Meshing from CAD vision: curved adaption to geometry and solution

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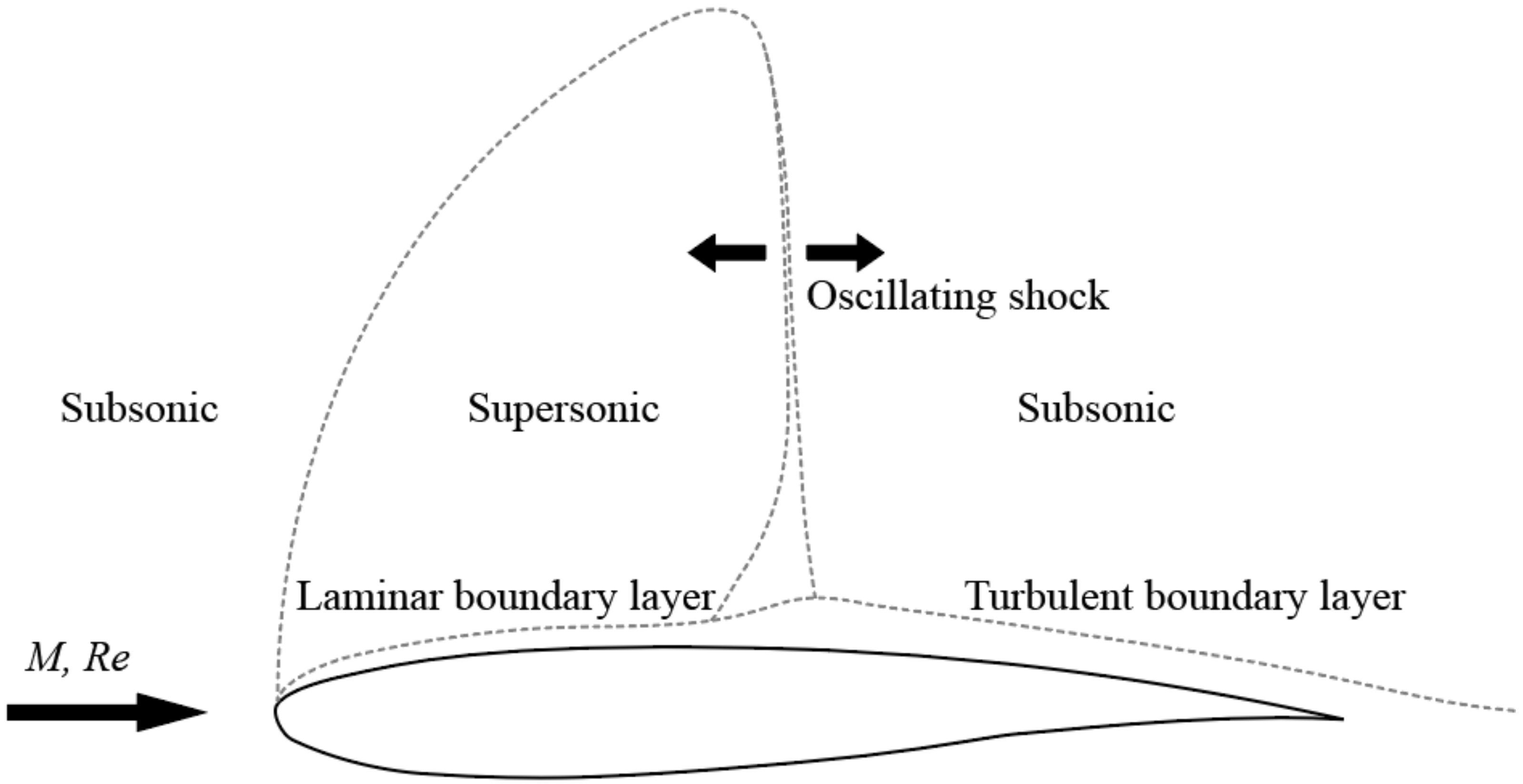
Thanks to the **ELEMENT** workshop

In mesh **adaption** and **CAD** for simulation give:

vision for what **meshing** would ideally look like **over the next decade**?

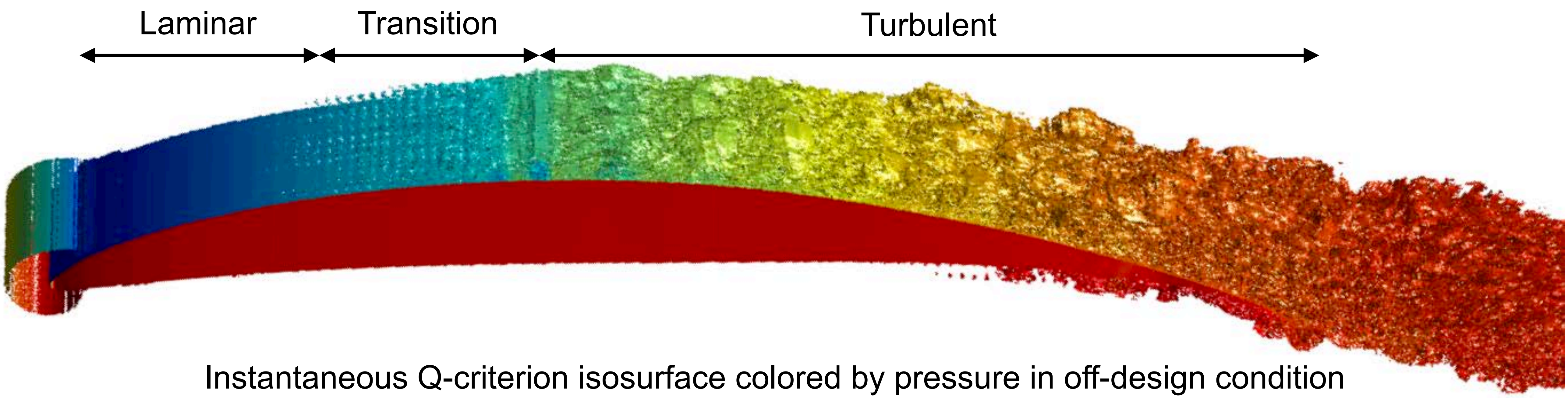
Grand challenge: wall resolved LES simulation of a full powered air-craft configuration in the full flight envelope
(NASA CFD Vision 2030'14)

Body-fitted & piece-wise polynomial curved tets



- *e.g.* **buffeting**: unsteady interaction of shock and turbulent BL
- Previous issues, current LES & adaption results. A **vision** of:
  - **body-fitted** adapted meshes from CAD models
  - **piece-wise polynomial curved tetrahedra**

Current LES & meshing: curved and adapted



Instantaneous Q-criterion isosurface colored by pressure in off-design condition
(Fernandez, Nguyen, Roca & Peraire, AIAA'16)

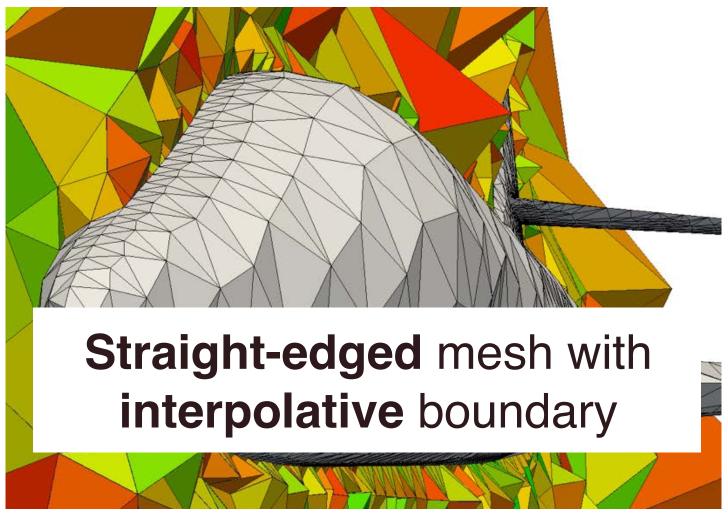
- Unstructured **high-order** methods & **curved** meshes: promising LES results for accurate prediction of **unsteady** transition to turbulence
  (Uranga, Persson & Peraire IJNMF'11) (NASA CFD Vision 2030'14) (HiOCFD AIAA'17) (Fernandez, Nguyen & Peraire JCP'17) (Mengaldo, Moxey, Turner, Moura, Jassim, Taylor, Peiro & Sherwin '19'20) (Nguyen, Terrana & Peraire AIAA'20)

- Unstructured methods & **adapted straight-edged** meshes: accurate quantities of interest for a fixed number of DOFs
  (Loseille & Alauzet JCP'10, SJNA'11, CAD'16) (Yano & Darmofal JCP'12)

Adapted meshing from CAD need: automatically capture highly **curved**, stretched & localized **unsteady** flow & geometry features

Meshing vision: curved adaption to geometry & solution

Current: automatic
straight-edged adaption
(INRIA, MIT, Boeing,
NASA, Pointwise, …)



Straight-edged mesh with
interpolative boundary

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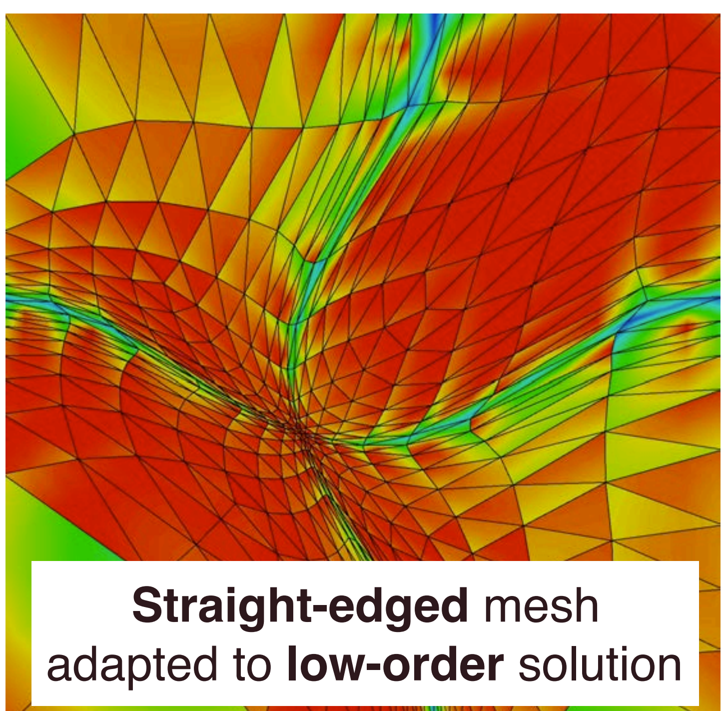
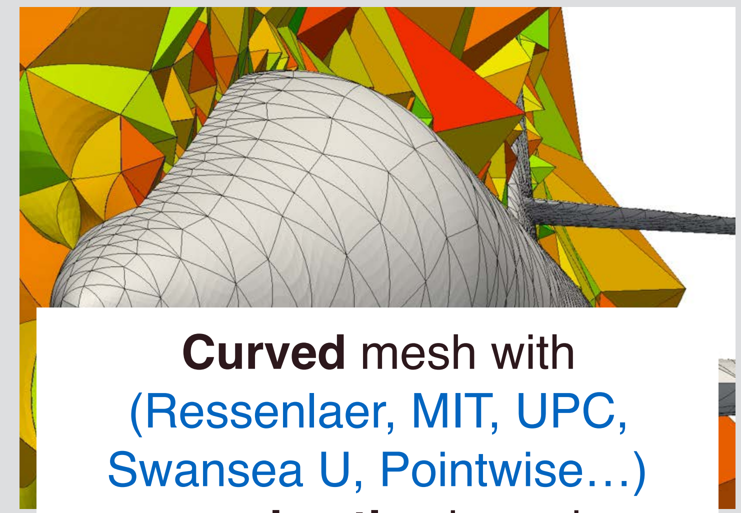


Straight-edged mesh
adapted to **low-order** solution

Vision: automatic
usnteady curved adaption
(Imperial College, UC Louvain,
LLNL, UC Berkeley, INRIA, BSC, …)



Curved mesh with
(Ressenlaer, MIT, UPC,
Swansea U, Pointwise…)
approximative boundary
(UC Louvain, INRIA, BSC, …)

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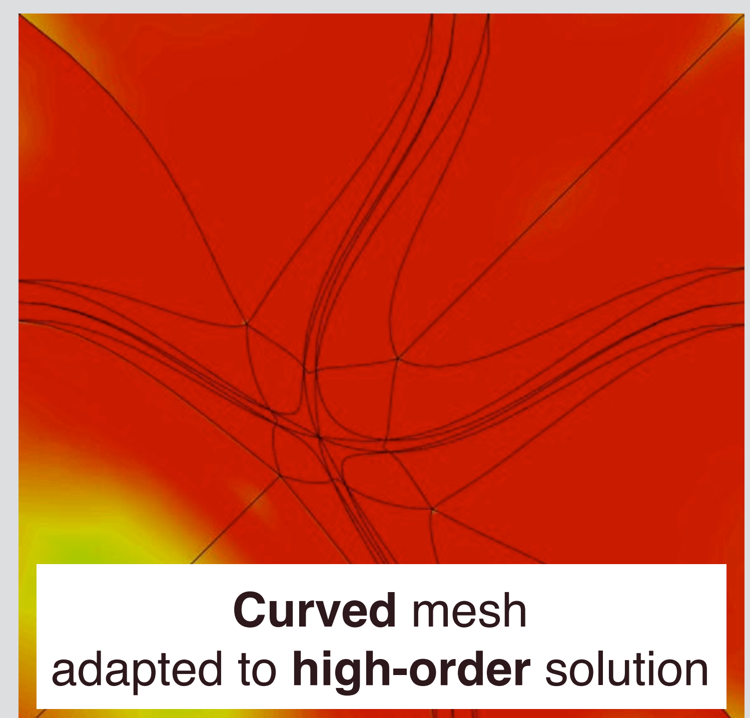


Curved mesh
adapted to **high-order** solution

Outline: curved adaption step & detailed visions

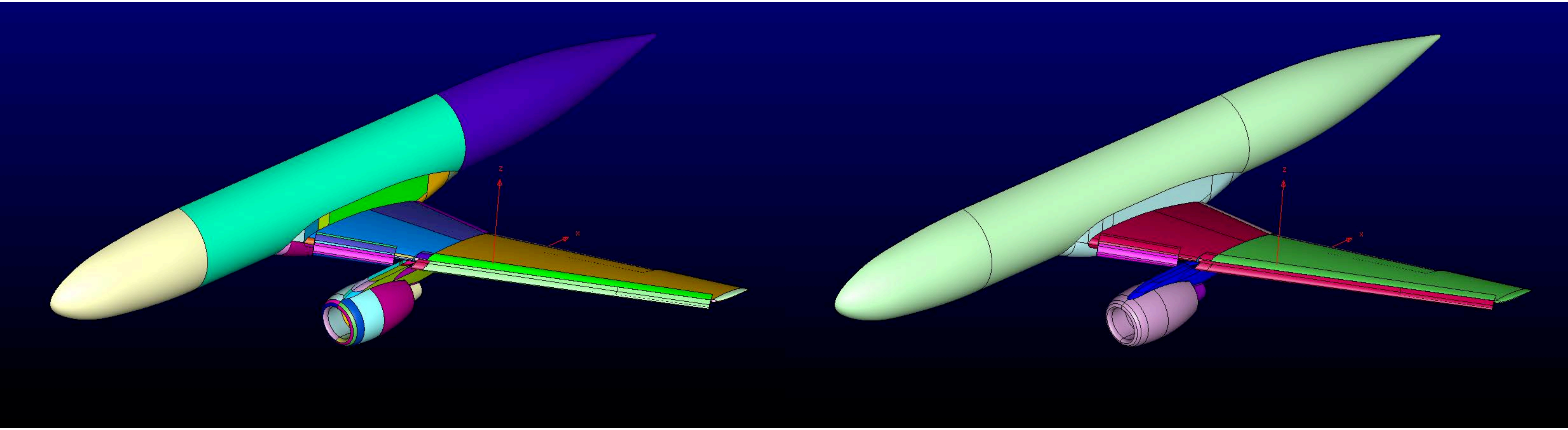
- **In**. Geometry proxy, curved tet. mesh, and high-order sol.
  - Local curved re-meshing: enough point-wise quality while,
  - approximating geometry proxy
- **Out**. Adapted boundary fitted curved mesh

- Virtual geometry
- Geometry queries
- Proxy access, storage & representation
- Mesh curving

Virtual geometry vision (1 / 2)

- **Virtual geometry**: group entities according to simulation intent

  (Geode Lite, Pointwise) (Tierney, Sun, Robinson & Armstrong, CAD'17)



CAD B-rep.: 409 surfaces   Virtual geometry: 105 simulation surfaces

High-Lift Jaxa Standard Model (using Pointwise)

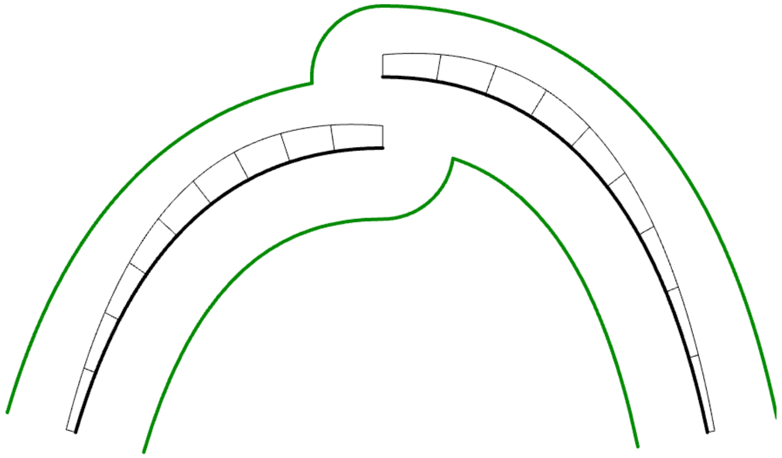
- **Current**: uses a CAD B-rep. with gaps & normal discontinuities
- **Issue**: fine meshes are meeting CAD tolerance and thus, they might **violate simulation intent** (steps & normal discontinuities)
- **CAD challenge**: will use CAD B-rep. with tighter tolerances or,

Virtual geometry (2 / 2)

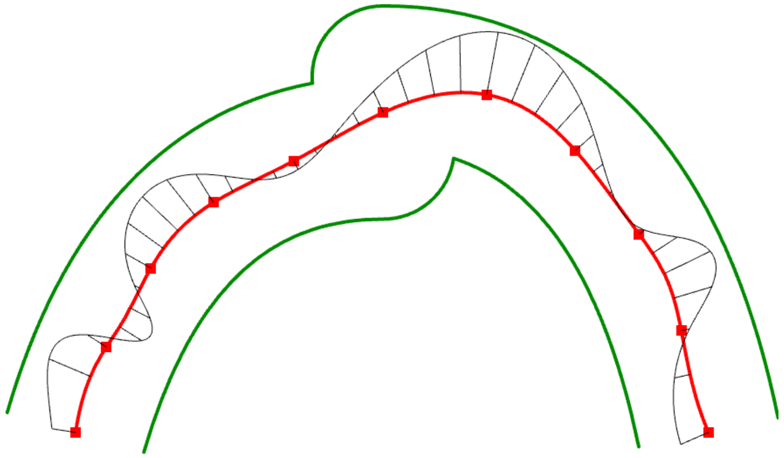
- **Meshing vision**: will use curved triangular meshes
  (Persson, Aftosmis & Haimes IMR'06) (Haimes, EGADS) (Loseille, feflo.a) (Jiménez *et al.* IMR'19)
  - preserving the simulation intent (simulation surfaces) and,

Isophote stripes: leading edge of a quartic triangular mesh proxy (Jiménez, Gargallo & Roca IMR'19)

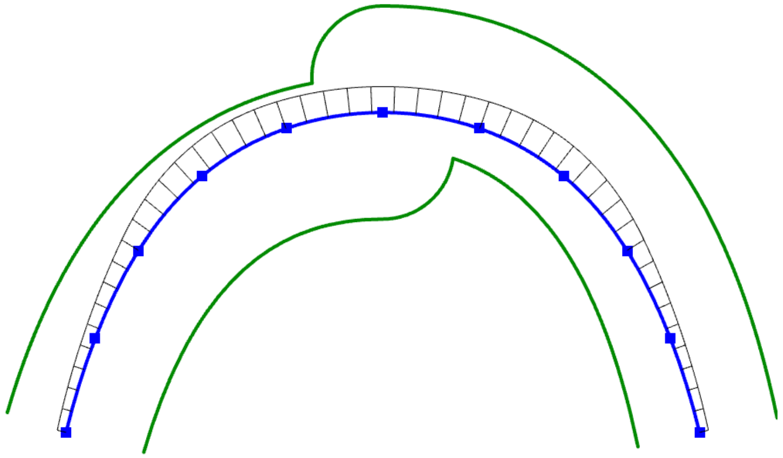
  - smoothly approximating a CAD B-rep. within model tolerance (green)



Virtual geometry: 1 simulation curve as 2 CAD curves & curvature viz.



Current mesh: CAD B-rep. interpolation & curvature viz.

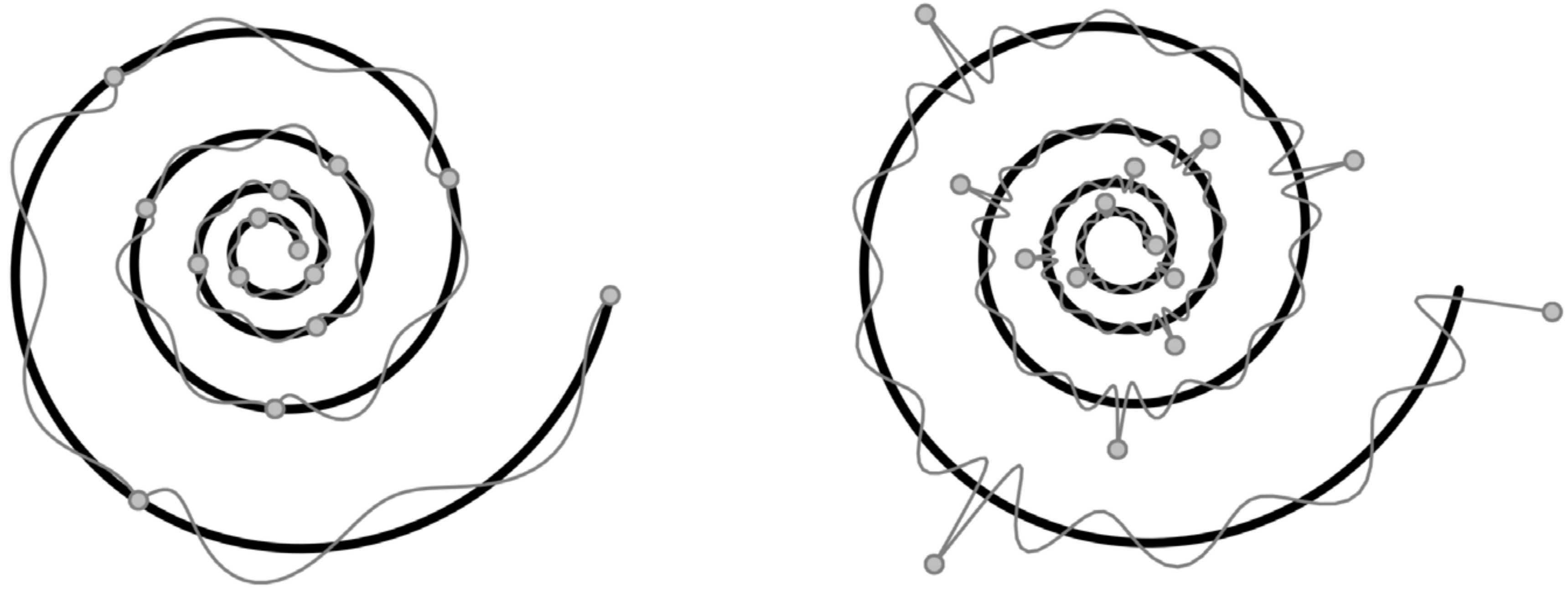


Mesh vision: smooth B-rep. approximation & curvature viz.

Geometry queries vision

- **Current state**: forward (& inverse) evaluations of values, 1st, and 2nd derivatives.
(Haimes, EGADS) (Pointwise, GEODE) (Open CASCADE)

- **Issue**: methods to improve geometric accuracy of surface meshes are tending to need higher derivatives
(Remacle, Lambrechts, Geuzaine & Toulorge IMR'14) (Ruiz, Sarrate & Roca IMR'15'16) (Feuillet, Loseille & Alauzet IMR'19) (Haimes, EGADS)



Interpolative quintic mesh & normal error amplified 2 10^3 times

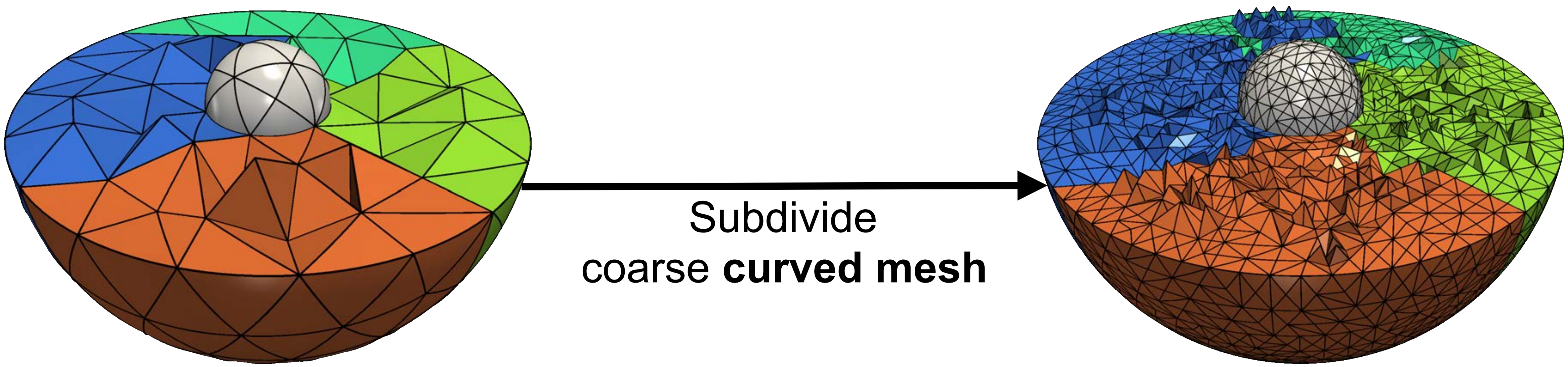
Approximative quintic mesh & normal error amplified 2 10^7 times

(Ruiz, Sarrate & Roca)

- **Vision**: will use up to 3rd derivatives (or even more)

Proxy access, storage & representation

- **Current state**: sequential and non-distributed surface proxies
- **Issue**: copies of full geo. proxy will miss-use scarce memory
  (Dongarrra *et al.*, App. Math. Res. for Exascale, DOE’14) (Chaurasia, Roca, Persson & Peraire IMR’12) (Moxey, Green, Sherwin & Peiró CMAME’15) (Gargallo, Hozeaux & Roca, IMR’17) (Haimes, EGADS)
- **Vision**: **distributed curved meshes of surfaces** or even, **volumes** (*e.g.* to enable parallel curved uniform refinements)

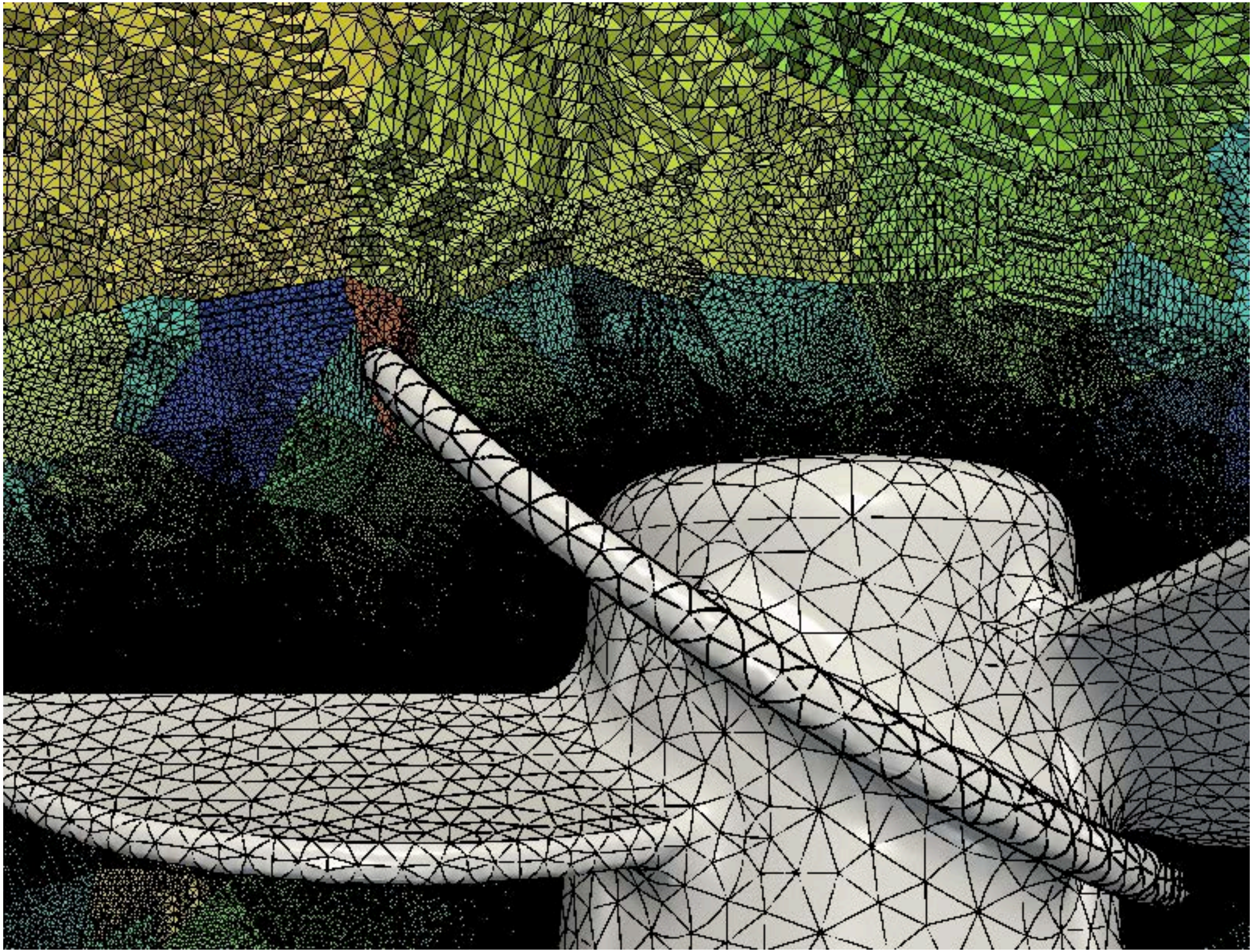


Distributed geometry proxy
Coarse curved mesh

Fine & distributed
Curved mesh

(Gargallo-Peiró, Ruiz-Gironés, Houzeaux & Roca, ICOSAHOM’18)

Proxy acces, storage & dims.: distri. subdi. (x 4096)

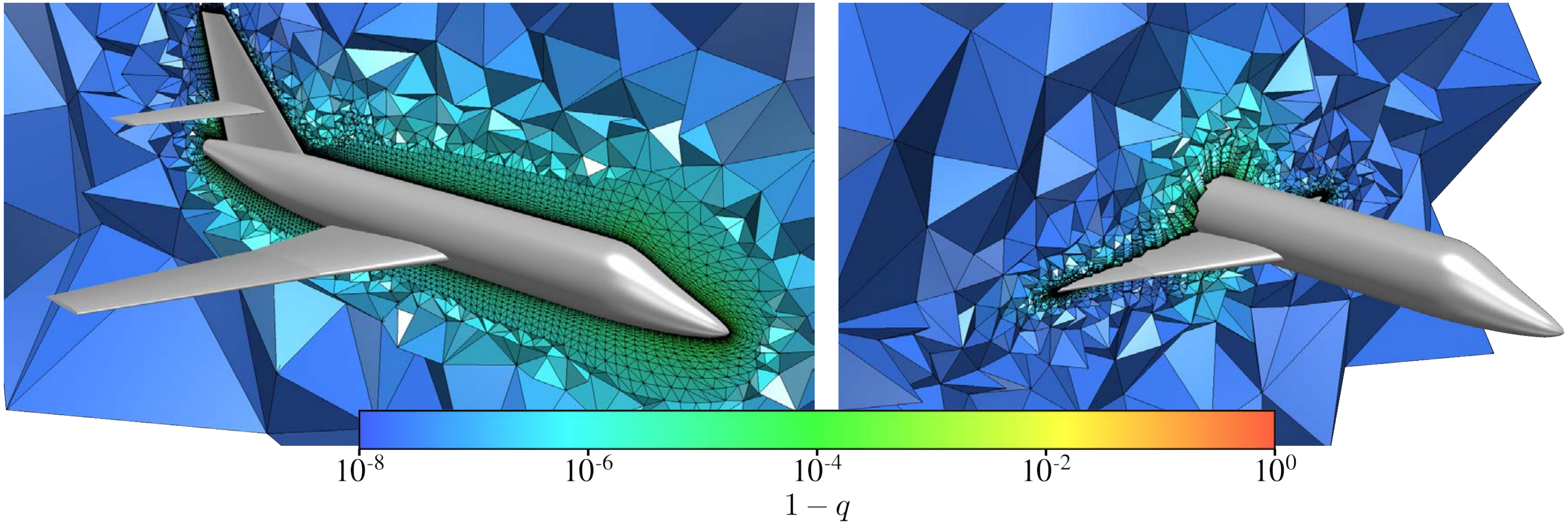


24 s, 768 cores (colored), 16 boxes, 208K (quadratic) to 860M (linear) elements, HDF5

(Gargallo-Peiró, Ruiz-Gironés, Houzeaux, Roca, ICOSAHOM’18)

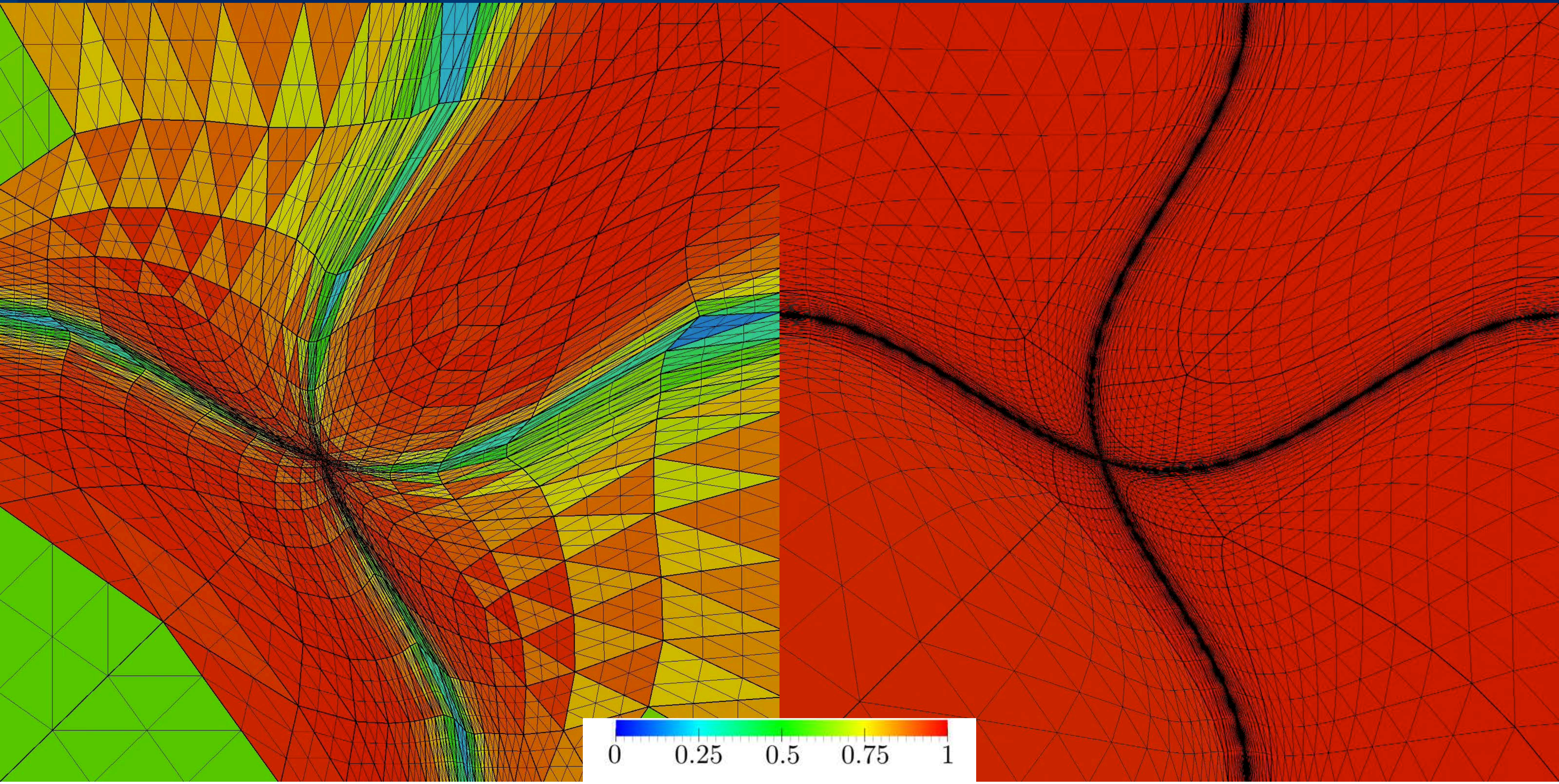
Mesh curving vision

- **Current state**: non-distributed curving (almost morphing)
- **Issues**: generate & distribute bottleneck. Only used to curve
  (Dongarrra *et al.*, Applied Math. Research for Exascale DOE'14) (Gargallo-Peiró, Hozeaux & Roca IMR'17) (Gargallo-Peiró, Ruiz-Gironés, Houzeaux & Roca ICOSAHOM'18)
- **Vision**: will be **distributed** & also used to ***r*-adapt** meshes between **local curved re-meshing** steps
  (Ruiz & Roca IMR'19) (Dobrev, Kolev & Rieben SJSC'12) (Marcon, Turner, Moxey, Sherwin & Peiró IMR'17) (Dobrev, Knupp, Kolev *et al.* SJSC'19) (Shi, Persson *et al.*, AIAA'19) (Zhang, Johnen & Remacle IMR'18) (Aparicio, Gargallo & Roca IMR'18'19) (Feuillet, Loseille & Alauzet IMR'18, CAD'20)



Distributed curving: laminar BL (1:400), 4M quartic tet. (like 256M tet.), 2400 cores, 17 minutes
(Ruiz-Gironés & Roca IMR'19)

Curving vision: curved *r*-adaption, 1:100

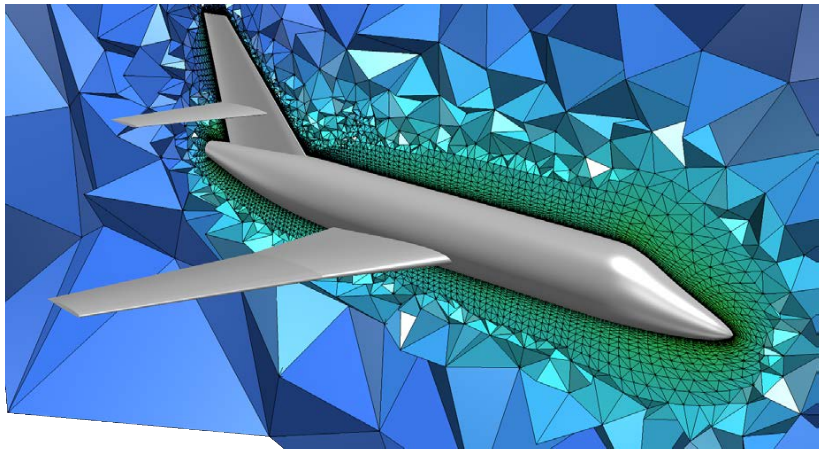


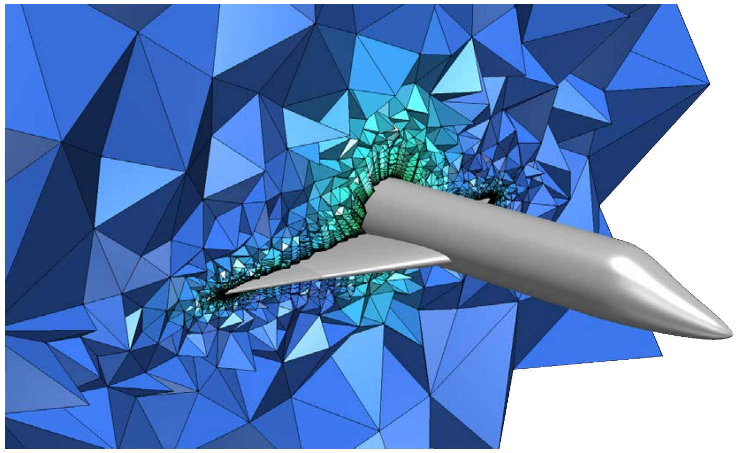
640 **linear** tris., iso-resolution, 353 nodes, visualization mesh, 5760 linear tris.

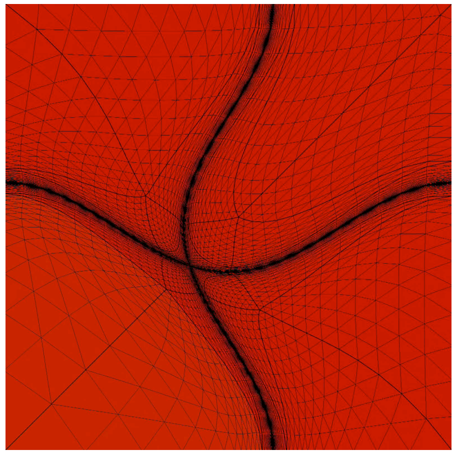
40 **curved quartic** tris., iso-resolution, 353 nodes, visualization mesh, 5760 linear tris.

- To meet point-wise stretching, alignment & sizing, **non-constant resolution of curved elements is key** (local re-meshing, too)
  (Aparicio, Gargallo & Roca IMR'18'19)

Summary: curved adaption to geometry & solution







- **Virtual geometry**: will use curved surface meshes preserving simulation intent and, smoothly approximating CAD B-rep. within model tolerance
- **Geometry queries**: will use up to 3rd derivatives (or even more) pushed by methods to improve geometric accuracy
- **Proxy access, storage & dims.**: will use distributed curved meshes of surfaces or even, volumes
- **Curved morphing**: will be distributed and, also used to *r*-adapt the mesh between local curved re-meshing steps

Curved adapted meshing from CAD: will automatically capture highly **curved**, stretched & localized **unsteady** flow & geometry features

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