sherwin

McLaren Racing/Royal Academy of Engineering Research Chair







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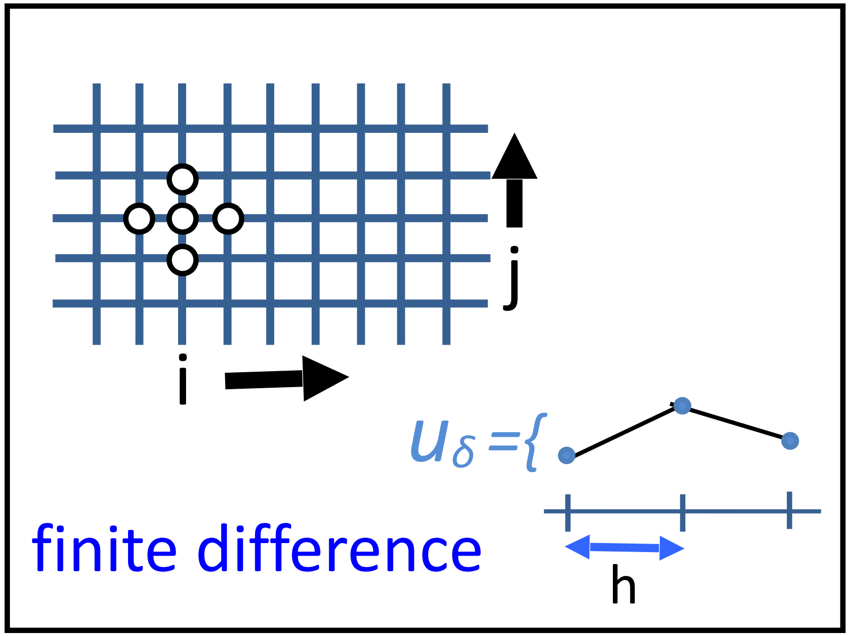
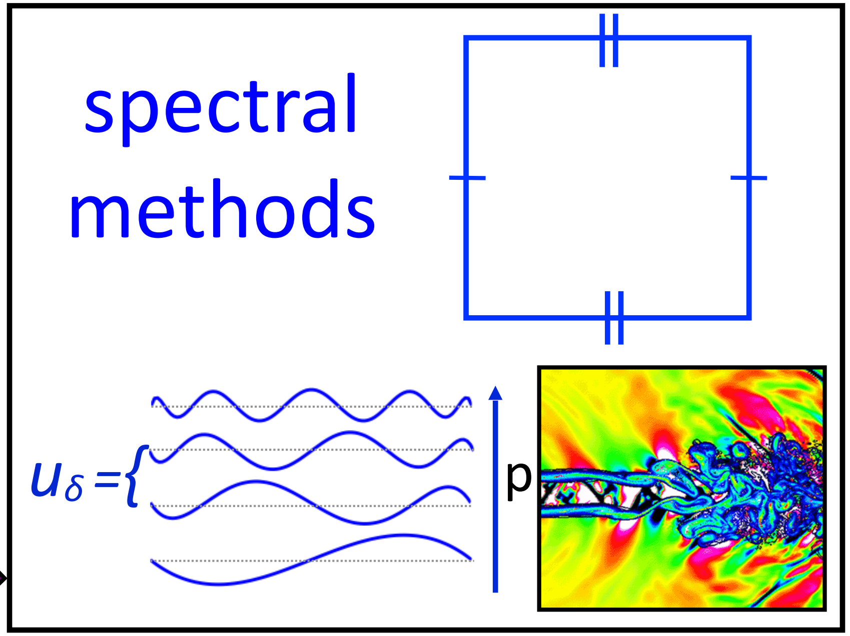
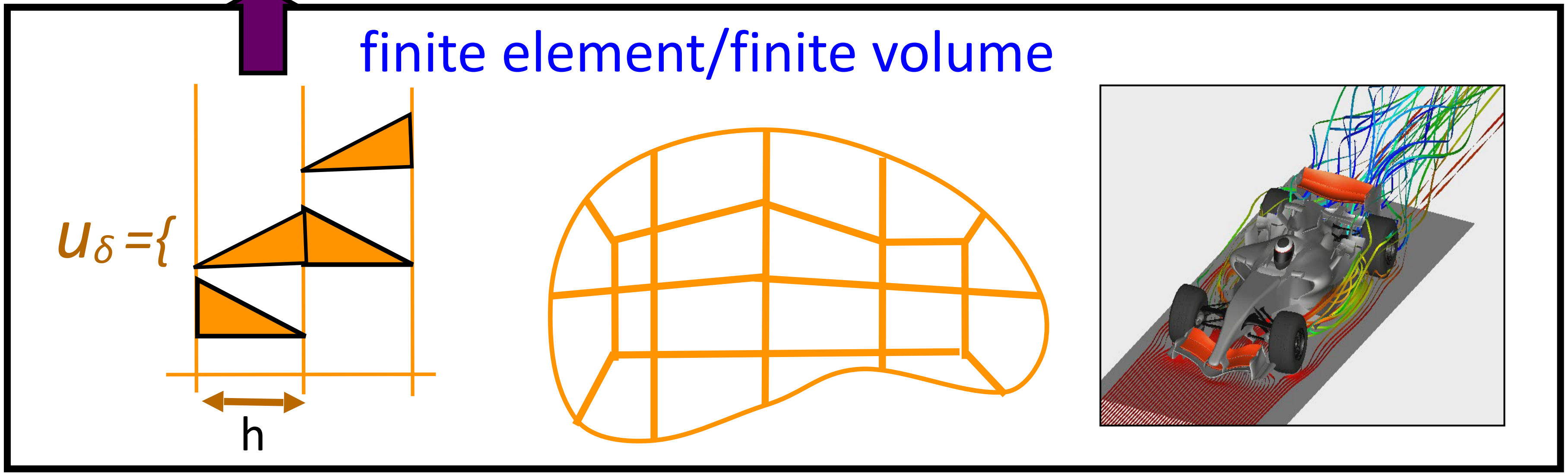
Outline

- Spectral/hp element methodology
- Motorsport in the UK
- Scale resolving simulations
  - High order meshing
  - Nodal/collocation space dealiasing
  - SVV Smoothing

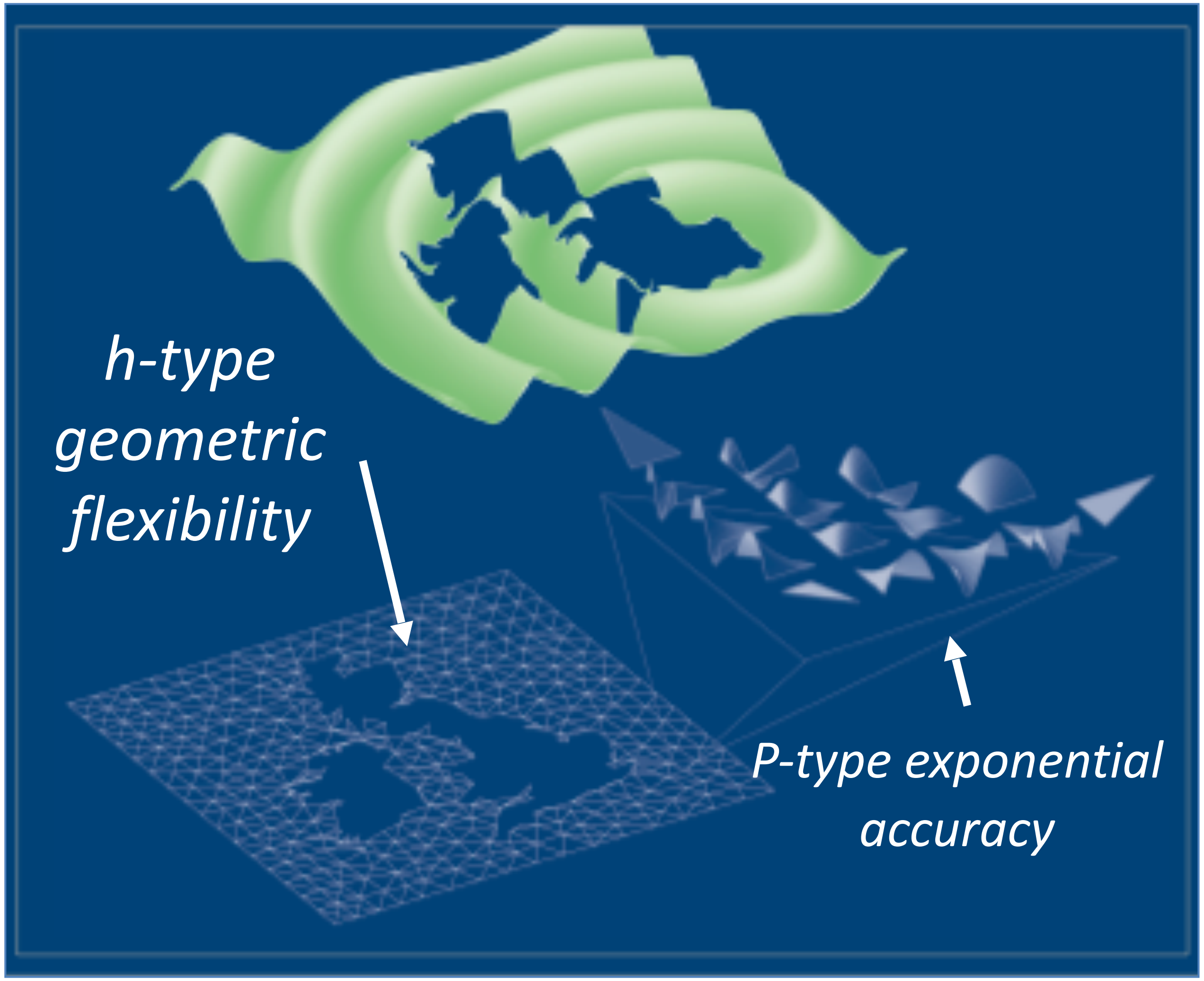




Spectral/hp methods



Spectral/hp element method



Computational cost ~ P^4 Computational error ~ h^P

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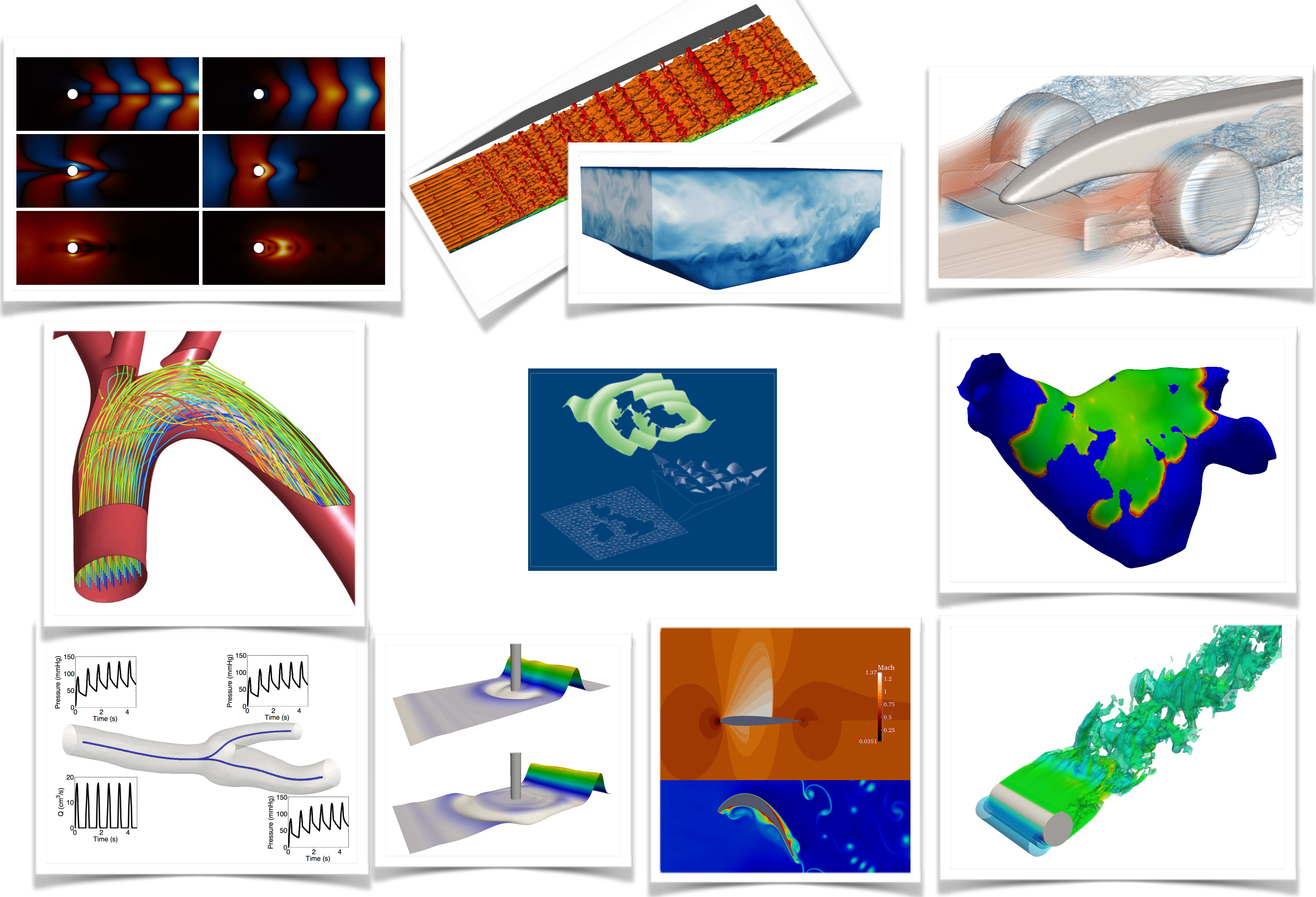
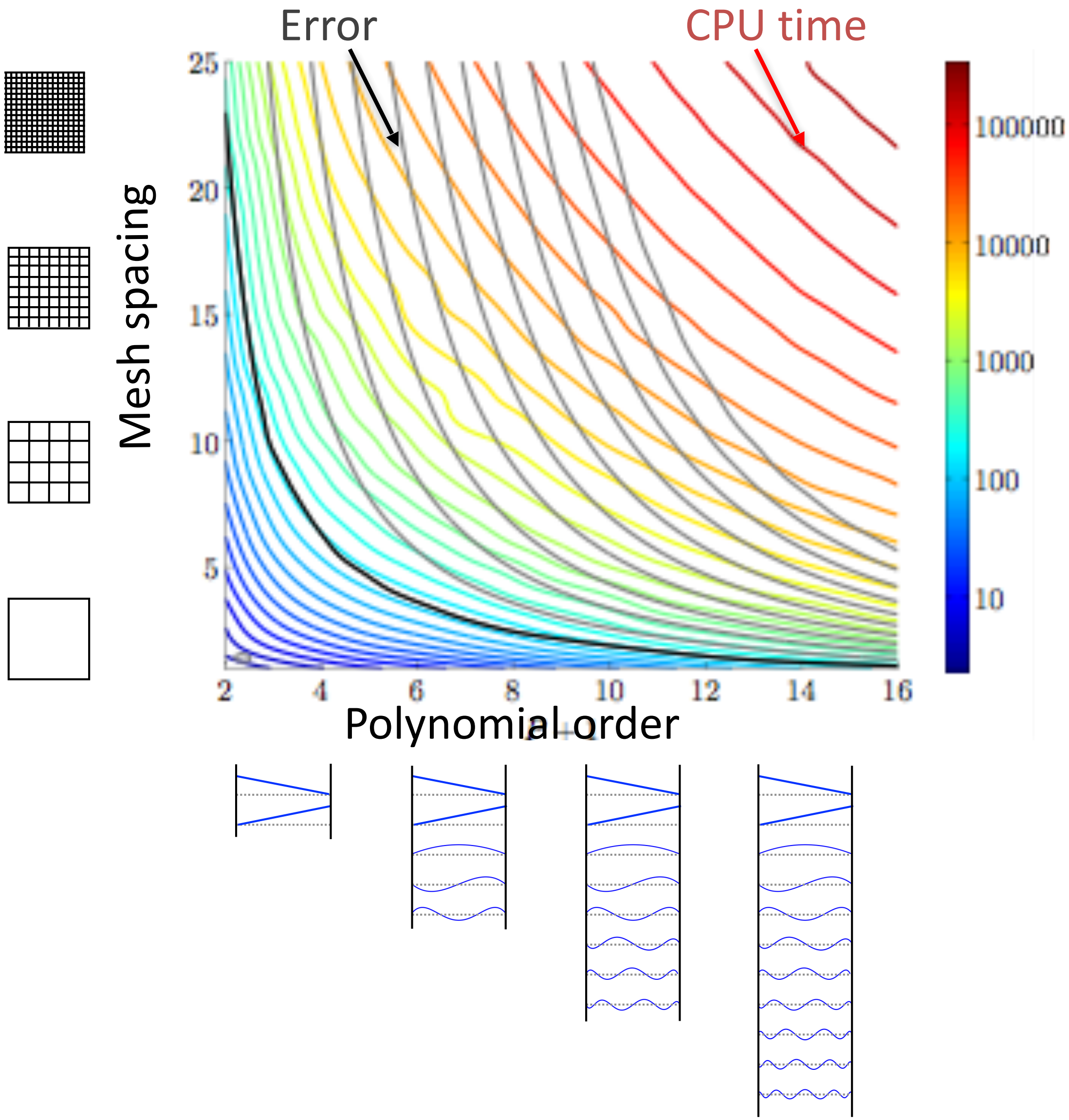
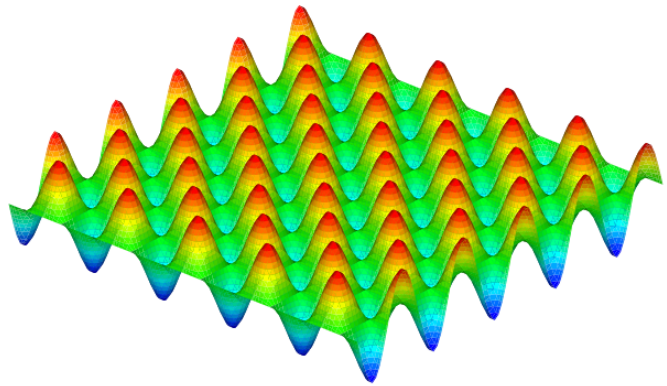
Nektar++ Framework



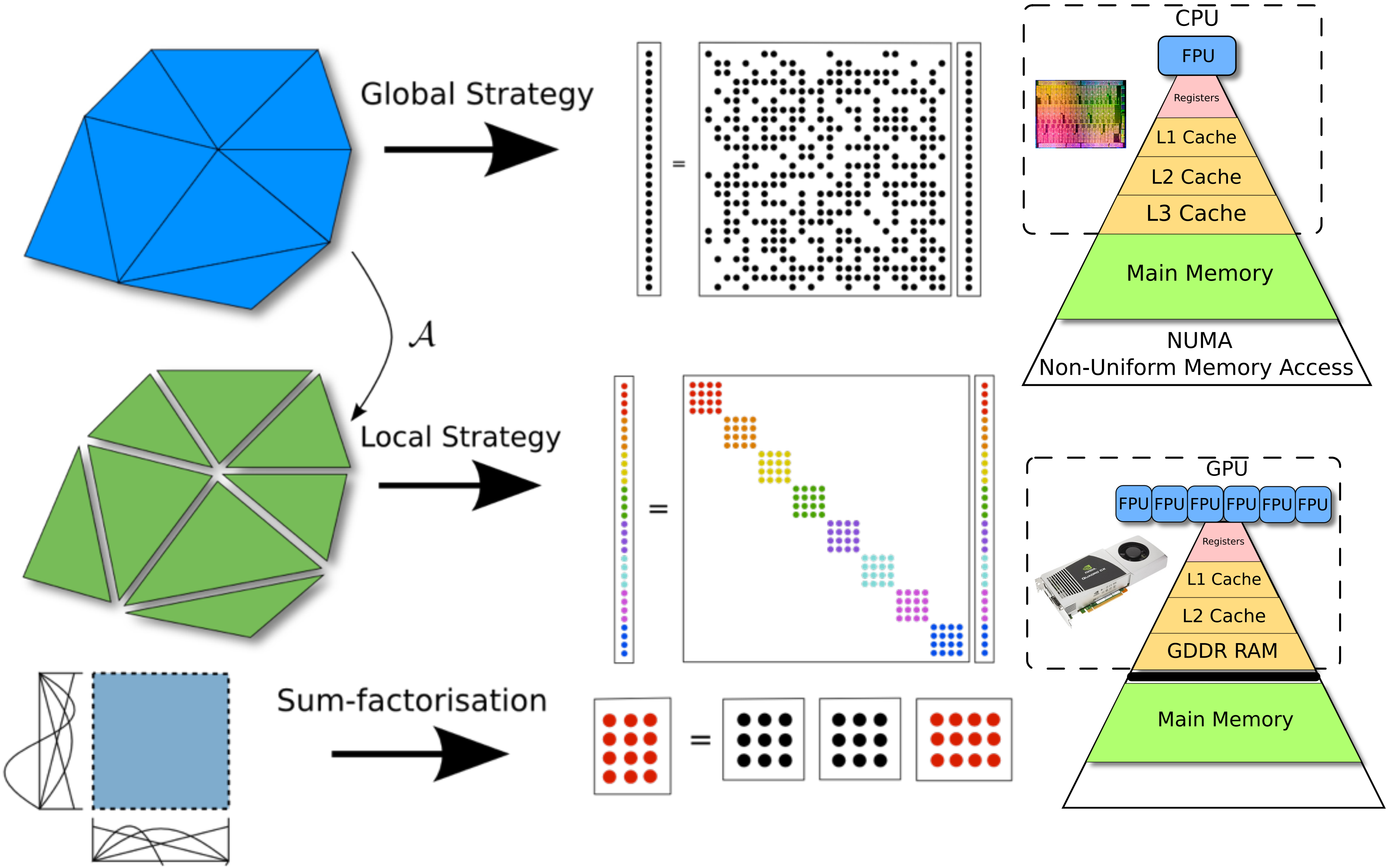
So what are the benefits?



$$\nabla^2\phi = f$$



Vos, Kirby, Sherwin, J. Com. Phys 2010   Cantwell, Sherwin, Kirby, Kelly, 2010



Vos, Kirby, Sherwin, J. Com. Phys 2010 Cantwell, Sherwin, Kirby, Kelly, 2010

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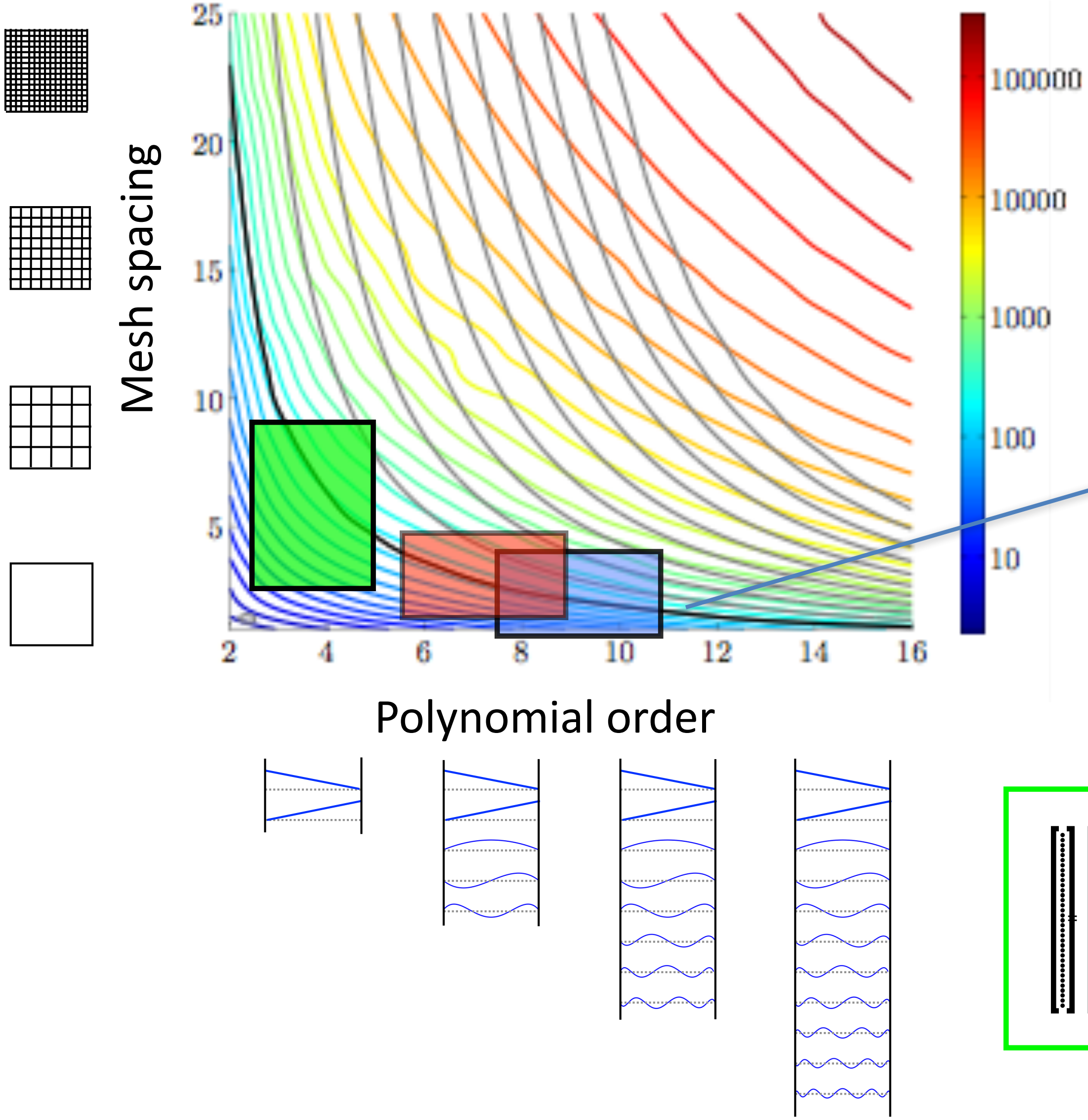
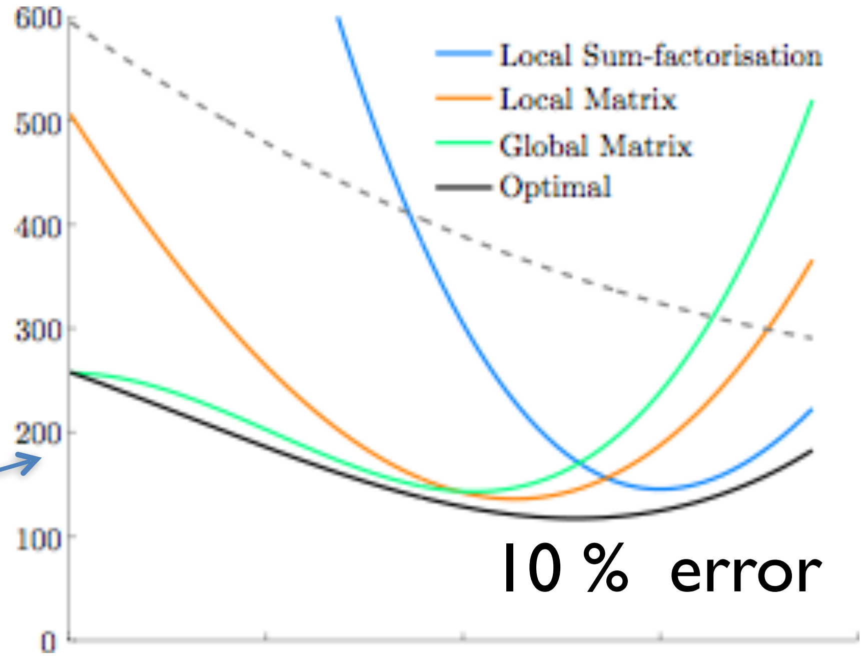
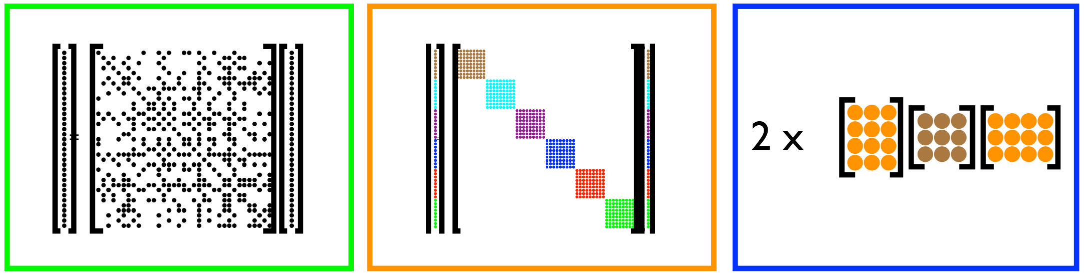
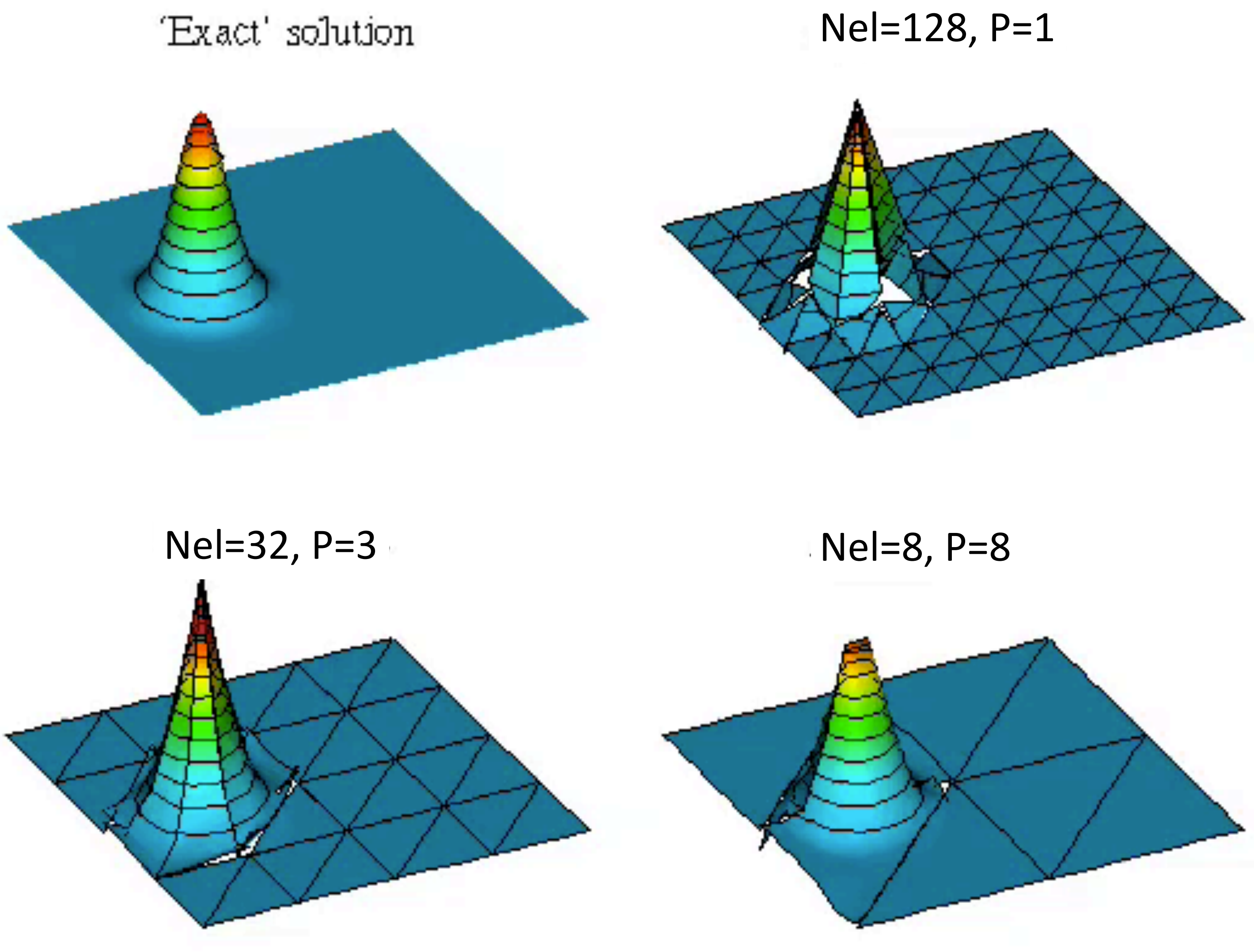




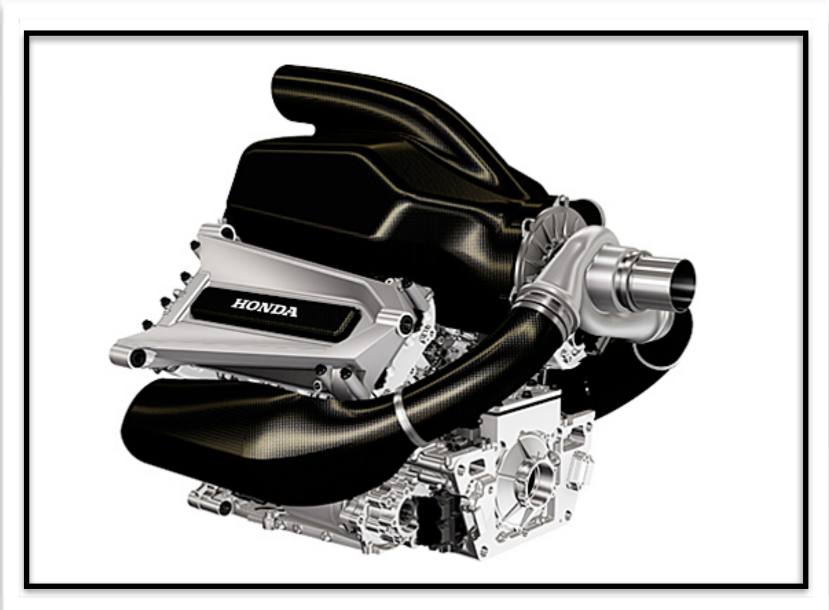


To P or not to P?



Bolis, Cantwell, Kirby, Sherwin Int J Num Method, 2014

Motorsport in the UK



- 4500 companies involved in UK Motorsport and Performance Engineering sector
- 40,000 employees of which 25,000 are qualified engineers
- Annual £6 billion per annum turnover - £3.6 billion of which exported
- On average spend 30% of turnover on R&D

  (compared to 15% for pharmaceutical industry)

Formula One

- Pinnacle of Motor sport
- 20 races in a year in 5 continents
- Complex set of Technical and Sporting Regulations
- 6 of 9 (8 of 11) teams are UK based winning 39 world championships since 1950
- UK F1 teams and their supply chains employ more than 5,000 people generating over £2bn in annual revenue

F1 Performance Figures

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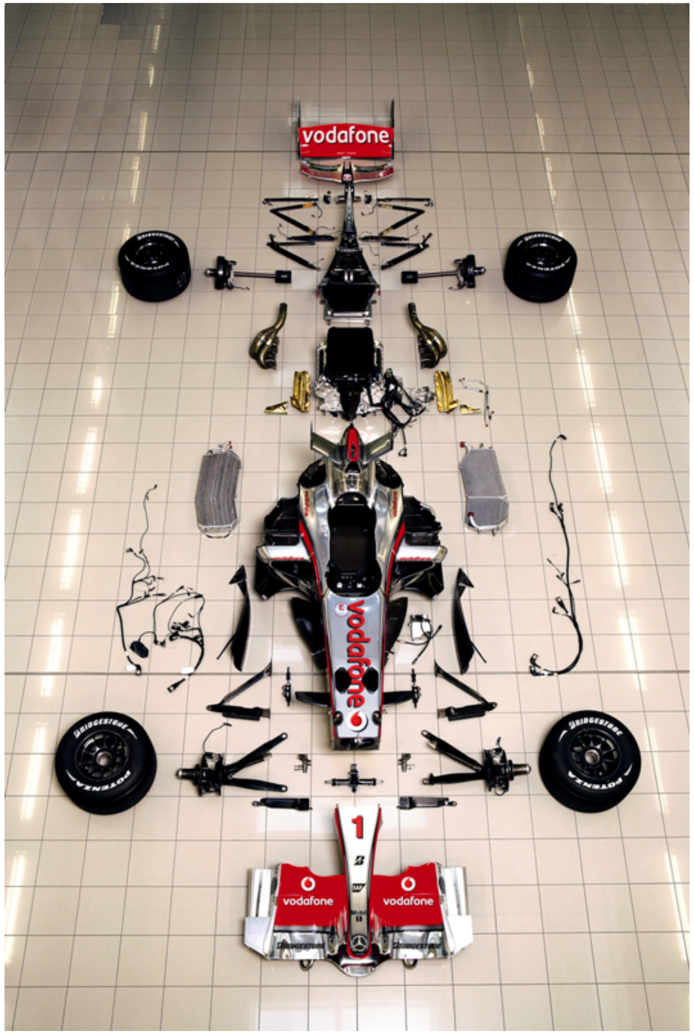
- Top Speed: >350 km/h
- Acceleration: 0 - 100 km/h: 2.3s
  0 - 200 km/h: 5.0s
- Braking: 330 -100 km/h: 3.2s
  'g' force 4.8g
  distance 169m
- Corner forces: ± 4.5g in 0.75s
- Car weight: 691 kg (including driver & no fuel)
- Downforce: >1500 kg at 250 km/h
- Gear Changes: Number: 3300 per race
  Duration: under 20ms
- Full Throttle: 70% of the time
  78% of the distance



15,000 unique parts

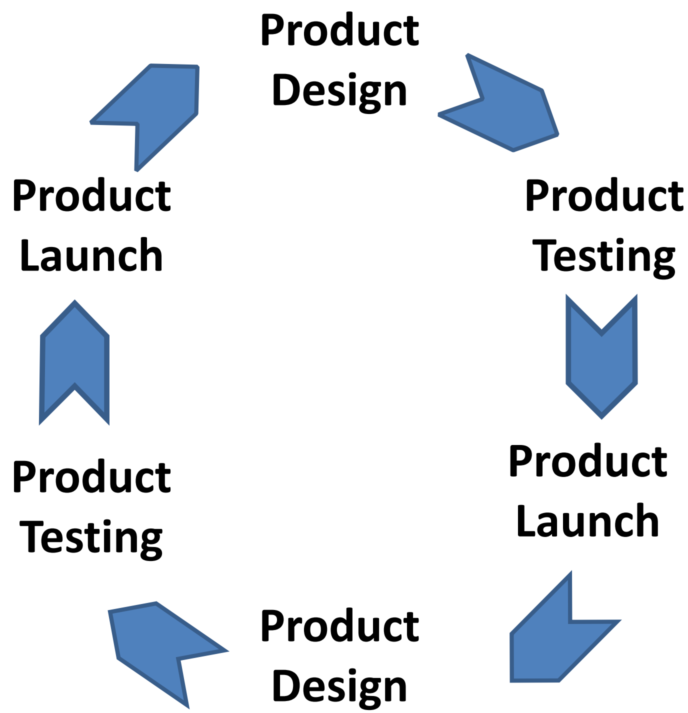
Competitive differentiation is measured in milliseconds

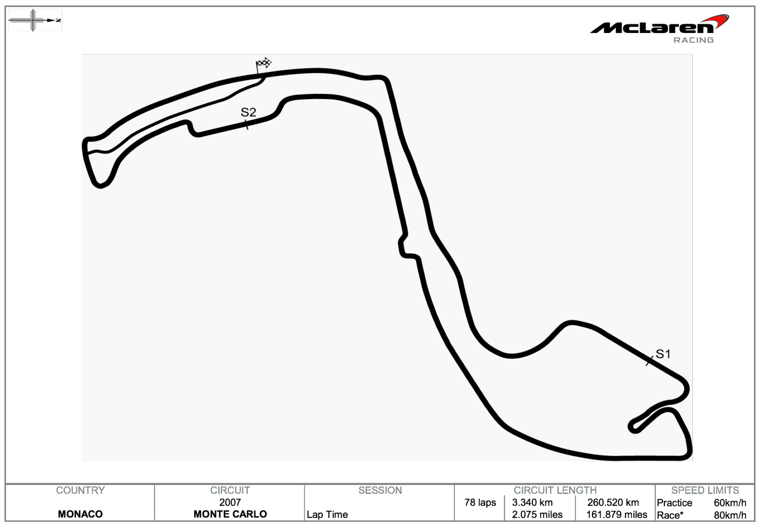
Only 2.0% performance gap between top 10 cars

Only 0.3% in top 3 cars

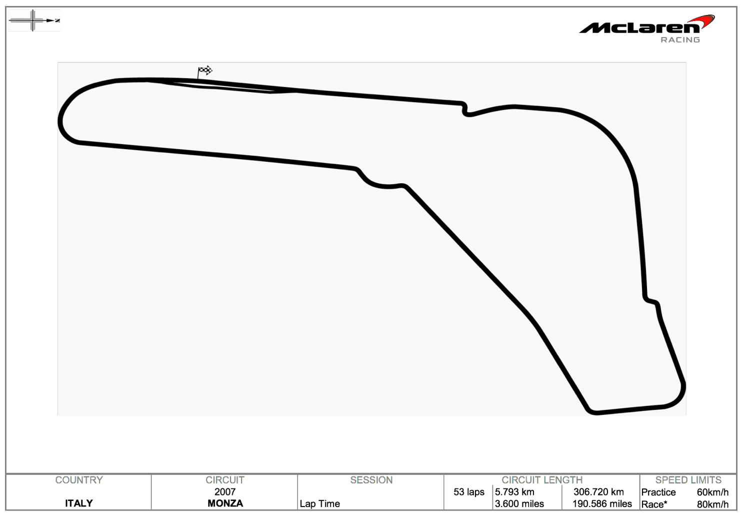
A Competitive Environment

- 6-12 month lead time to design a new car
- 12 days of testing before race 1
- Continuous product development
- Car changes every race
- Car aerodynamics optimised for each circuit





Monte Carlo



Monza

The Overall Challenge

Through corner simulation requires:

- *Roll, yaw, steer changes*
- *Ride height variation*

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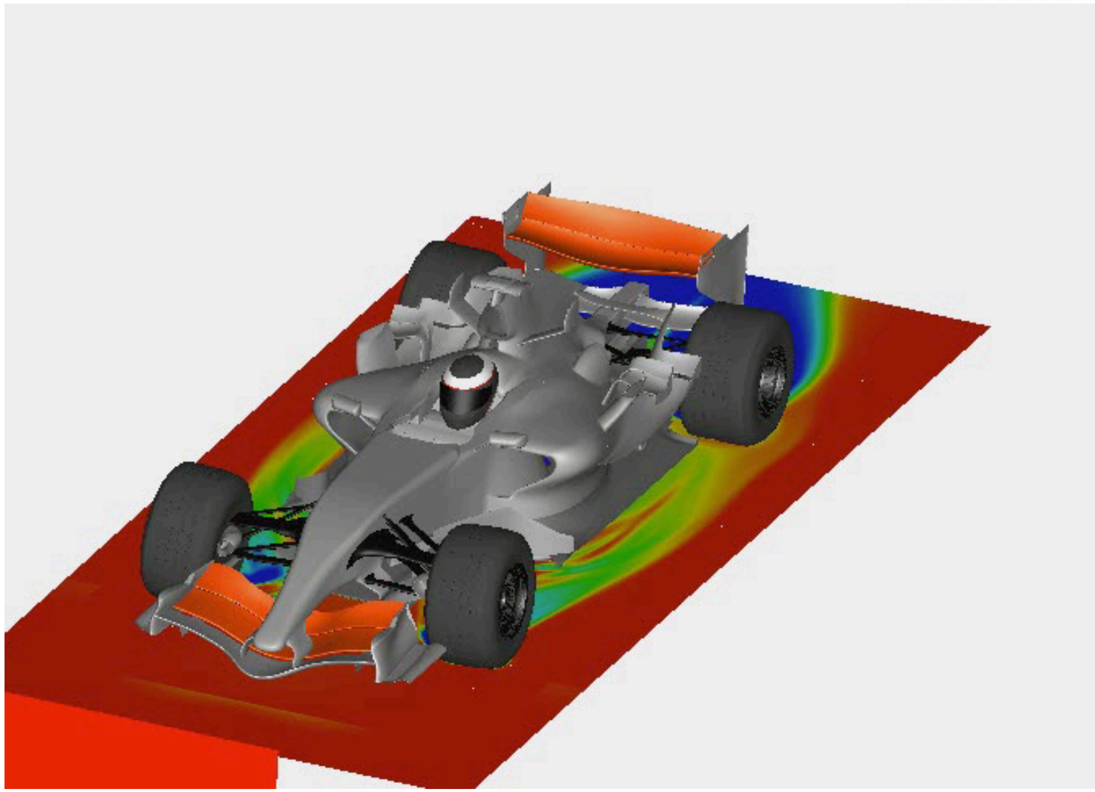
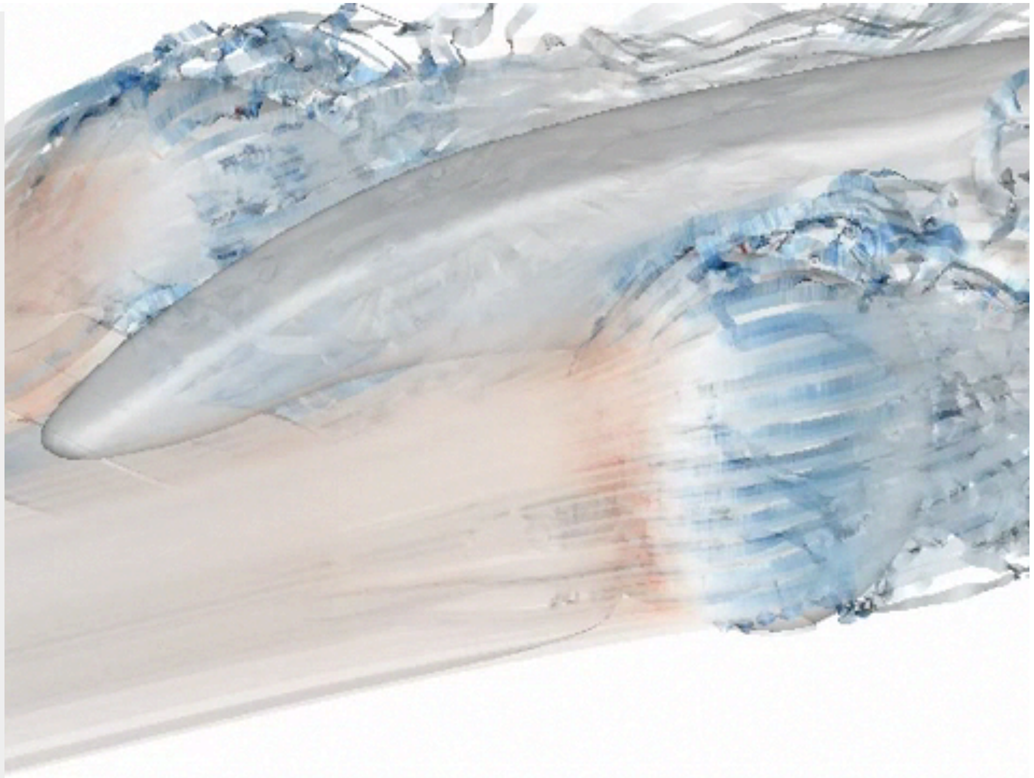
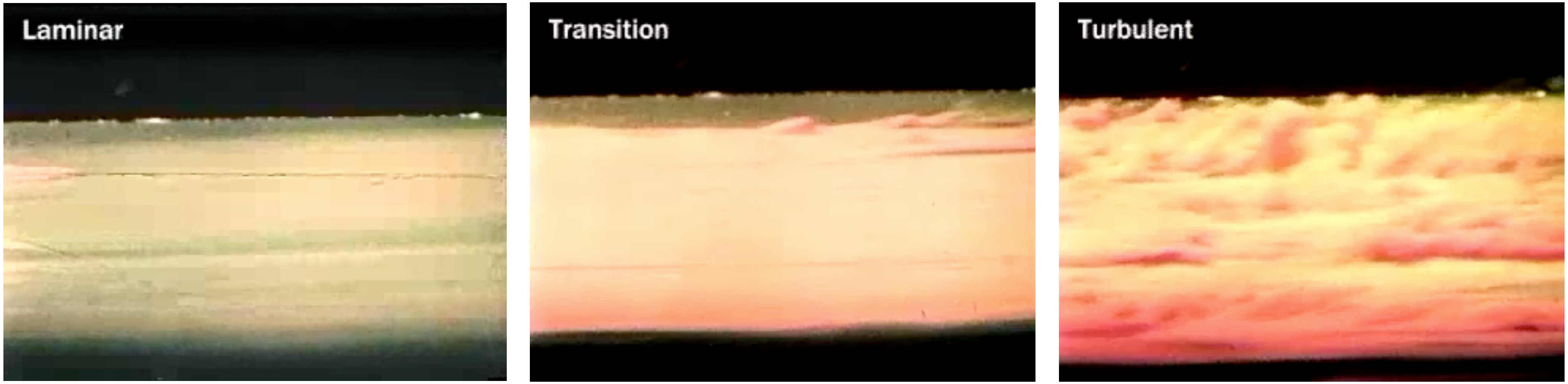
Transient flow modelling





Transient flow modelling

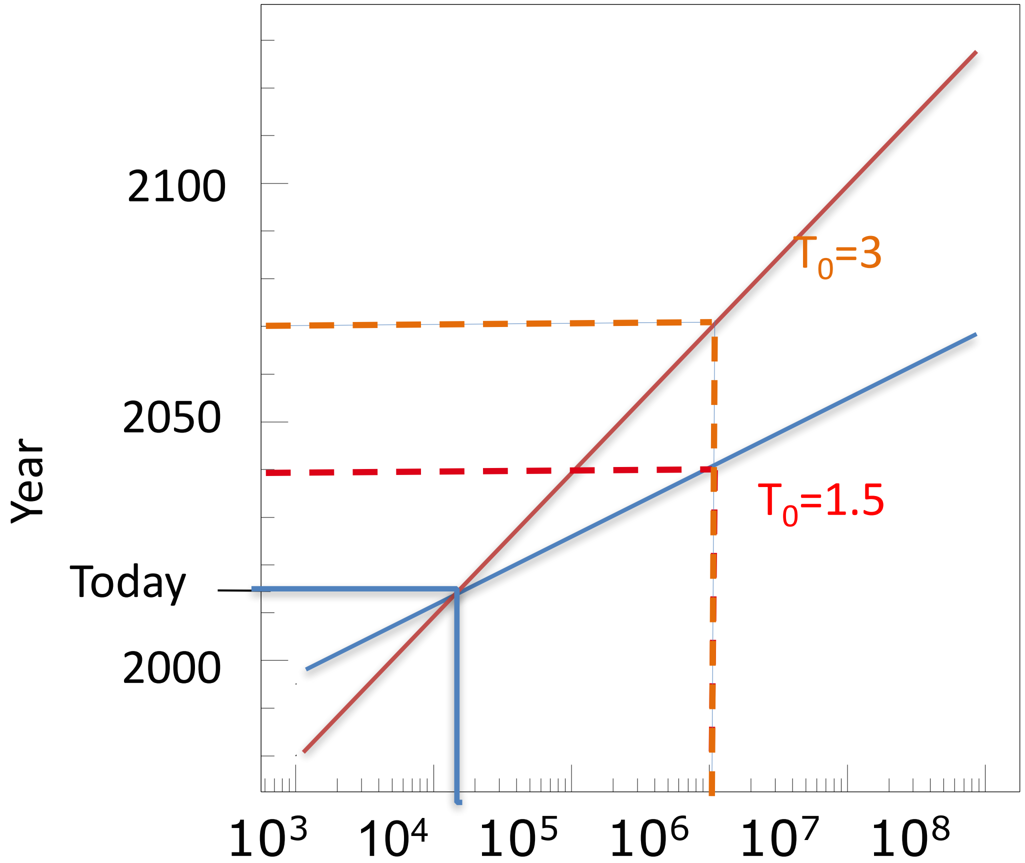


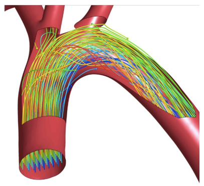
Multimedia fluid mechanics, Cambridge University Press,

10^3 10^4 10^5 10^6 10^7 10^8

Reynolds number

Transient flow modelling





Reynolds number

Flops required for Reynolds No:

$$flops \propto Re^3$$

Moore's Law

$$\frac{flops_t}{flops_{T_0}} = 2^{t/T_0}$$

Spectral/hp for high Reynolds number applications

- High order meshing
- Nodal/collocation space dealiasing
- SVV Smoothing

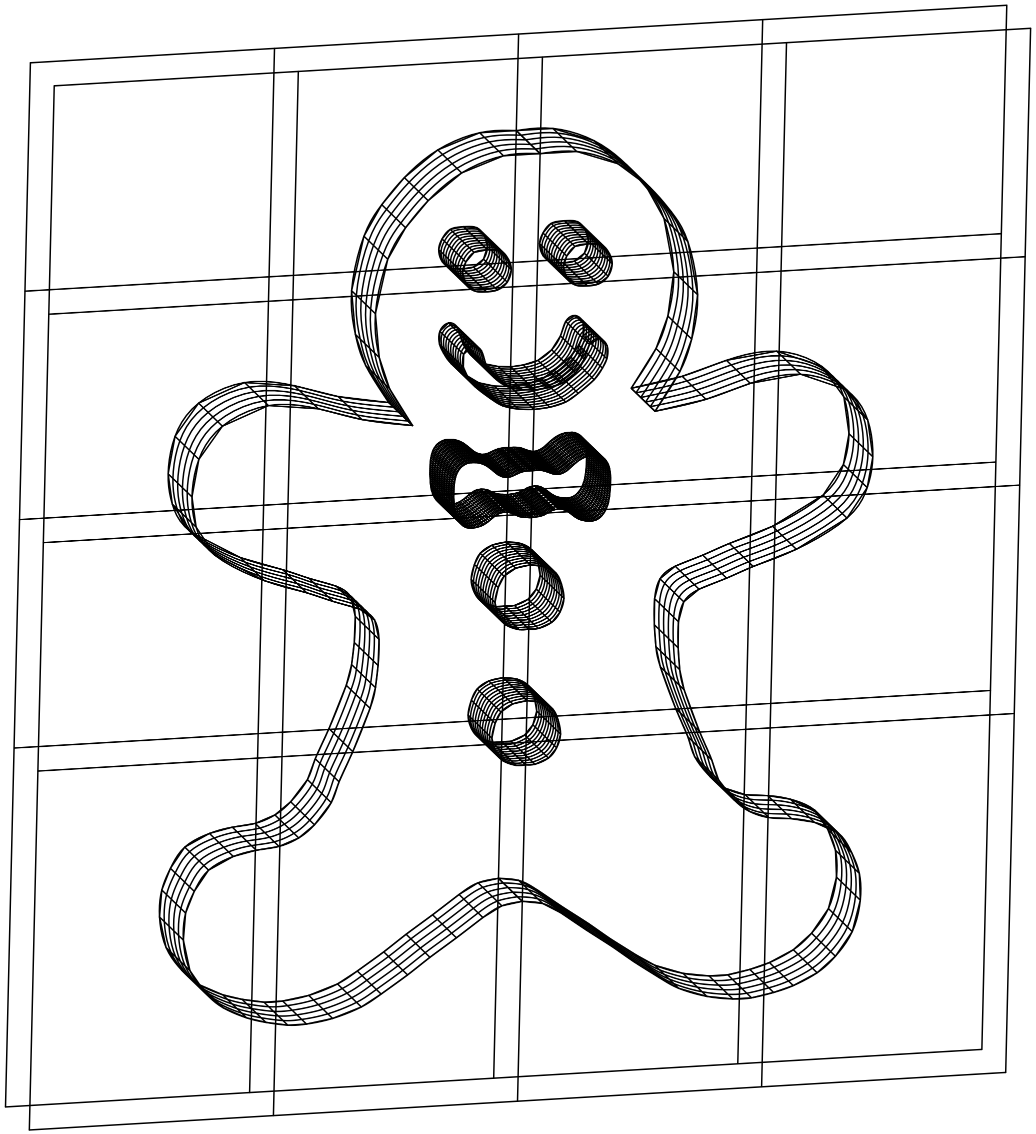
High order Mesh Generation

or

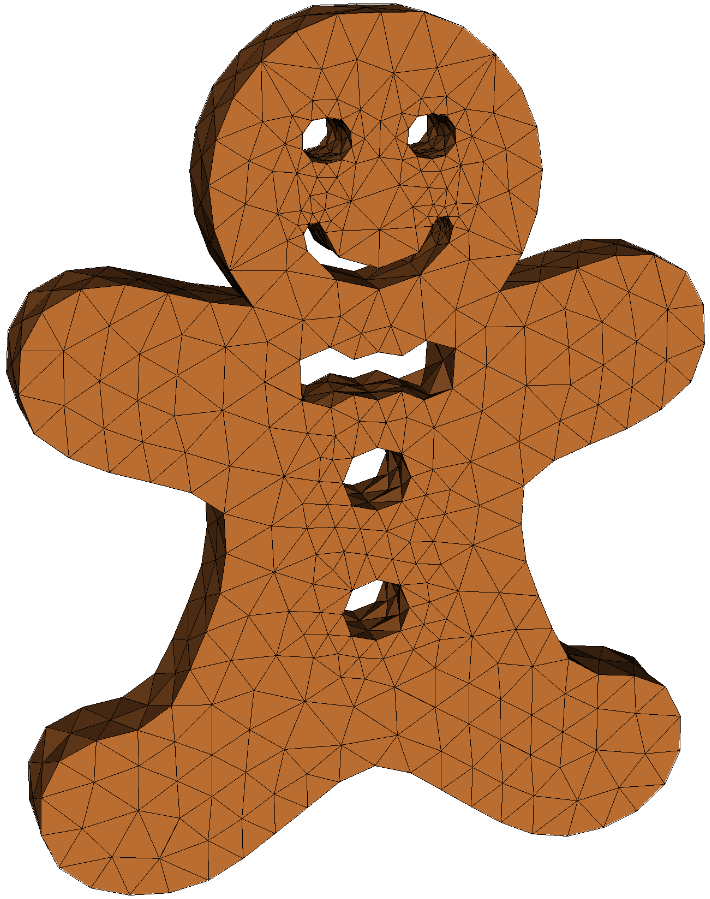
Mesh Modifications for High Order Methods

Dave Moxey & Joaquim Peiro

High-order mesh generation (1)



B-Rep



Linear mesh

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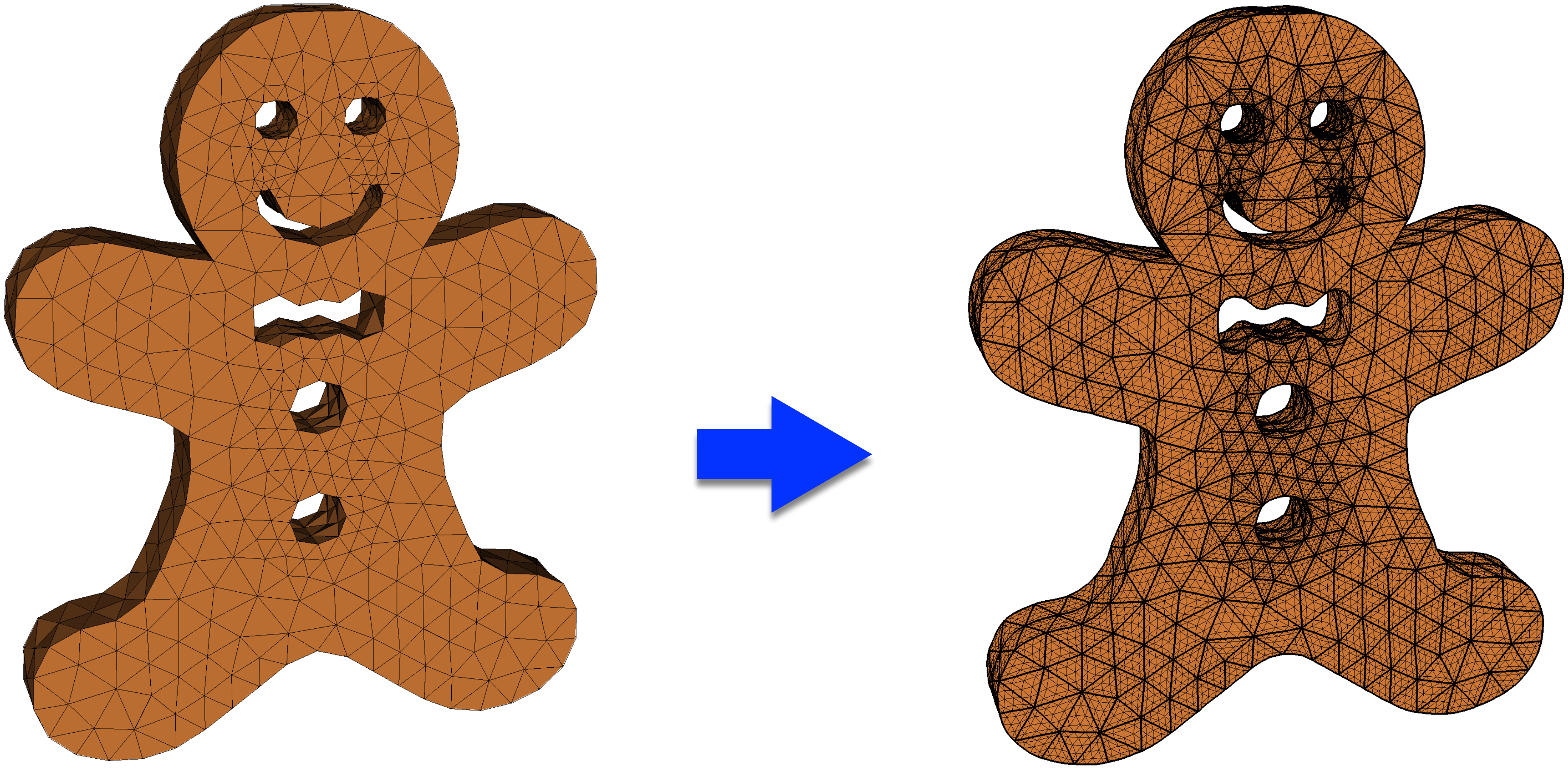
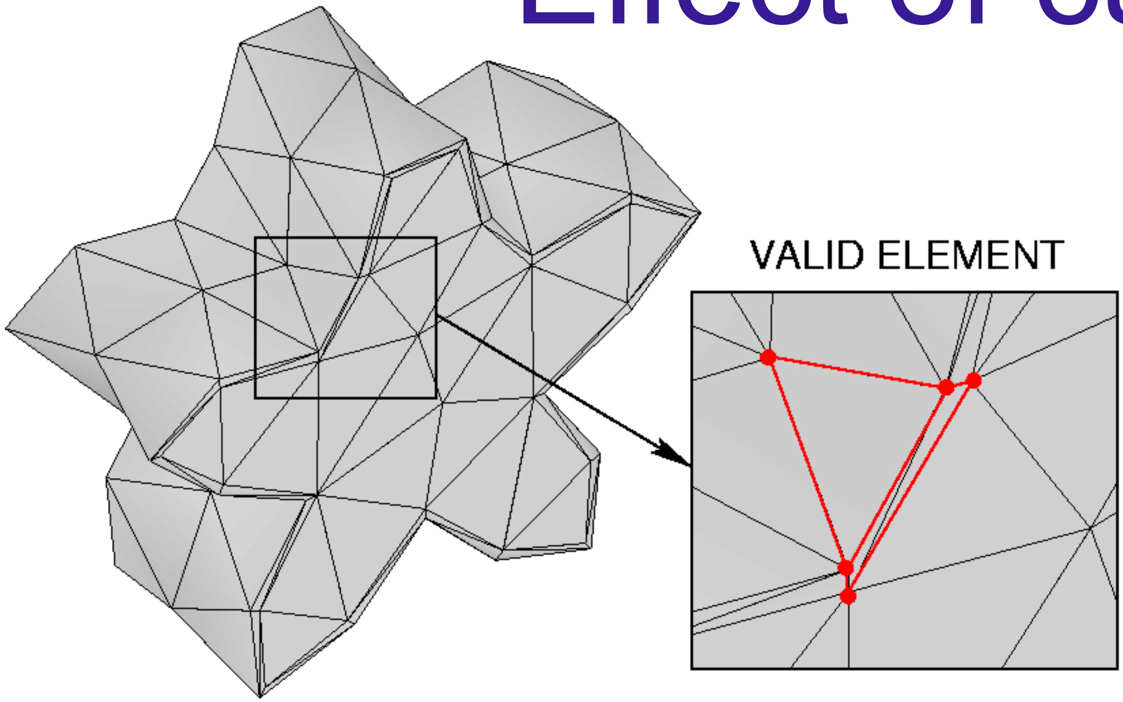
High-order mesh generation (2)

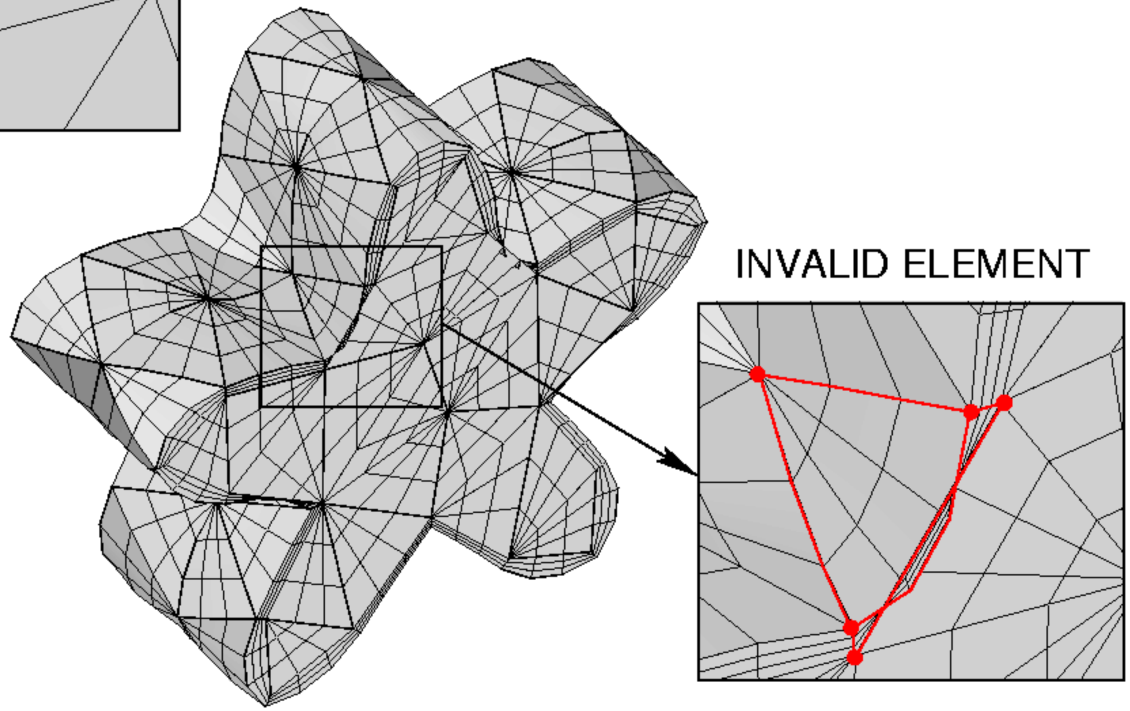


Linear mesh High-order mesh

"Mesh generation in curvilinear domains using high-order elements"
S.J. Sherwin and J. Peiro, *Int. J. Numer. Meth. Engng* 2002; 53:207–223

Effect of curvature

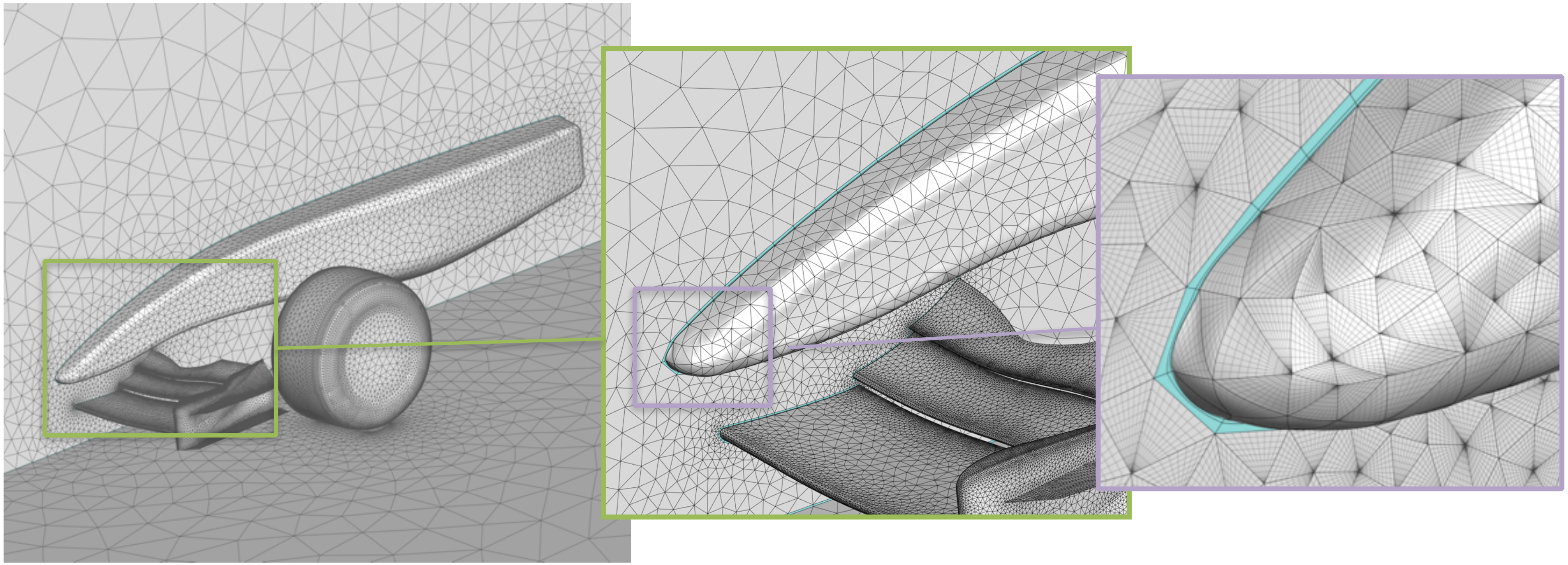




Producing meshes for high-Re simulations

Viscous flows ➙ boundary layer around walls.

- From the surface triangulation, we generate a prismatic boundary layer (better mesh quality).
- Rest of the volume is constructed using tetrahedra.



"An isoparametric approach to high-order curvilinear boundary-layer meshing"
Moxey, Hassan, Sherwin, Peiro, CMAME, 283, (2015)

Producing meshes for high-Re simulations

Viscous flows → boundary layer around walls.

- From the surface triangulation, we generate a prismatic boundary layer (better mesh quality).
- Rest of the volume is constructed using tetrahedra.

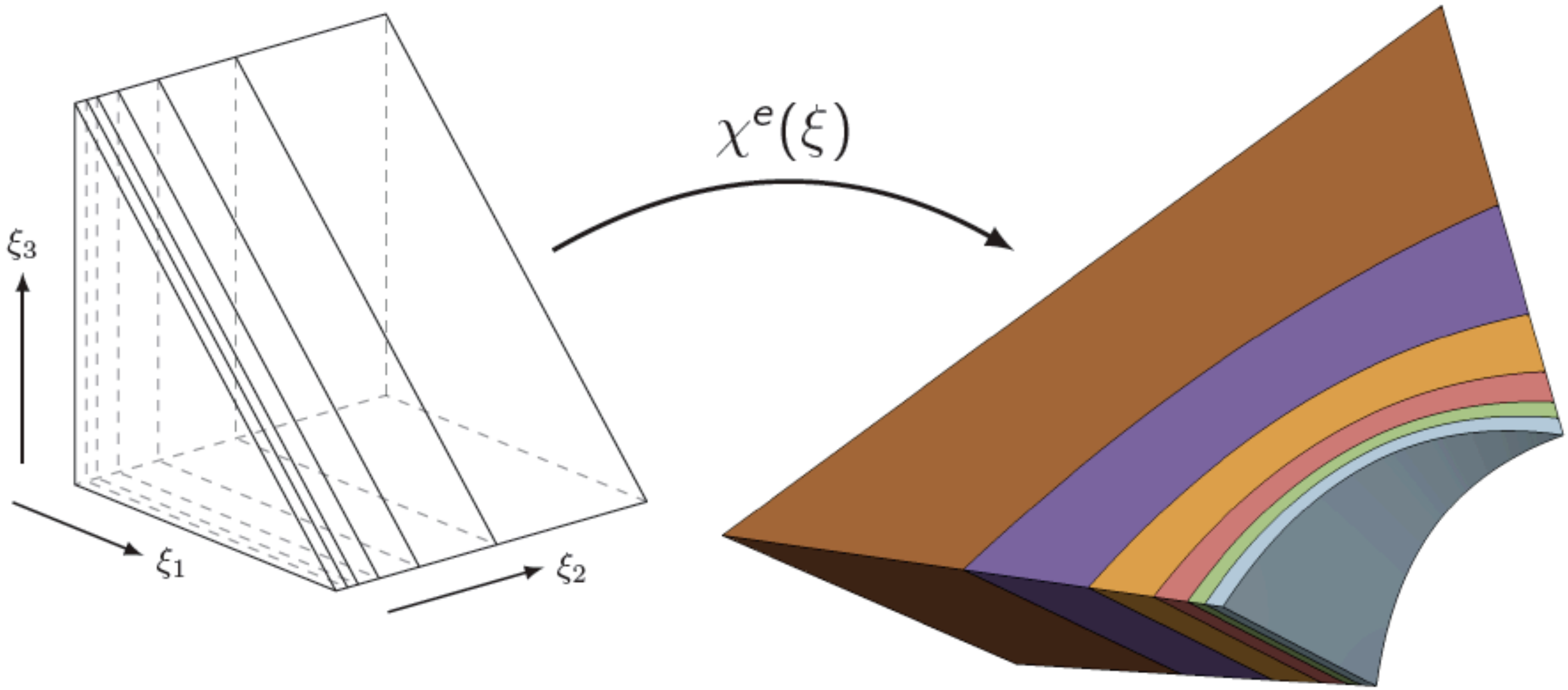
For high Reynolds number simulations:

- Require an extremely thin boundary layer ($y^+ \sim 1$)
- Must not contain invalid elements.

Refine a ***valid*** coarse prismatic mesh to produce a ***valid*** mesh of triangular prisms or tetrahedra.

"An isoparametric approach to high-order curvilinear boundary-layer meshing"
Moxey, Hassan, Sherwin, Peiro, CMAME, 283, (2015)

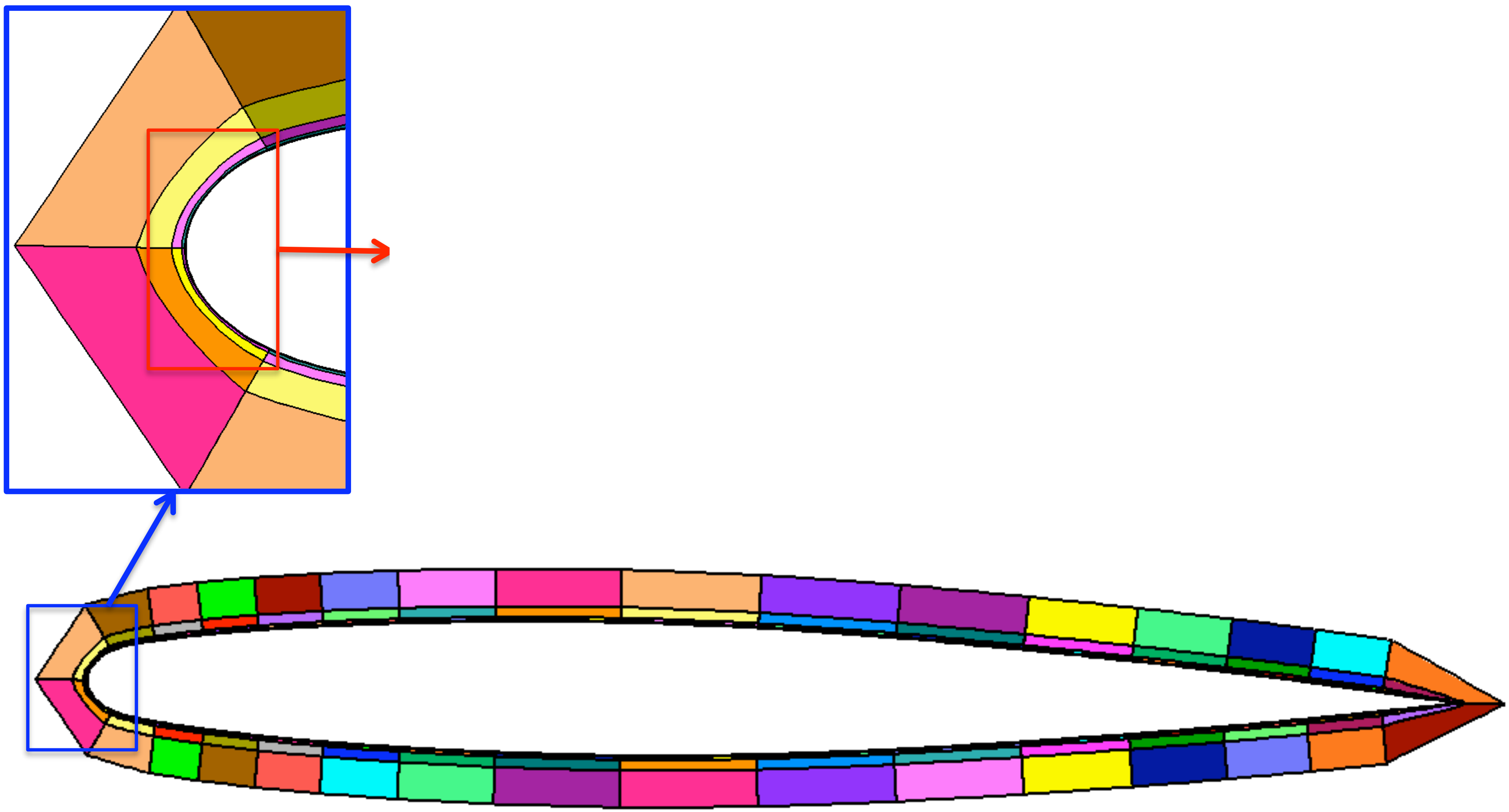
Boundary-layer mesh generation



Subdivide the master element to generate a boundary-layer mesh

"An isoparametric approach to high-order curvilinear boundary-layer meshing"
Moxey, Hassan, Sherwin, Peiro, CMAME, 283, (2015)

Proof of Concept



7 layers of refinement

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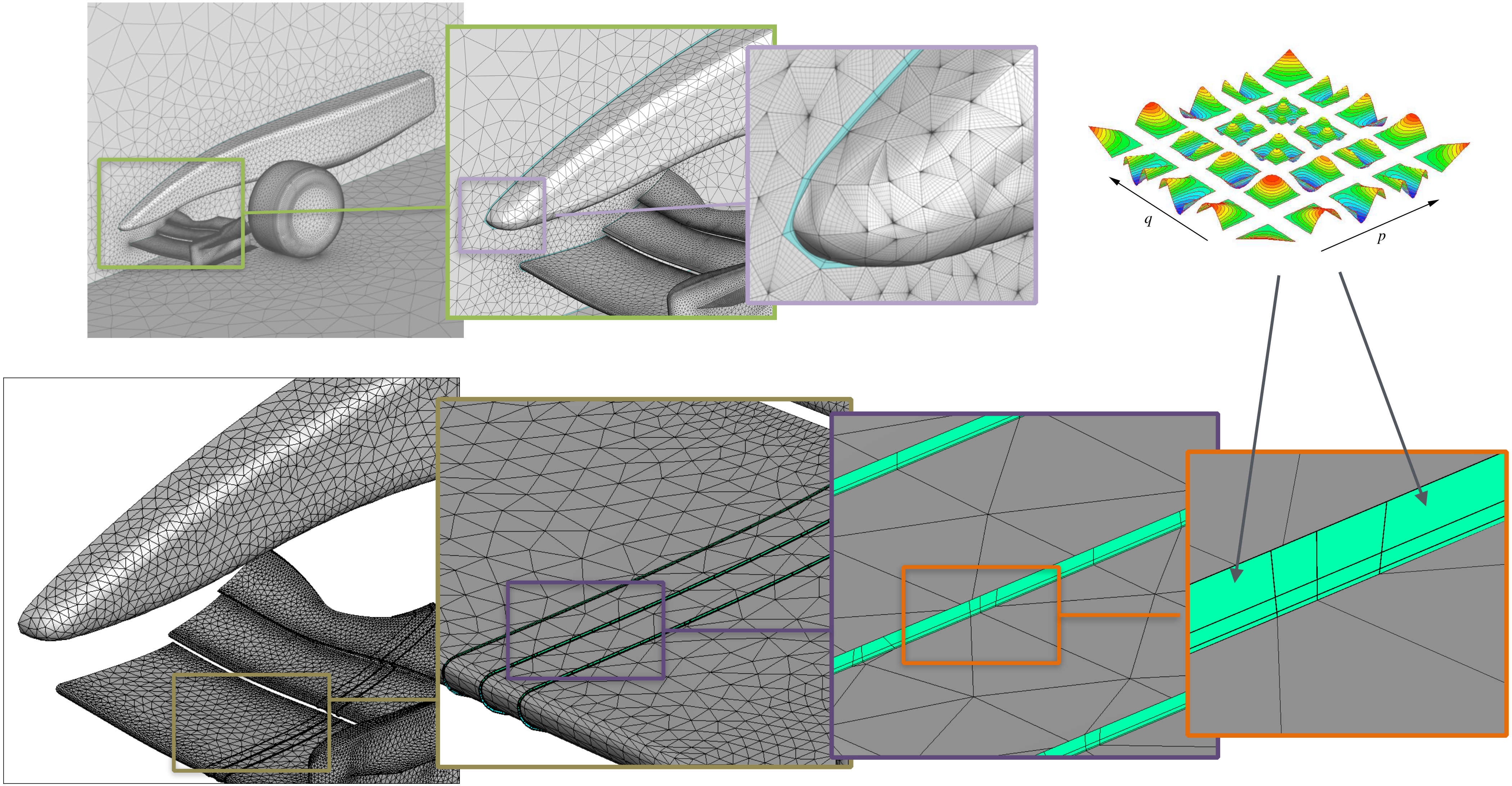
IDIHOM

Application to F1 Geometry

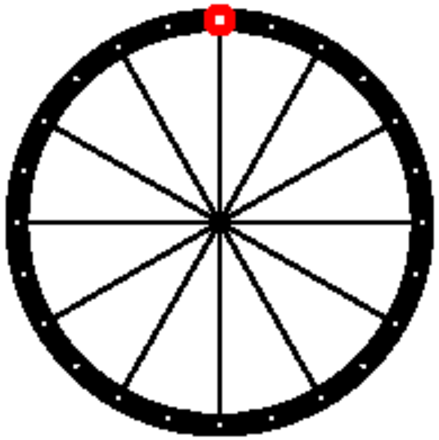
Meshing

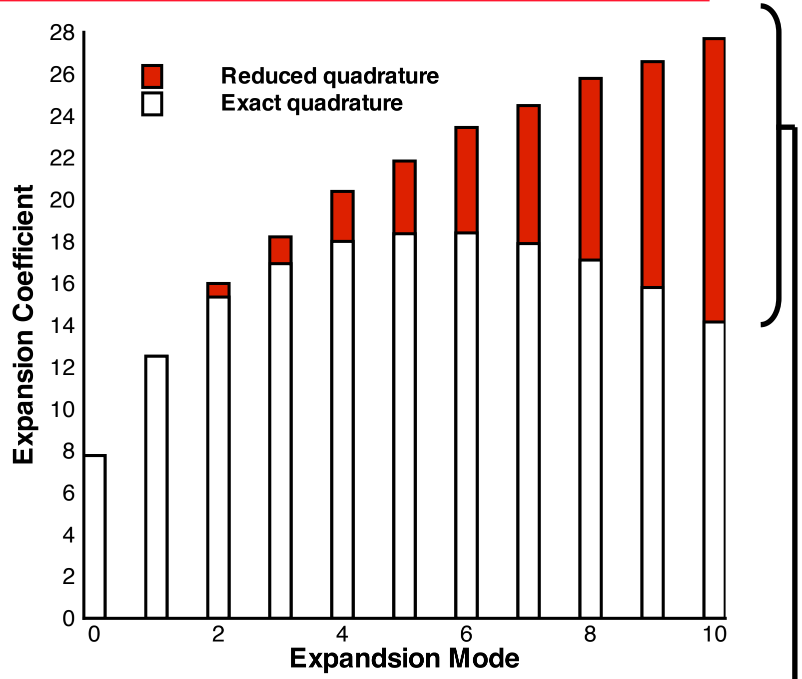


Spectral/hp for high Reynolds number applications

- High order meshing
- Nodal/collocation space dealiasing
- SVV Smoothing

Aliasing



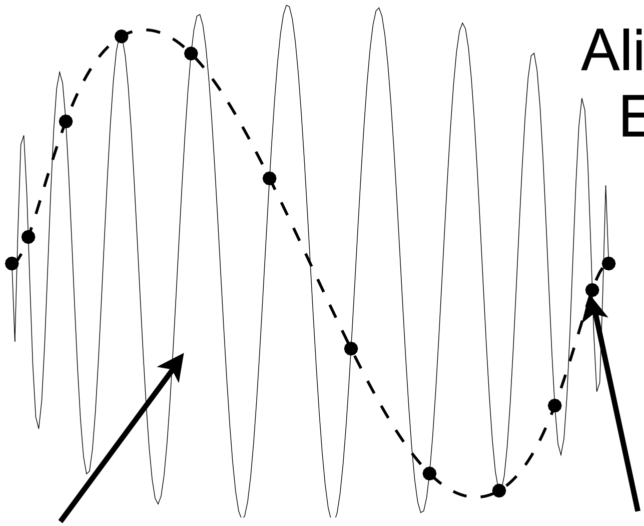


Example: $u(\xi) = \sum_{i=0}^{10} \phi_i(\xi)$

Galerkin projection of u^2 using:

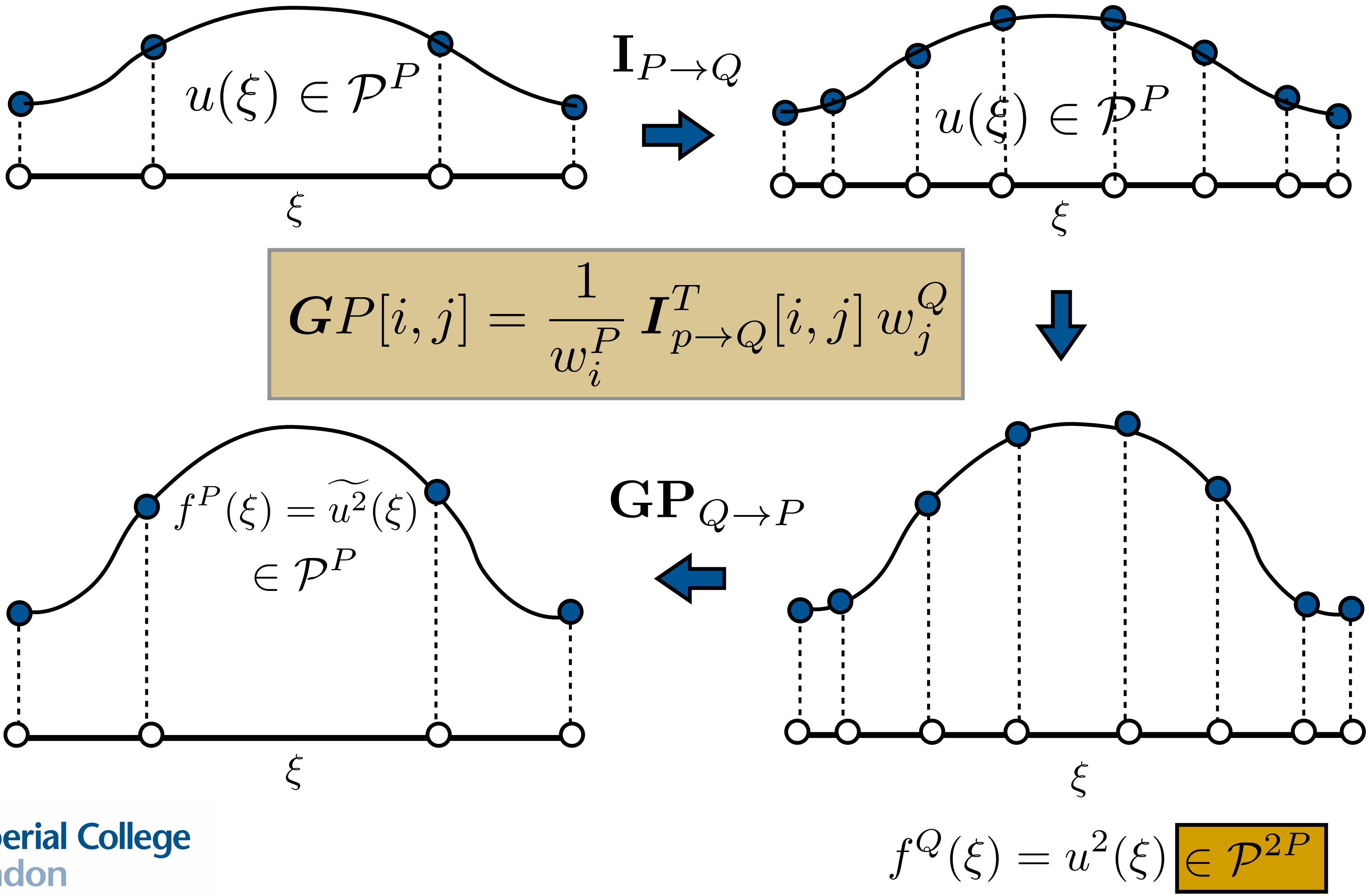
- Q = 17 – exact Quadrature
- Q = 12 – sufficient for integrating 20th degree polynomials

Aliasing Error

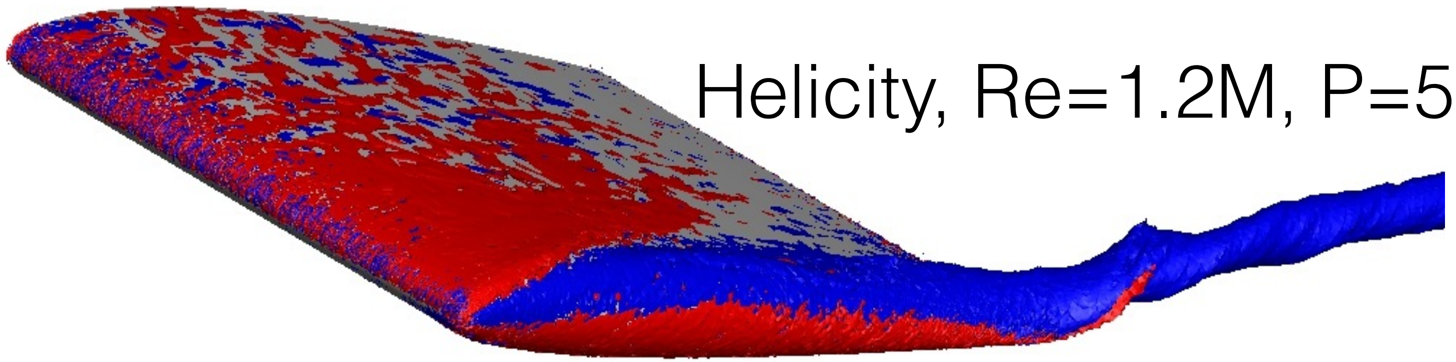


Example from Kirby & Karniadakis, J. Comp. Phys (2003)

Overview of nodal projection of u^2

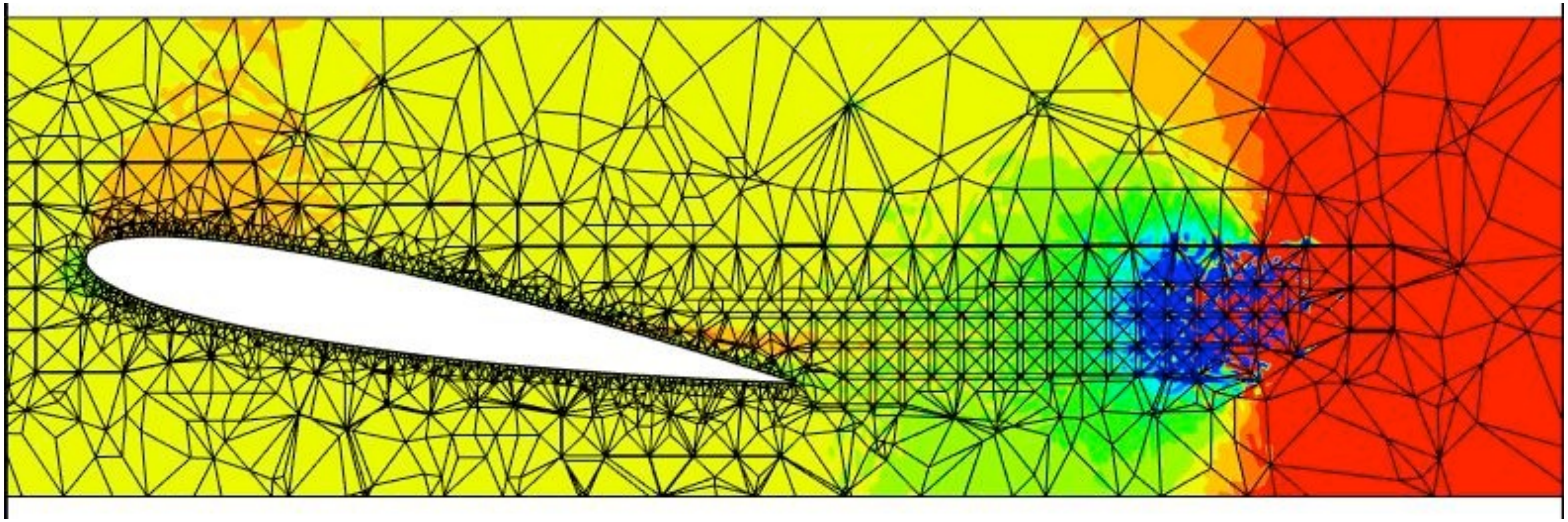


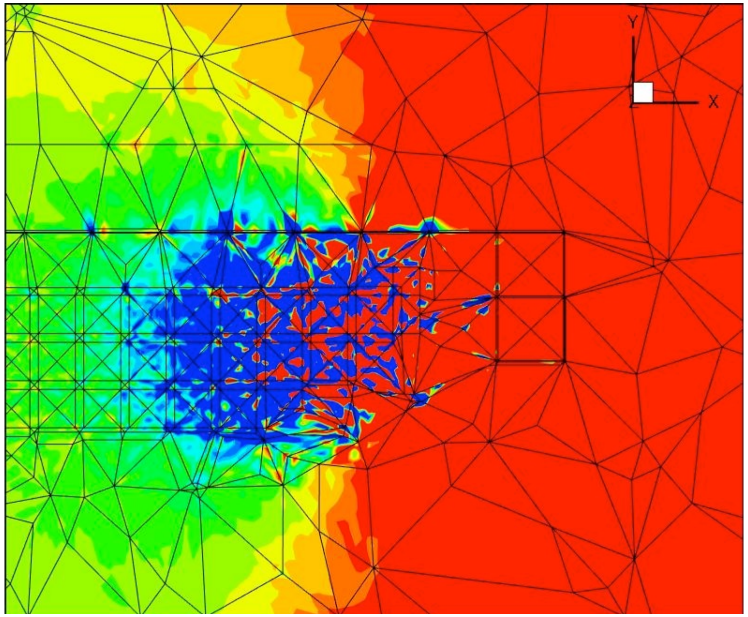
Aliasing error in boundary layer



Helicity, Re=1.2M, P=5

Re=500K, P=7 Instability





Spectral/hp for high Reynolds number applications

- High order meshing
- Nodal/collocation space dealiasing
- SVV Smoothing

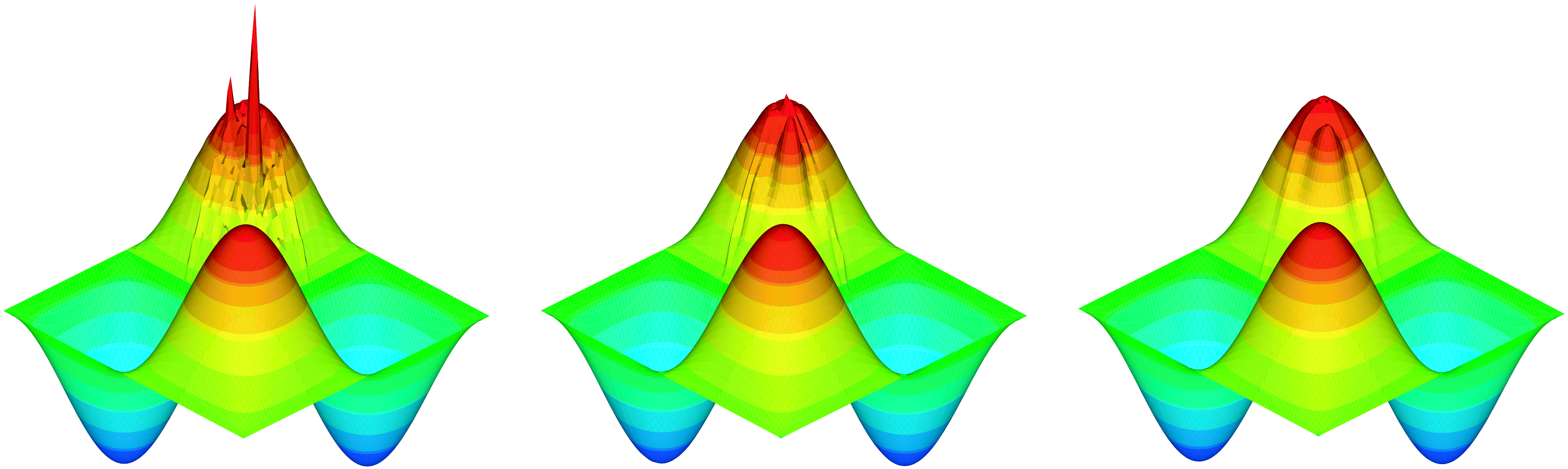
Stabilisation through smoothing

- Filtering often used in Finite Difference Methods
- Legendre Filtering used by Fischer in Nek5000
- Spectral Vanishing Viscosity is a temporal smoothing/filtering
    - Used by Pasquetti, Stiller for High Re Simulation

Spectral vanishing viscosity

Tadmor, (89) Maday, Kaber & Tadmor (93) :

$$\frac{\partial}{\partial t}u(x,t) + \frac{\partial}{\partial x}\left[\frac{u^2(x,t)}{2}\right] = \epsilon\frac{\partial}{\partial x}\left[Q_\epsilon\frac{\partial u}{\partial x}\right] \qquad \hat{Q}_k = e^{-\frac{(k-N)^2}{(k-P_{\mathrm{cut}})^2}}, \quad k > P_{\mathrm{cut}}.$$



No SVV

$P_{cut} = 7,$

$\epsilon_{SVV} = 0.1$

$P_{cut} = 3,$

$\epsilon_{SVV} = 0.1$

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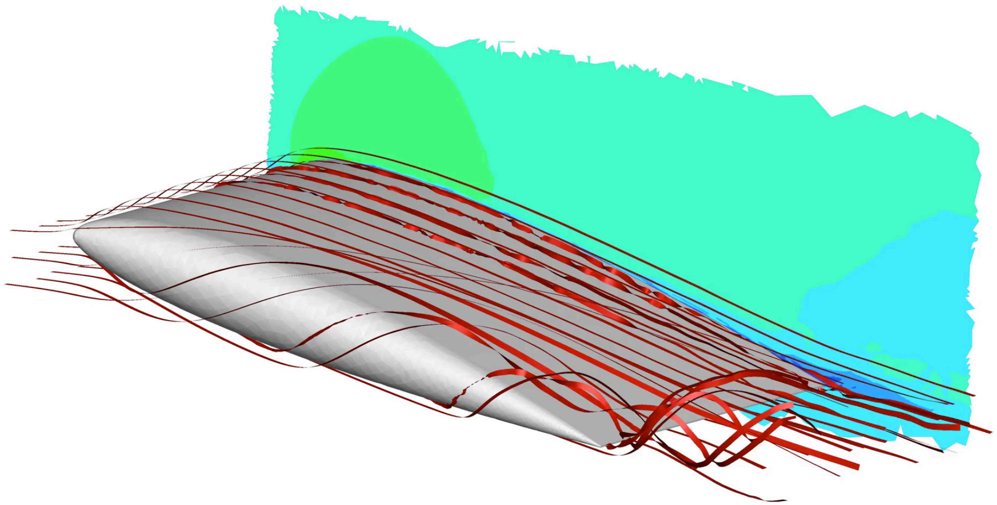
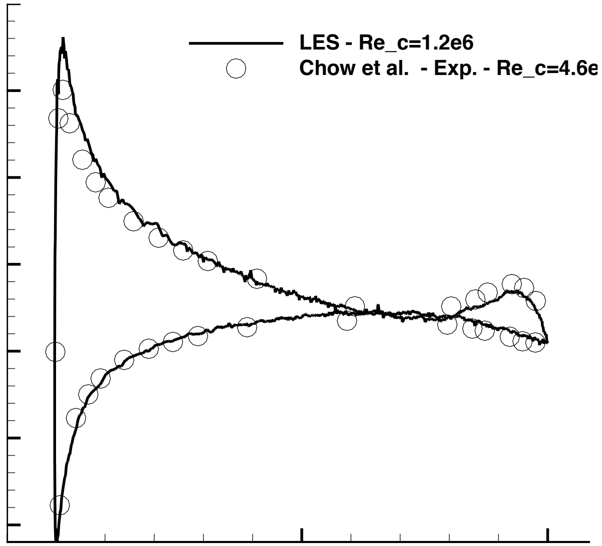
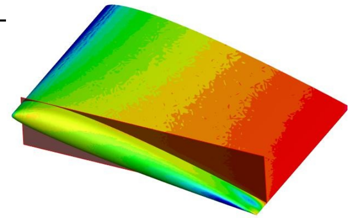
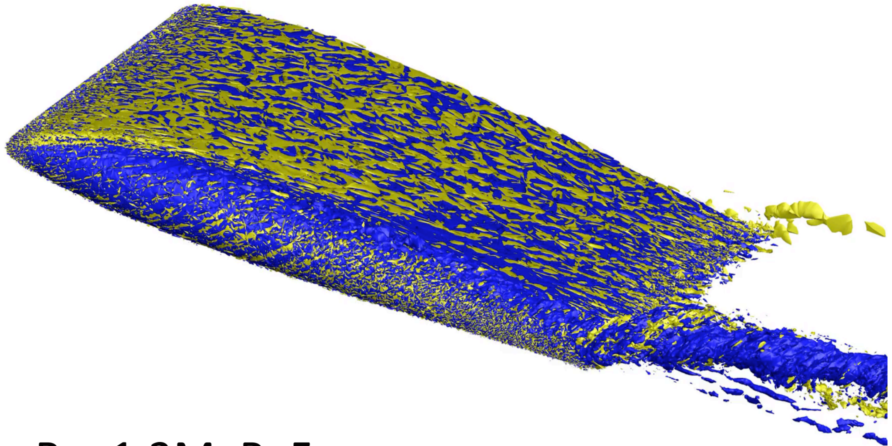
Comparison with Commercial Tools

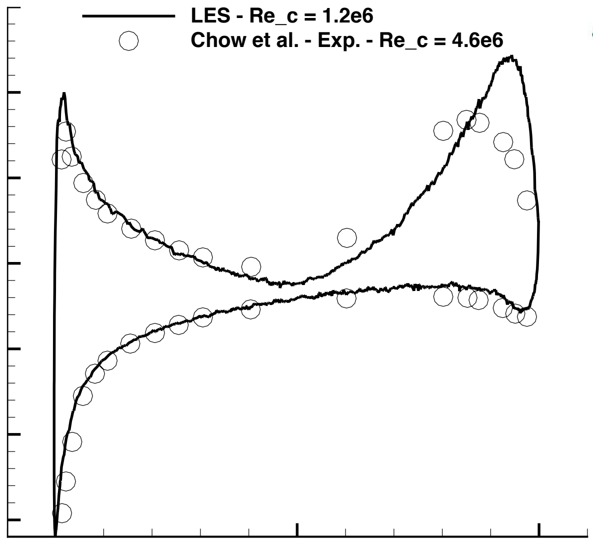






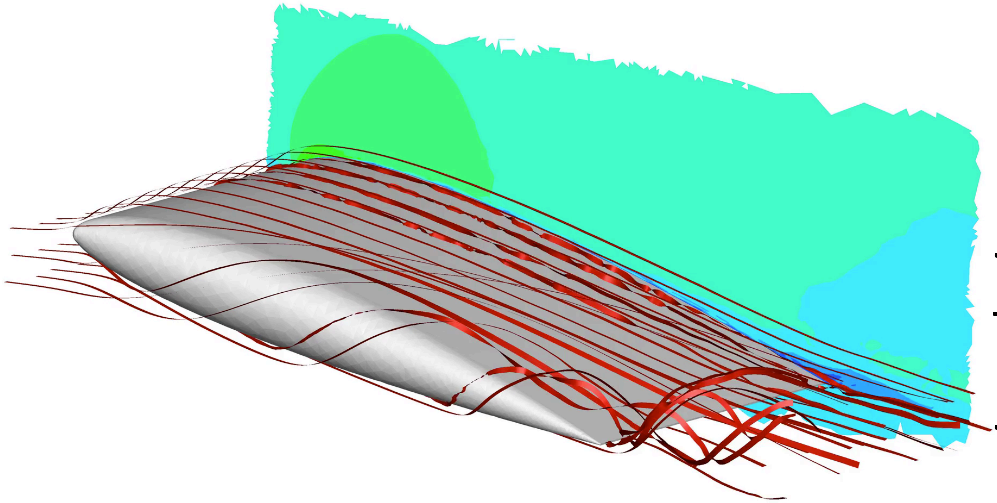


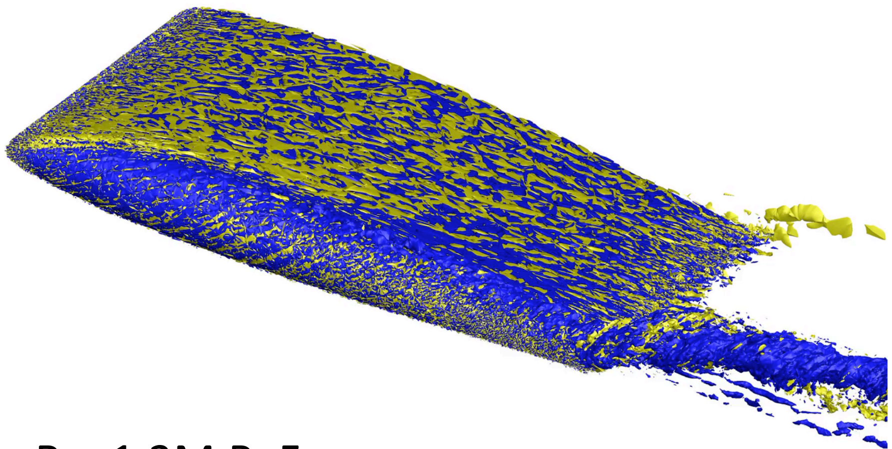
Re=1.2M, P=5

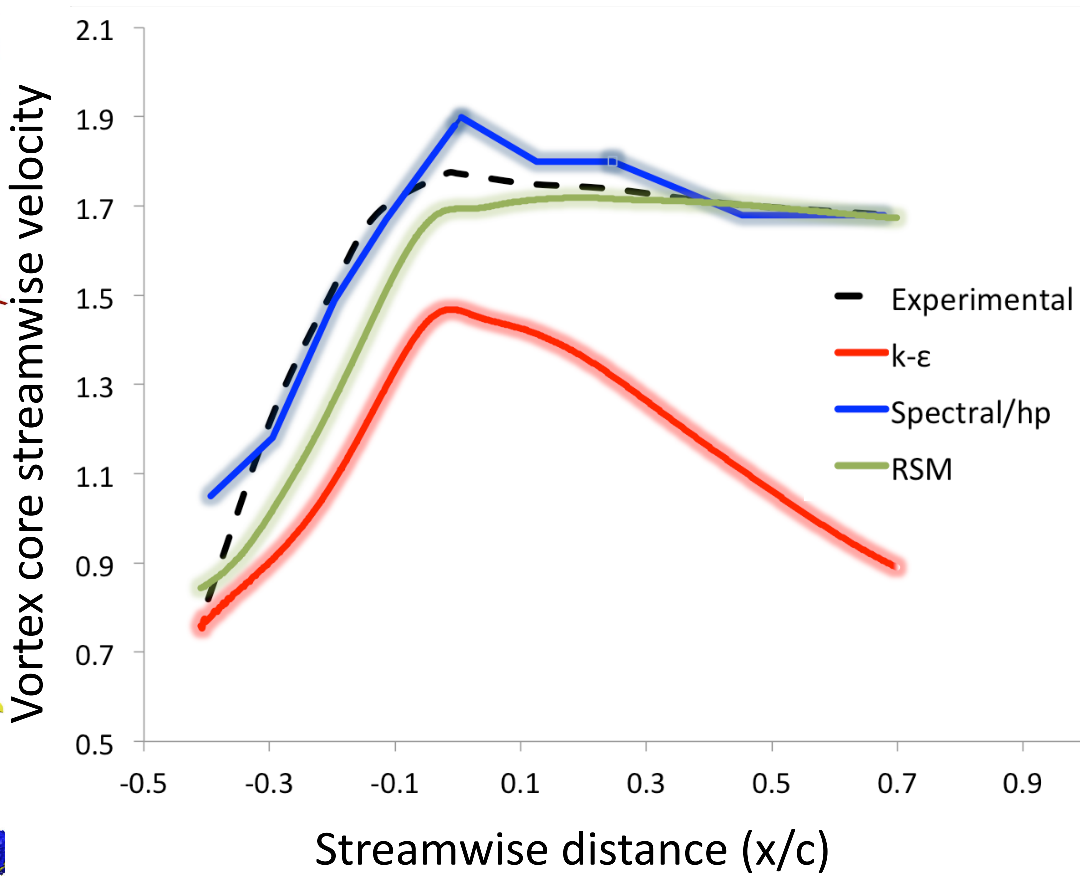


Lombard, Moxey, Sherwin, Hoessler, Dhandapani, Taylor, Submitted to AIAA

Comparison with Commercial Tools







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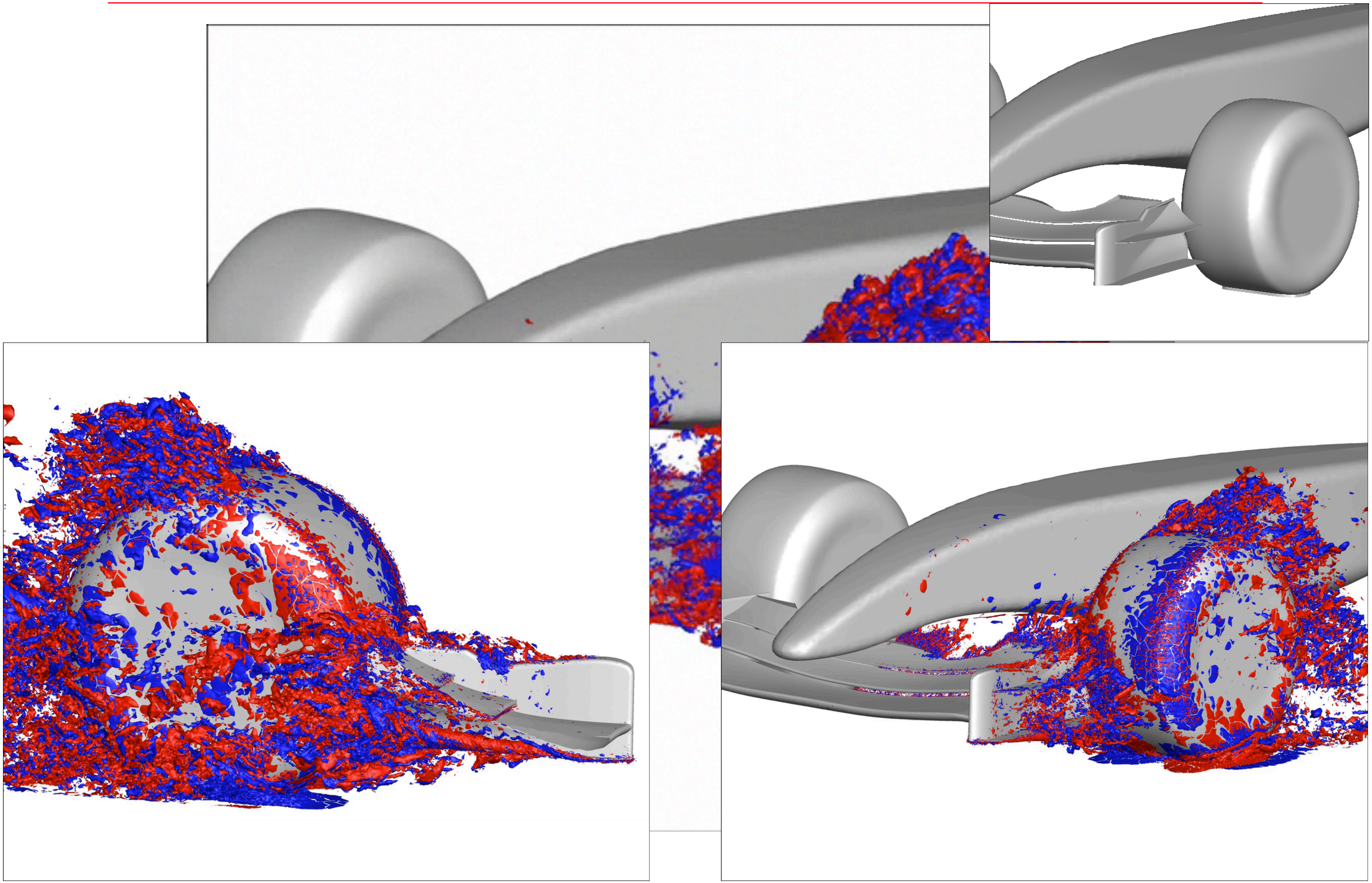

Summary

- High order compact discretisations such as spectral/hp element methods provide a suitable discretisation for current/emerging HPC hardware

- High accuracy transient flow modelling is an enabling technology for high-end engineering such as automotive and aeronautical sectors.