Geometry modeling and Meshing

Numerical Flow Simulation

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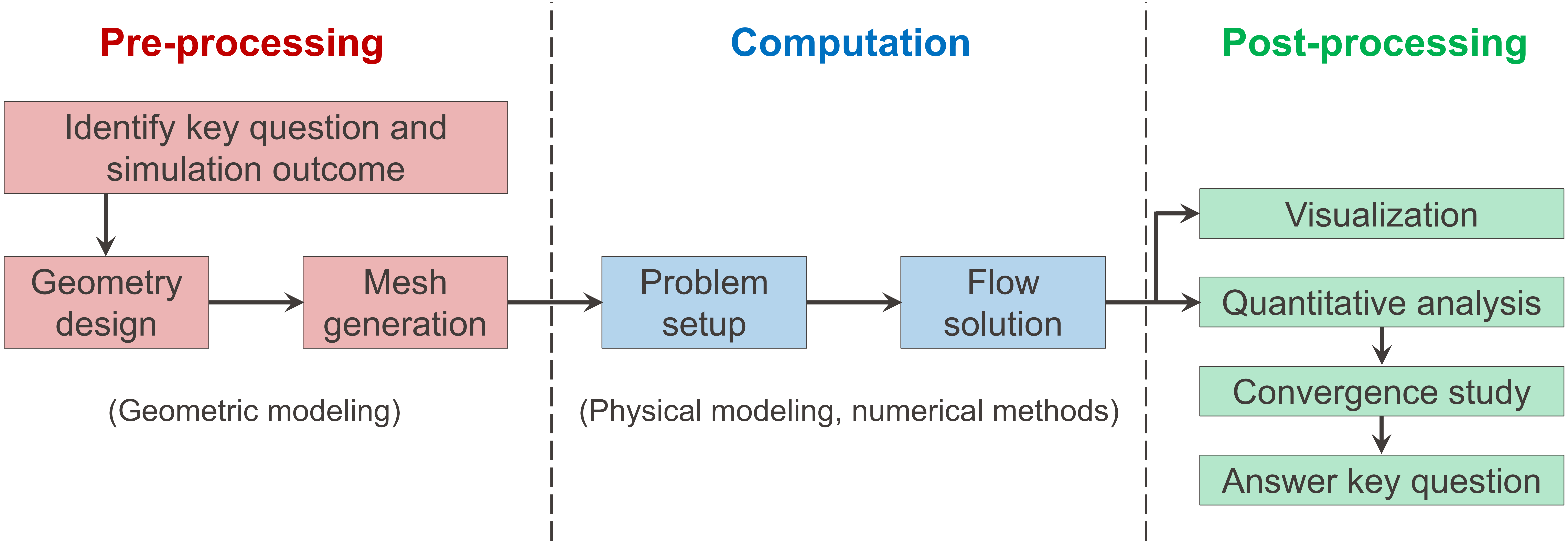
Numerical simulation workflow

- Reminder:



Pre-processing

Identify key question and simulation outcome

Geometry design

Mesh generation

(Geometric modeling)

Computation

Problem setup

Flow solution

(Physical modeling, numerical methods)

Post-processing

Visualization

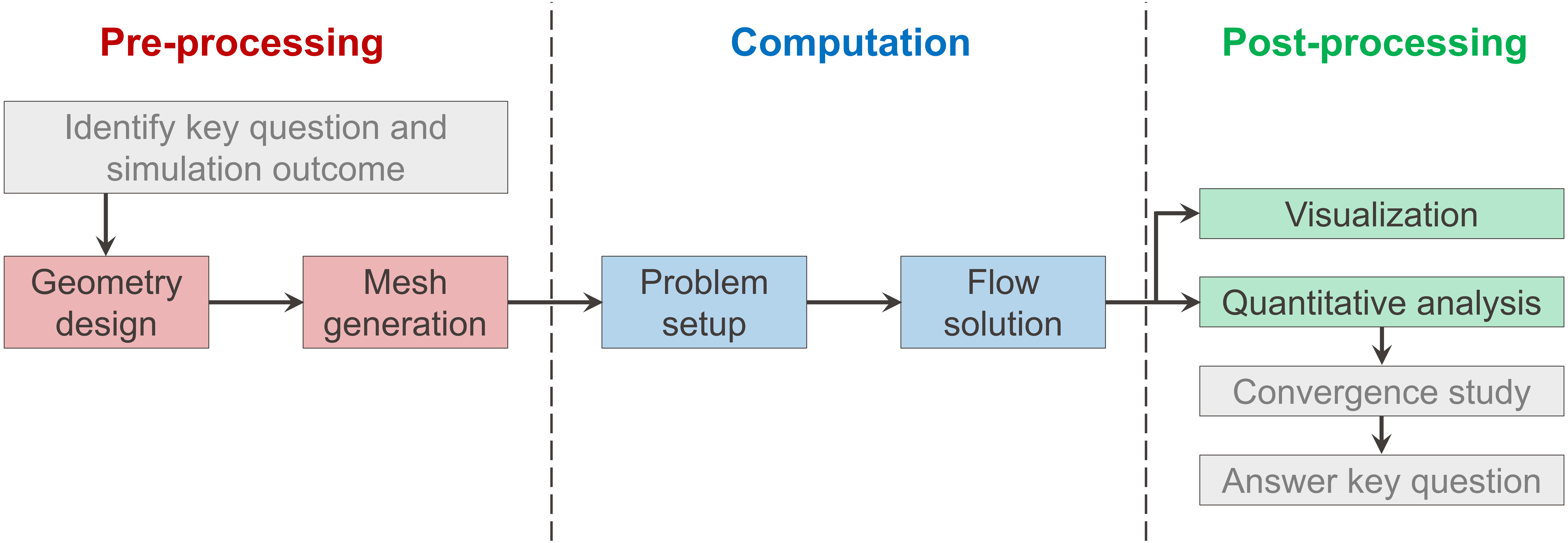
Quantitative analysis

Convergence study

Answer key question

Numerical simulation workflow

- Some of the software available in Ansys:

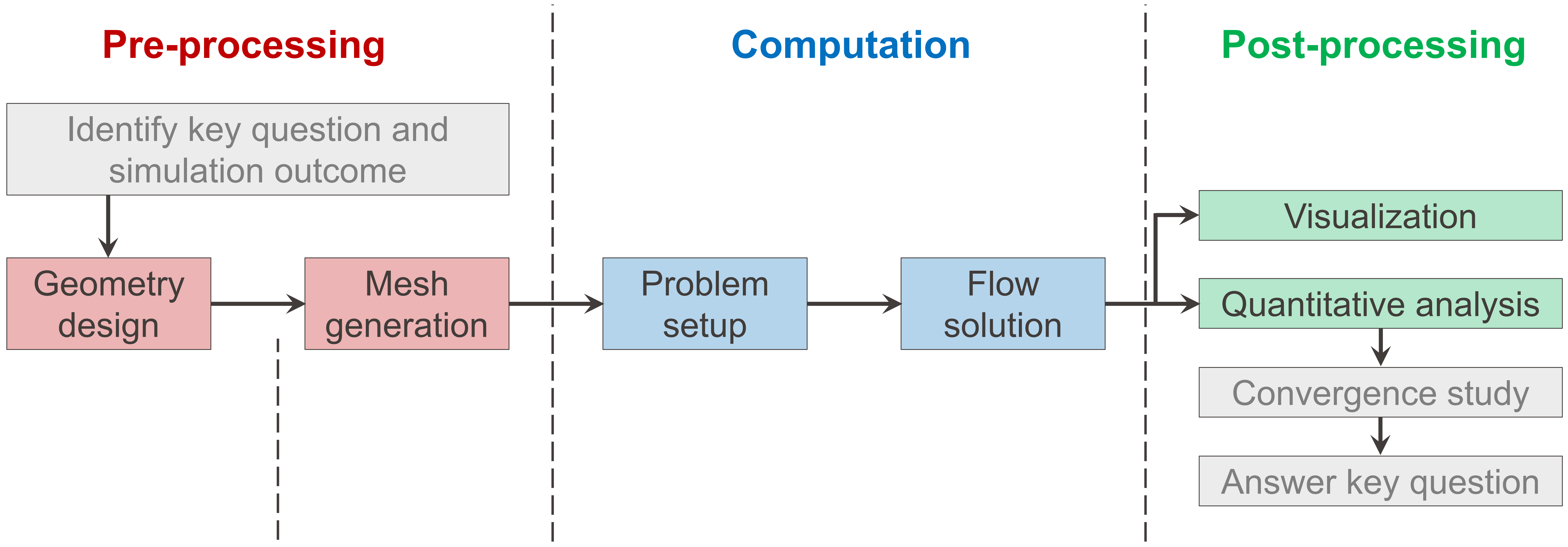


- Design Modeler (soon obsolete)
- SpaceClaim*
- External soft

(*) Available both in Workbench and stand-alone

Numerical simulation workflow

- Some of the software available in Ansys:



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Answer key question

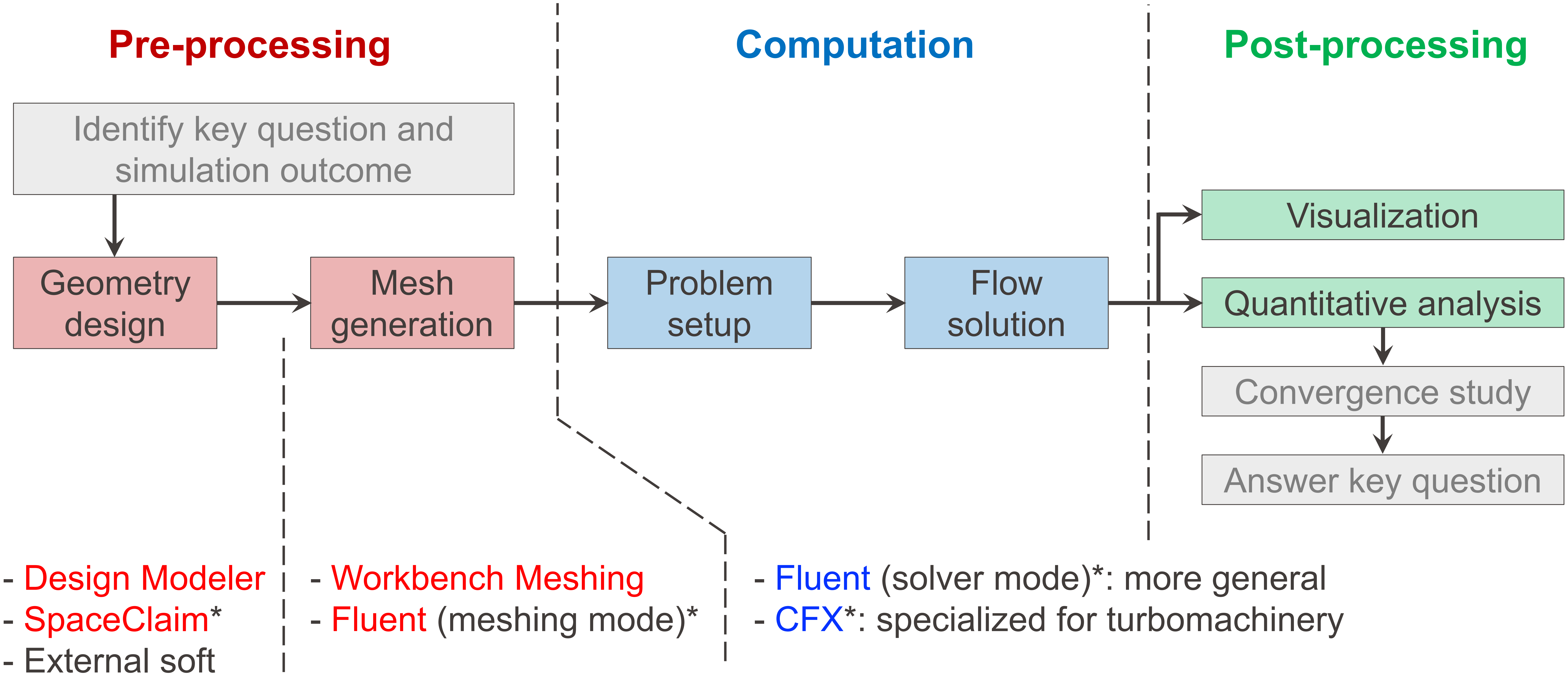
- Design Modeler
- SpaceClaim*
- External soft

- Workbench Meshing: more control, but steeper learning curve. Both 2D and 3D.
- Fluent (meshing mode)*: easier to learn, but less control. Only 3D

(*) Available both in Workbench and stand-alone

Numerical simulation workflow

- Some of the software available in Ansys:



Pre-processing

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Answer key question

- Design Modeler
- SpaceClaim*
- External soft

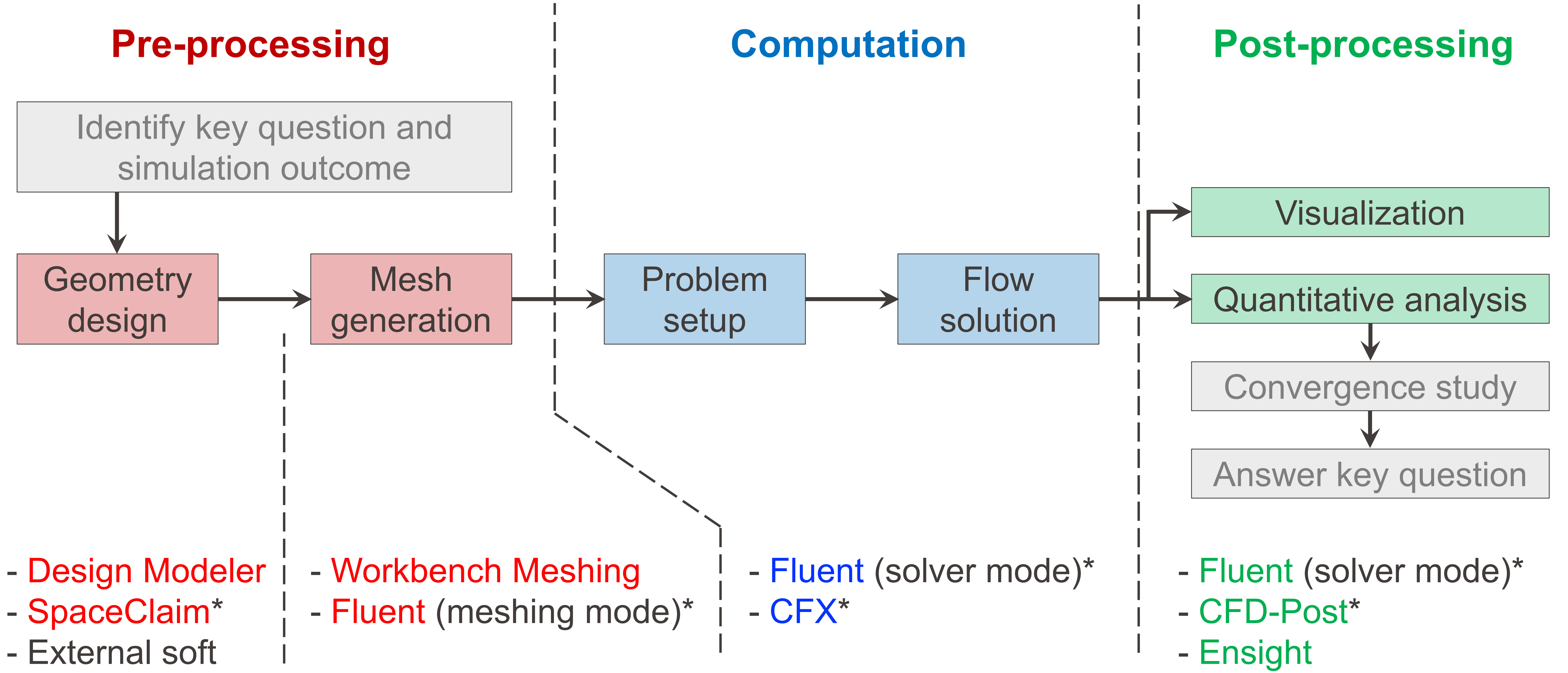
- Workbench Meshing
- Fluent (meshing mode)*

- Fluent (solver mode)*: more general
- CFX*: specialized for turbomachinery

(*) Available both in Workbench and stand-alone

Numerical simulation workflow

- Some of the software available in Ansys:



Pre-processing

Identify key question and simulation outcome

Geometry design

Mesh generation

- Design Modeler
- SpaceClaim*
- External soft

- Workbench Meshing
- Fluent (meshing mode)*

Computation

Problem setup

Flow solution

- Fluent (solver mode)*
- CFX*

Post-processing

Visualization

Quantitative analysis

Convergence study

Answer key question

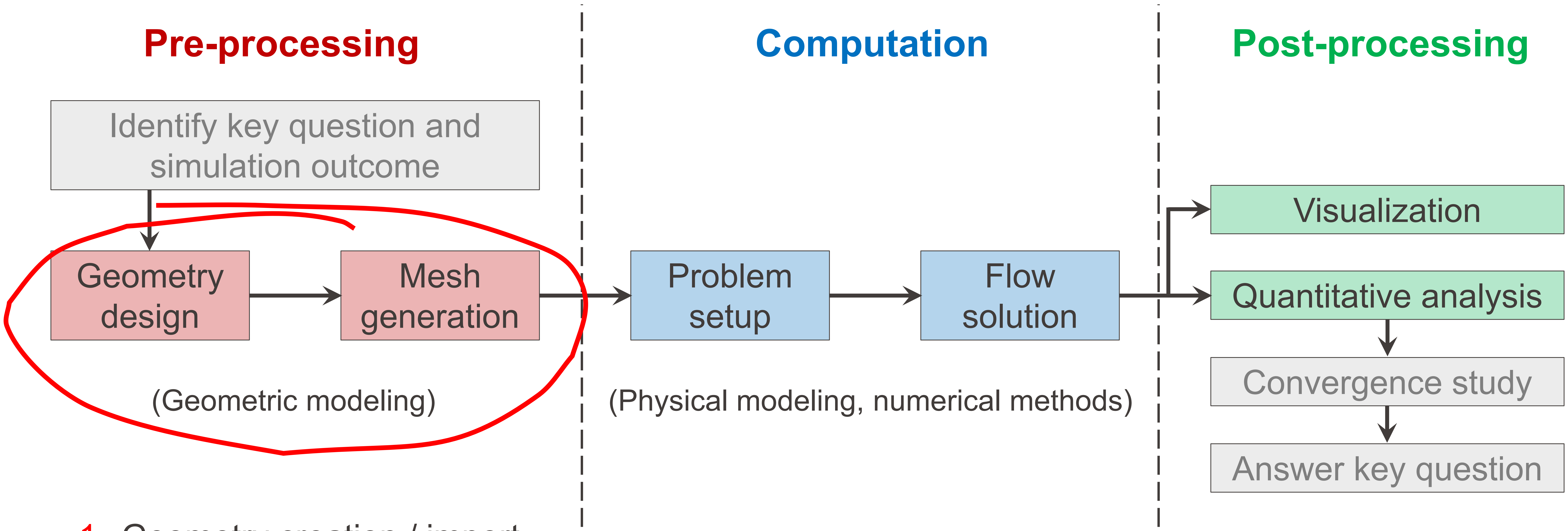
- Fluent (solver mode)*
- CFD-Post*
- Ensight
- External soft (Paraview etc.)

(*) Available both in Workbench and stand-alone

Numerical Flow Simulation

Numerical simulation workflow

- This week:



Pre-processing

Identify key question and simulation outcome

Geometry design

Mesh generation

(Geometric modeling)

Computation

Problem setup

Flow solution

(Physical modeling, numerical methods)

Post-processing

Visualization

Quantitative analysis

Convergence study

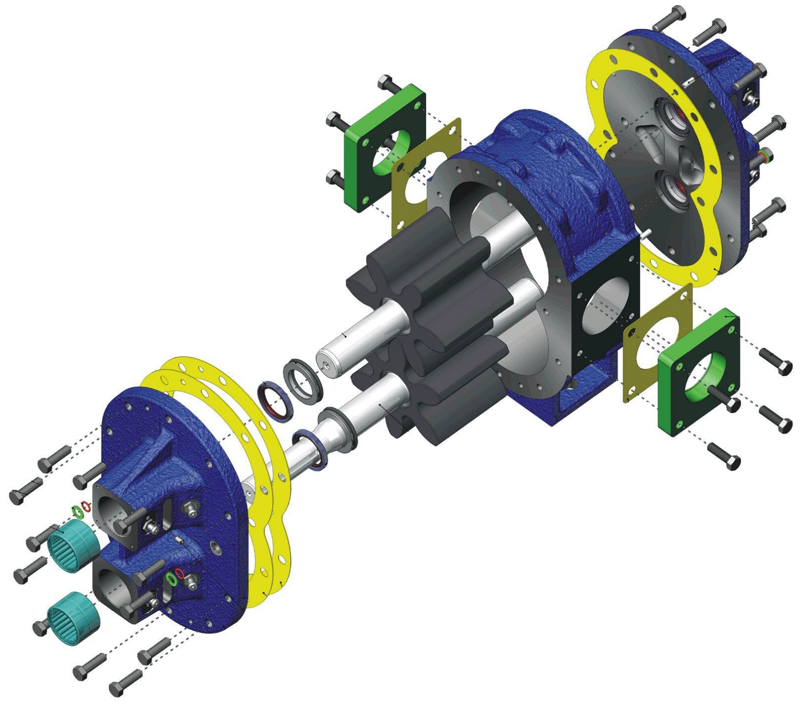
Answer key question

Numerical Flow Simulation

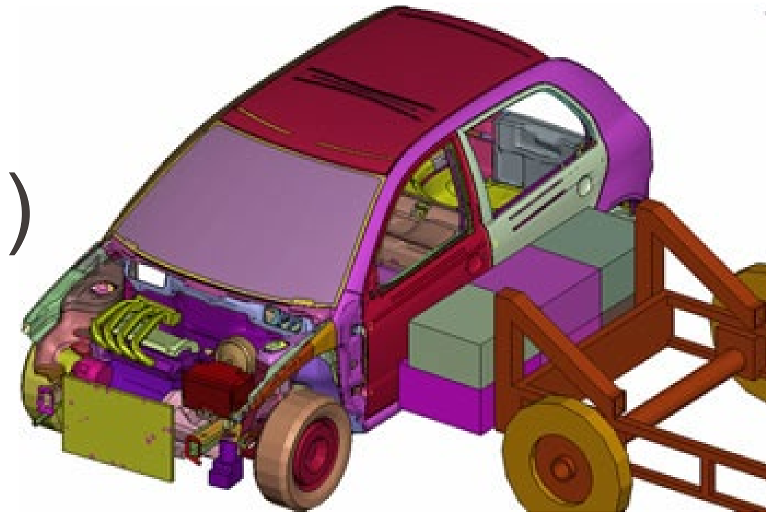
1. Geometry creation / import
2. Geometry clean-up (if needed)
3. Mesh creation / import
4. Mesh quality control + improvement

Geometry design

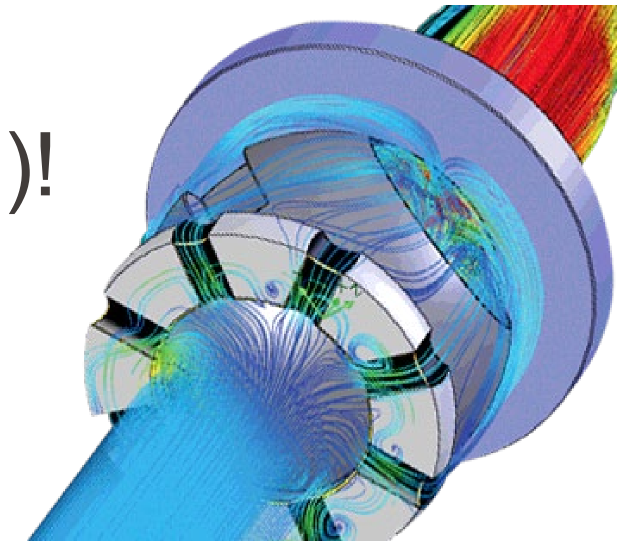
- Different processes for different needs:
  - Computer-Aided Manufacturing (CAM)
    - Interest: **manufacturing**, **interaction** between objects
    - Conception: generally complex objects / parts / assemblies



  - “Finite Element” Analysis (FEA)
    - Interest: simulation domain for **structural analysis** (deformation, stress…)
    - Conception: boundary surfaces / volumes (not necessarily closed)



  - Computational Fluid Dynamics (CFD)
    - Interest: simulation domain for **flow analysis**
    - Conception: volume occupied by the fluid. Must be closed (“watertight”)!



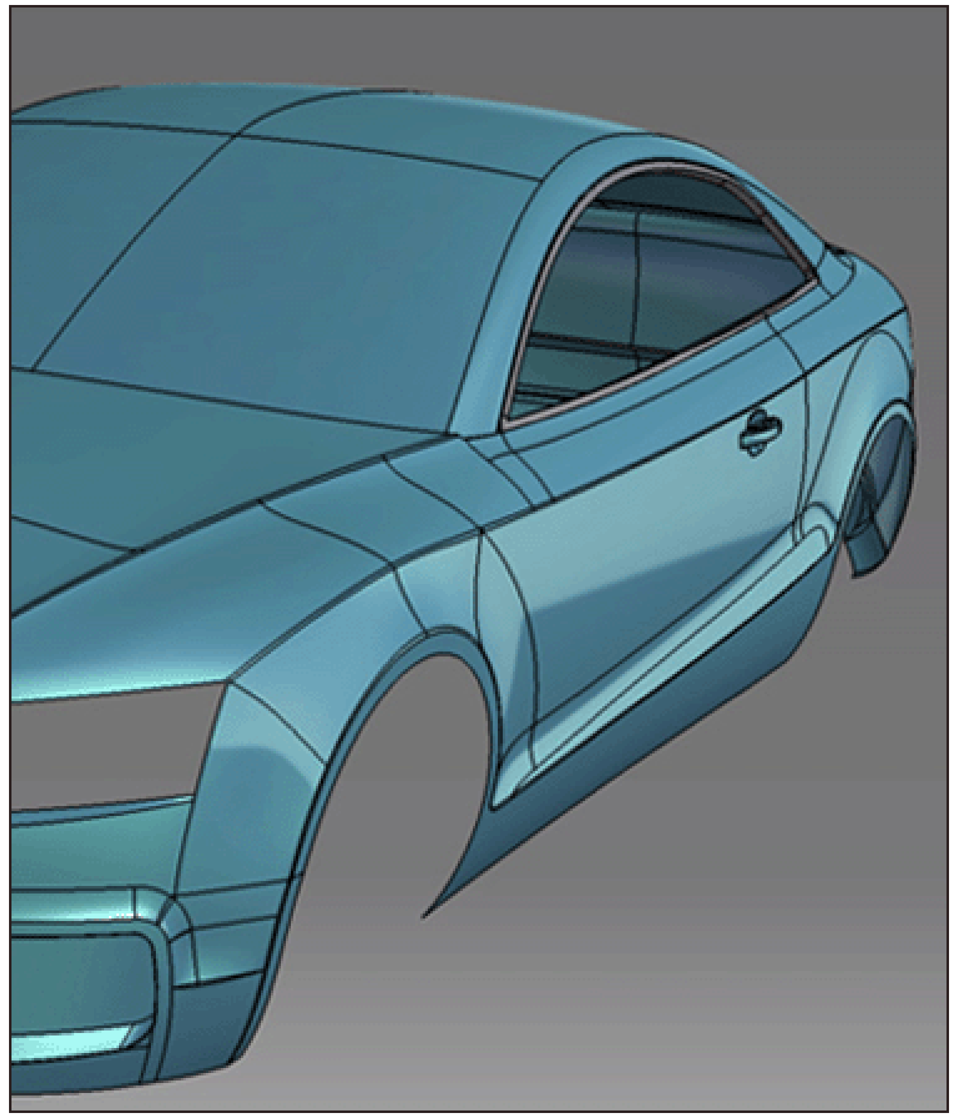
  - Others: computer graphic design (for publishing, advertising or education), etc.

Geometry import/export

- Various ways to exchange geometry:

  - “Geometric modeling kernels”:
    - Parasolid [.x_t, .x_b] (used in Abaqus, Workbench, SolidWorks, Solid Edge, ANSYS, Comsol…)
    - ACIS [.sat] (used in Gambit / Trelis, AutoCAD, Cadkey, TurboCad…)
    - Convergence Geometric Modeler (used in CATIA)
    - …

  - Industry standard file formats:
    - STEP [.stp] ("Standard for the Exchange of Product model data”, ISO 10303)
    - IGES [.iges, .igs] (“Initial Graphics Exchange Specification”)
    - …



Geometry clean-up

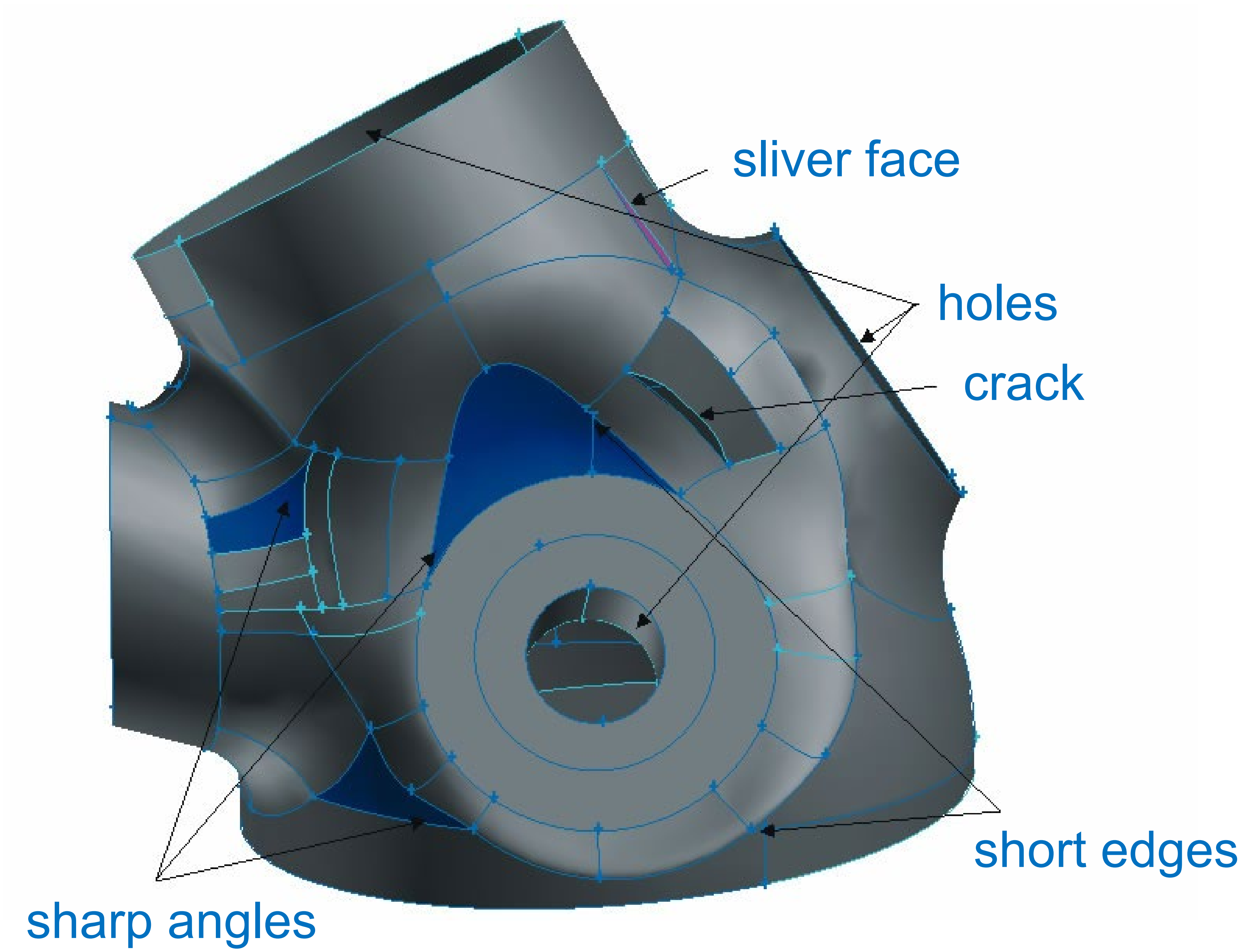
- Many problems may arise at import, especially if original CAD geometry was designed for a different purpose:
  - Volumes not closed (not watertight).
  - Small features that are difficult to mesh but do not influence significantly the flow.
  - Small surfaces that must be merged to simplify meshing (because each independent surface in the geometry will be meshed independently).
  - Translation between different CAD systems may result in corrupt / incomplete geometry / topology.

- Clean-up:
  - Identify problems: holes, sliver faces / cracks (too small to be meshed), sharp angles / short edges (give poor mesh), etc.
  - Automated “healing”: geometry simplification, stitching (connect edges or faces), geometry building.

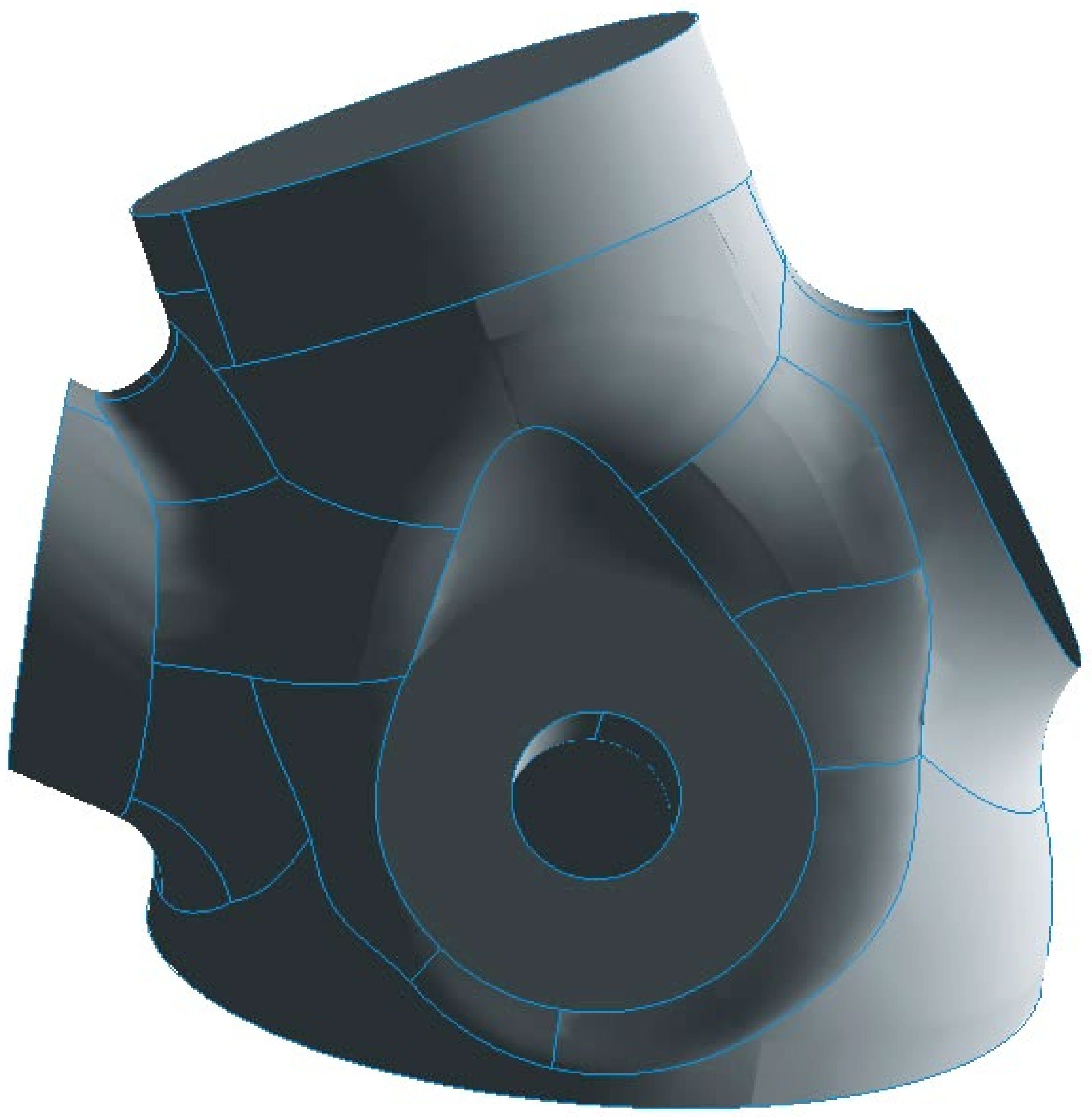
Geometry clean-up

- Example

Imported geometry

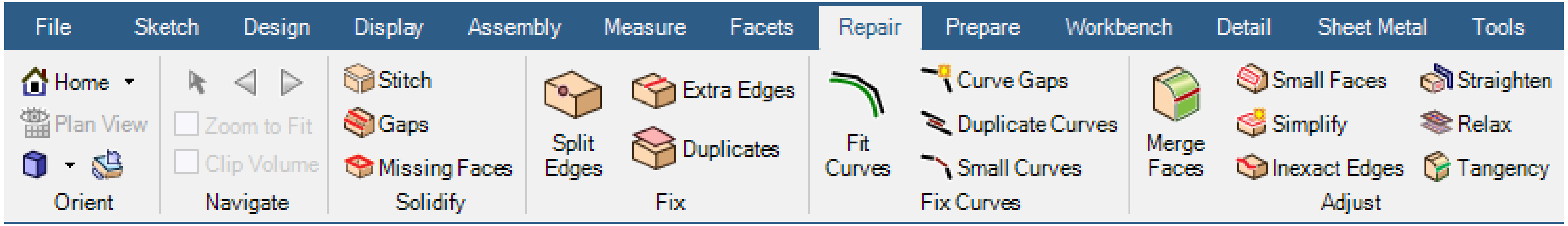


Geometry after “healing”

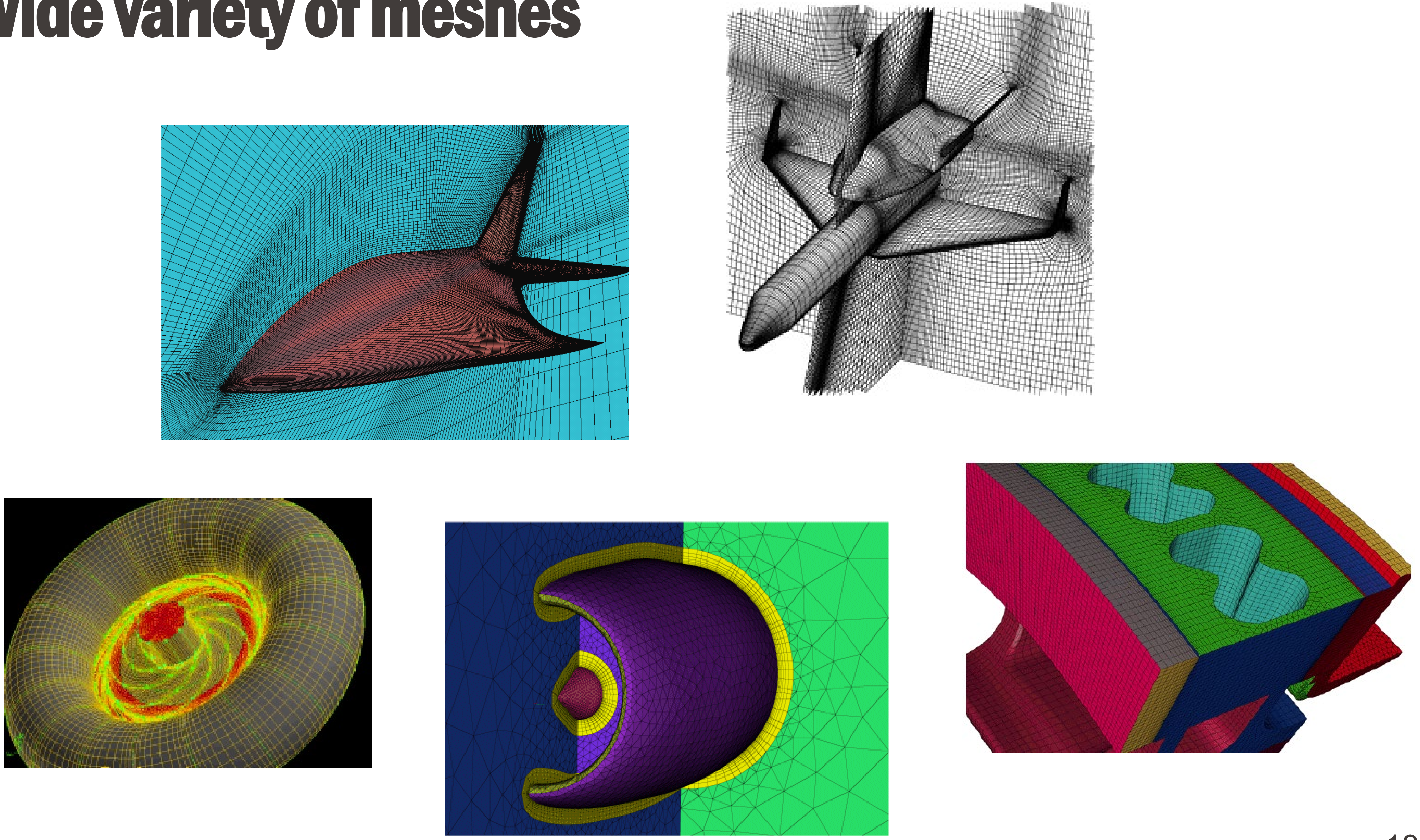


Geometry clean-up

- In SpaceClaim: Repair tab



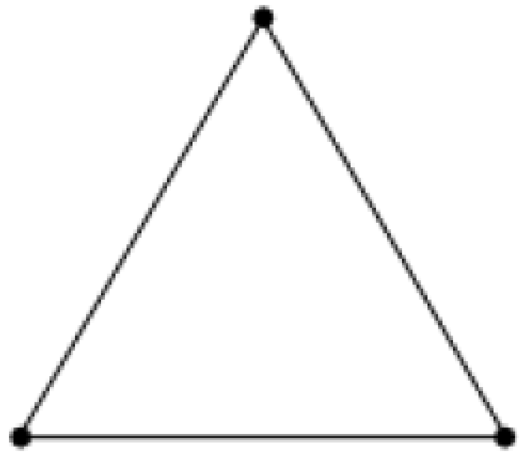
Wide variety of meshes



Mesh elements

- Common types of mesh elements (= cells = control volumes):

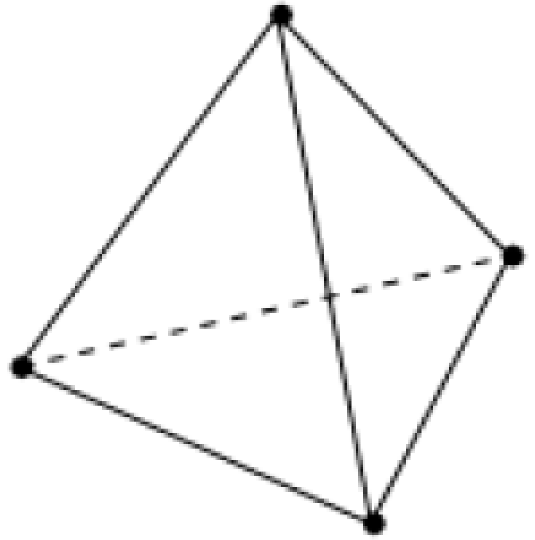
2D elements



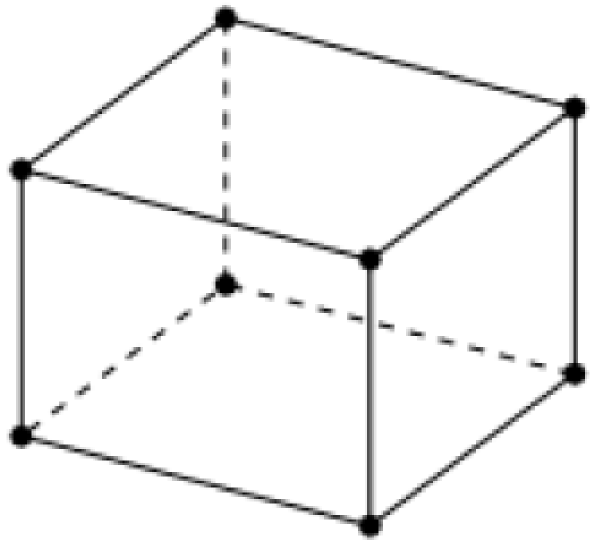
Triangle
3 nodes/edges
(not necessarily
equilateral…)

Quadrilateral
4 nodes/edges
(not necessarily
orthogonal…)

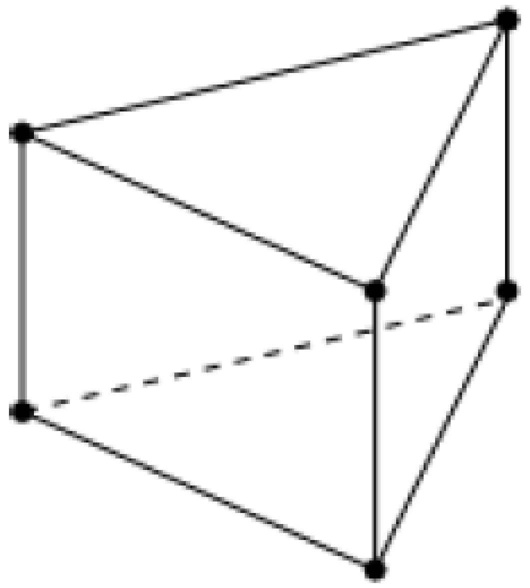
3D elements



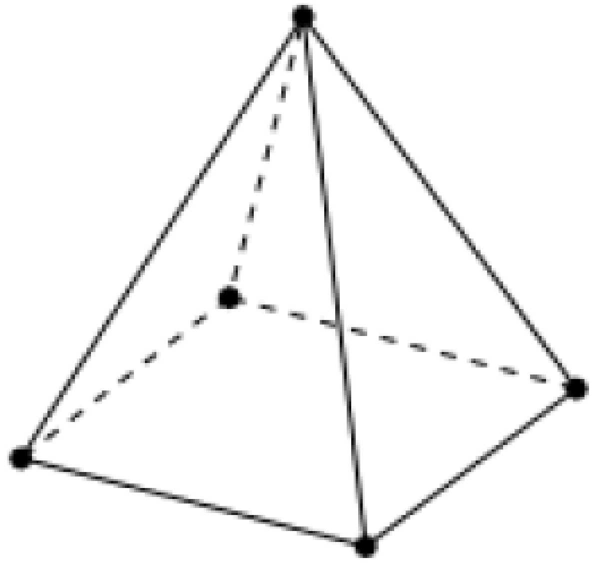
Tetrahedron
4 nodes, 4 faces



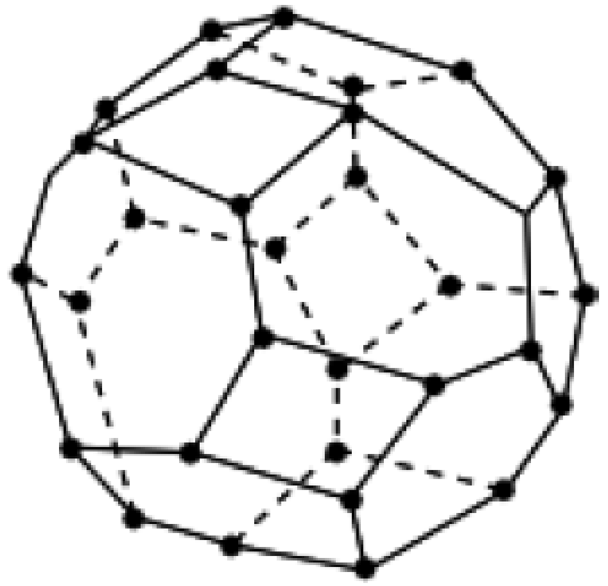
Hexahedron
8 nodes, 6 faces



Wedge/Prism
6 nodes, 5 faces



Pyramid
5 nodes, 5 faces

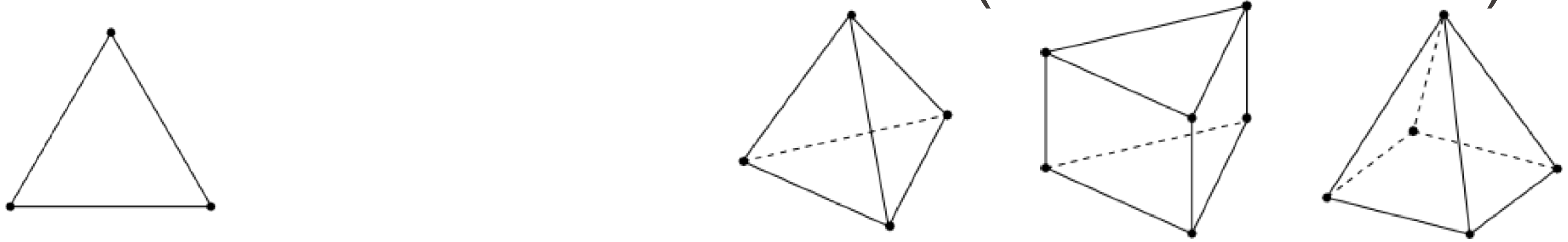


Polyhedron

Mesh elements

- Each type of element has different properties regarding the numerical approximation of gradients and fluxes.
- In general, quads / hex are more accurate (under some conditions) and can help reduce the number of elements (larger aspect ratio).

- Triangles, tetras, prisms etc. make it easier to mesh complex geometries and can help reduce the number of elements (local refinement).

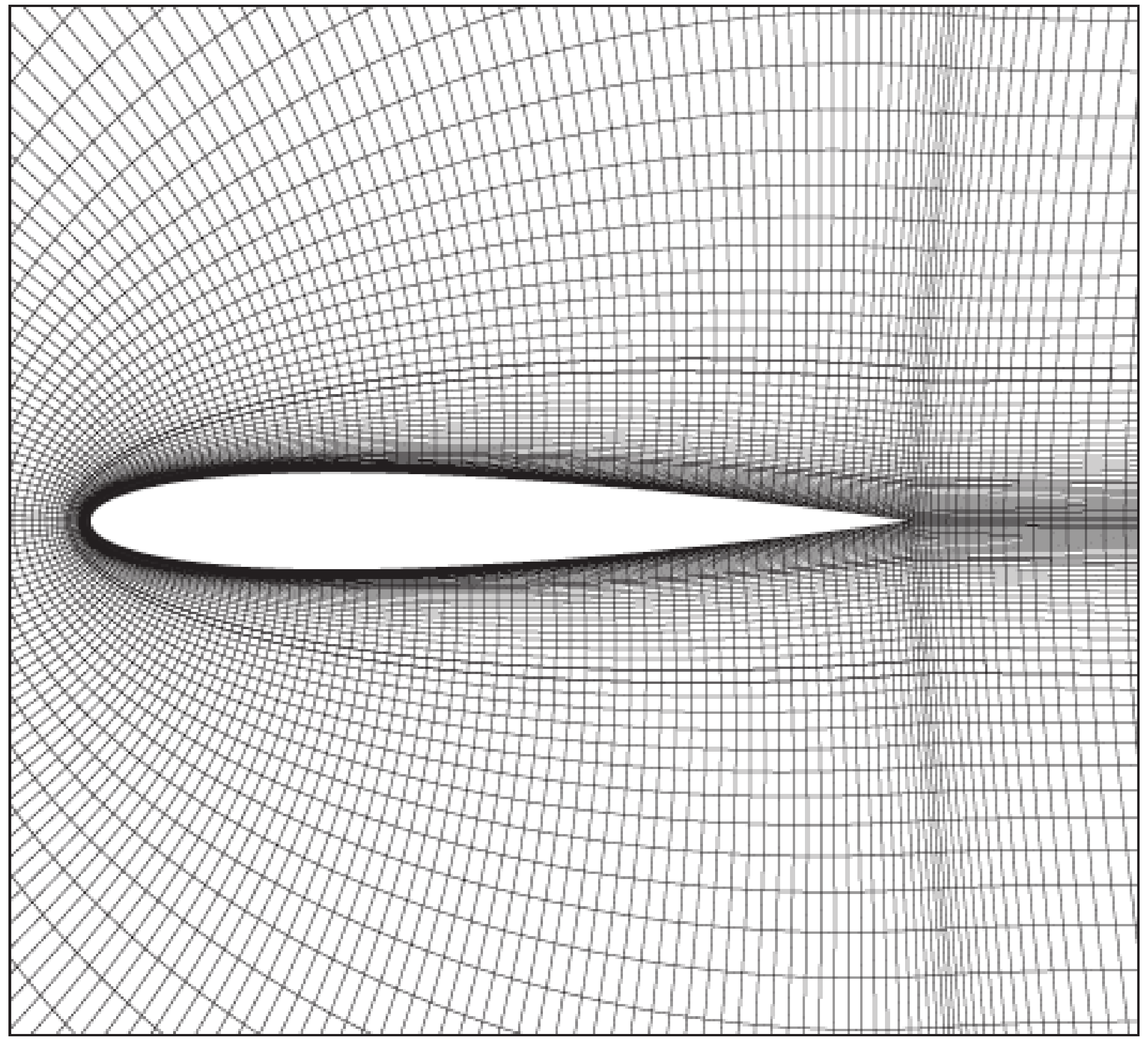


- In the end, choice up to the user, as long as mesh size and quality acceptable.

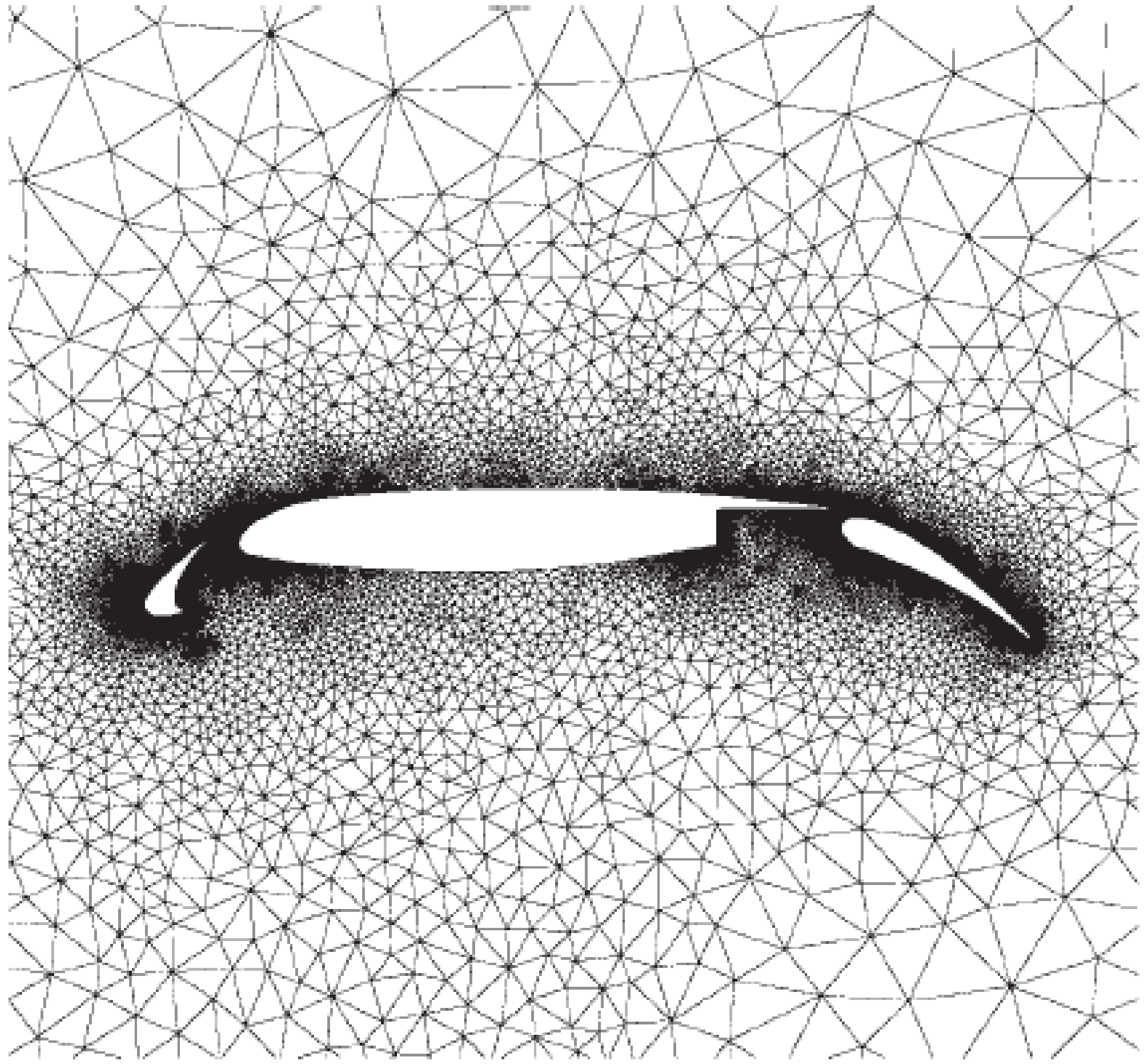
Mesh types

- Two basic types:

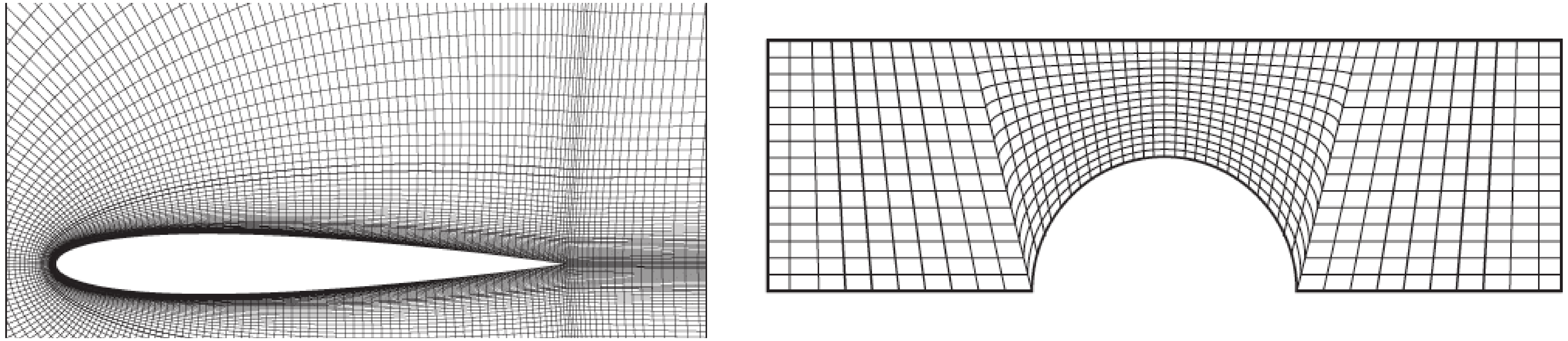
1. Structured



2. Unstructured



Mesh types



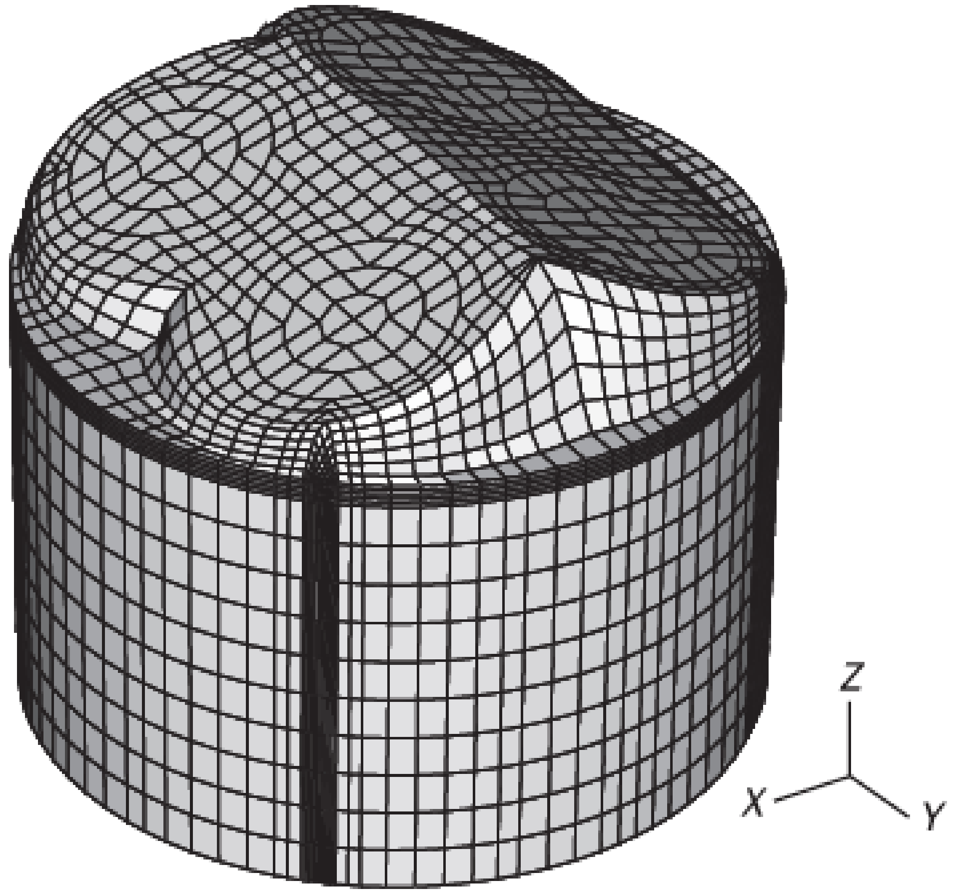
1. Structured mesh

- Sets of lines where members of the same set don’t cross, and members of different sets cross only once → position of any CV uniquely defined by two or three indices (in 2D or 3D). Fixed number of neighbors.

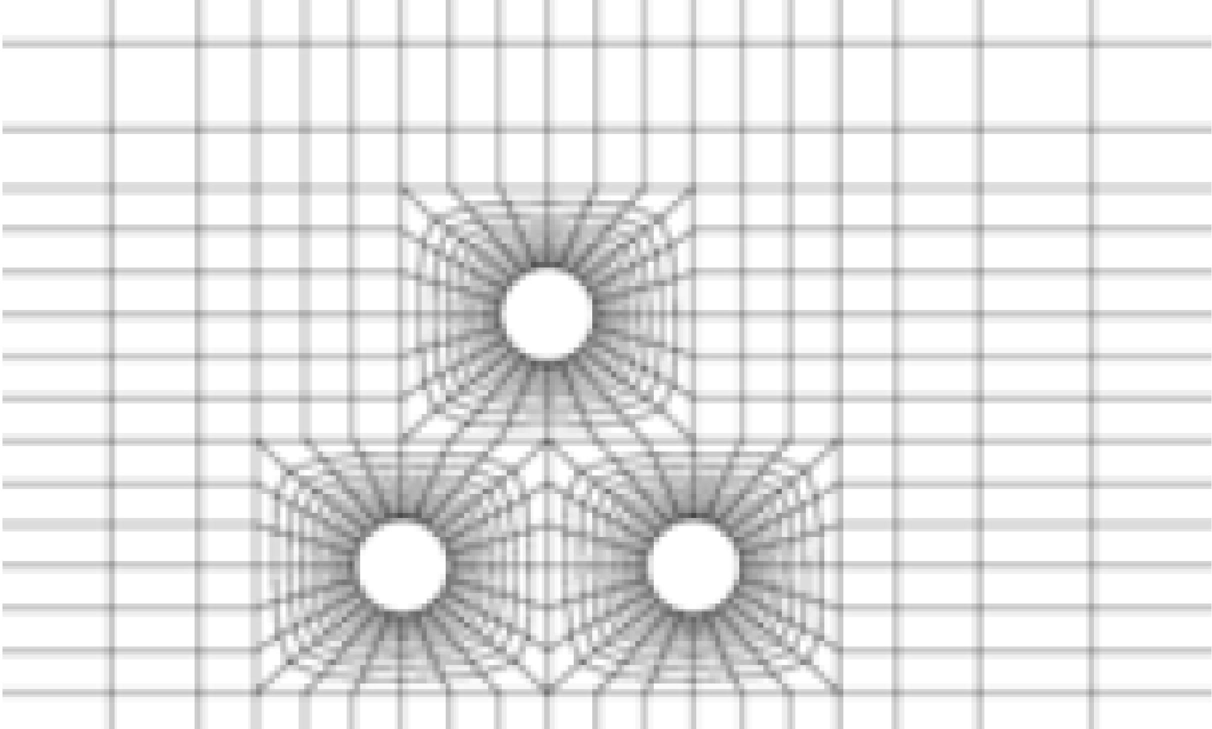
- Simple neighbor connectivity, structured matrix, efficient solution algorithms.

- Generally quad / hex. (Orthogonal or not.)

- Difficult/impossible to use with complex geometries.
- Difficult to refine locally. (Inefficient use of resources.)

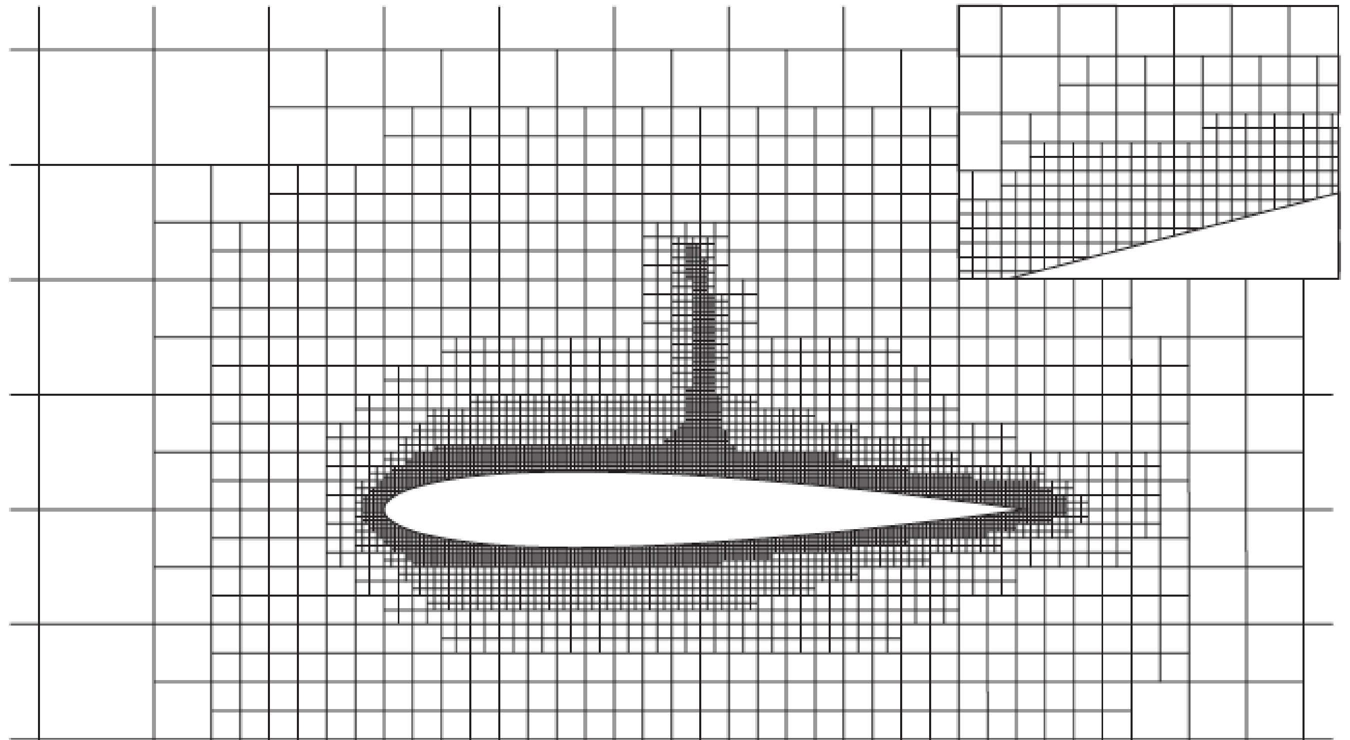


Mesh types

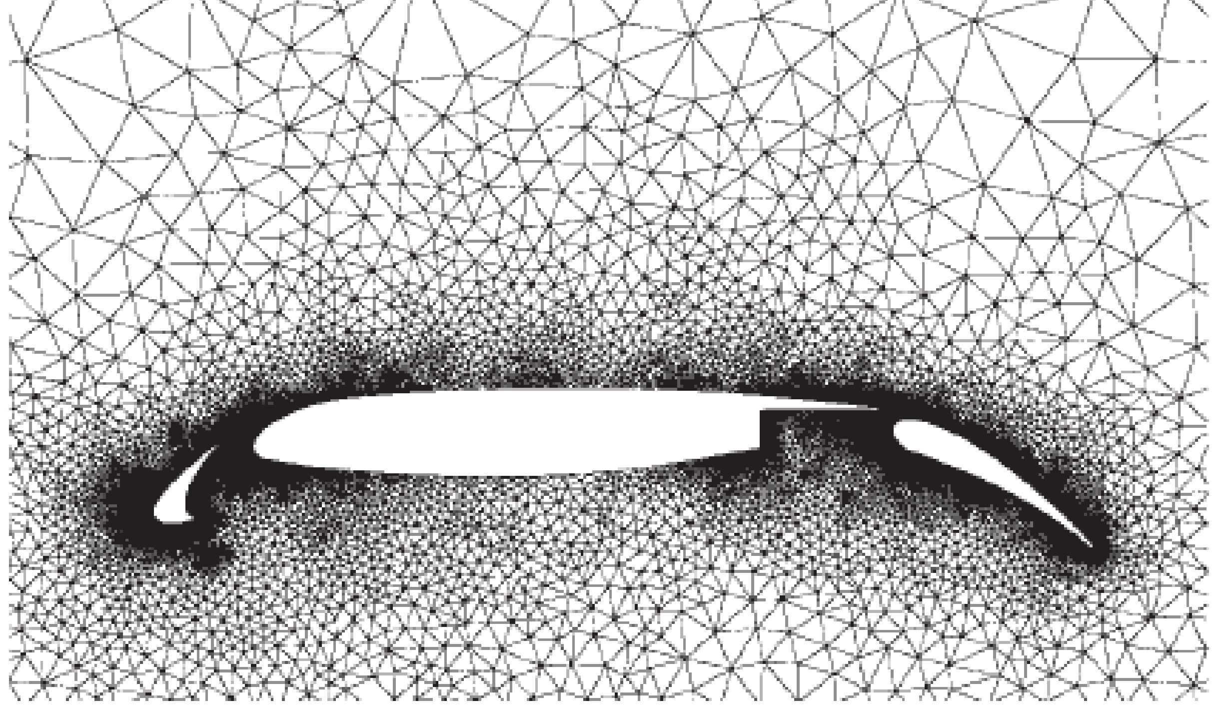


1. Block-structured mesh

   - Domain divided into subdomains (blocks), each with a structured grid.
   - More flexible, can mesh more complex geometries.
   - Easier local refinement (block-wise).
   - Special case: adaptive mesh. Recursive refinement.



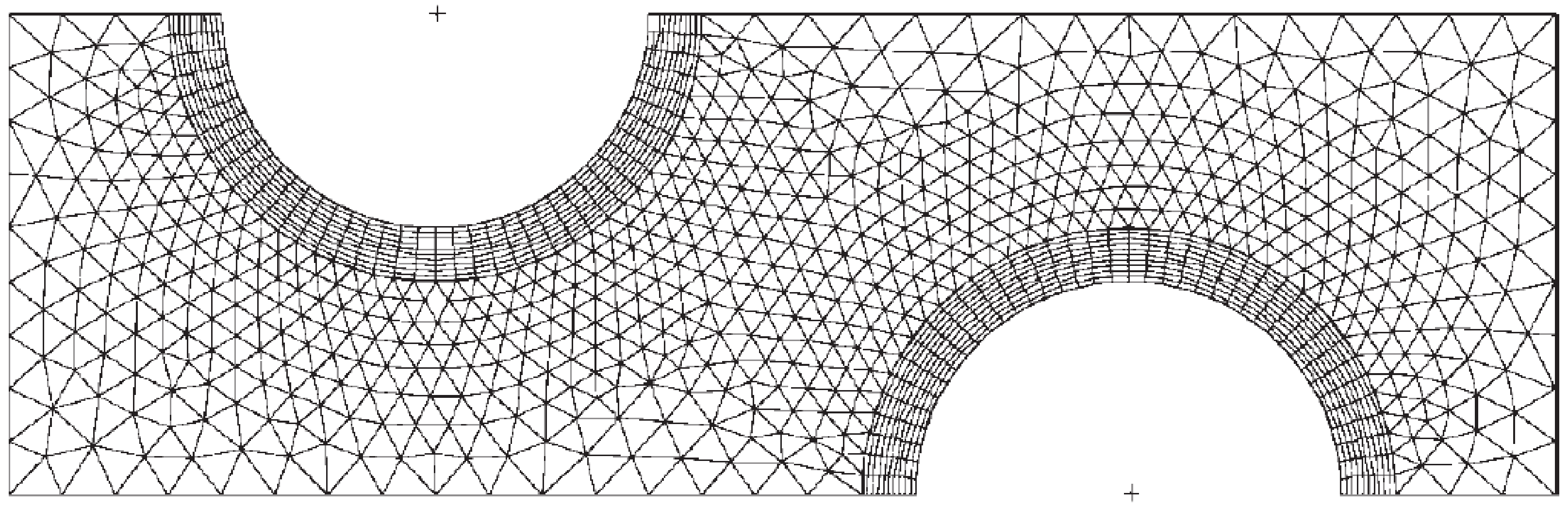
Mesh types



2. Unstructured mesh

- No structure. Arbitrary element shape, connectivity and number of neighbors.

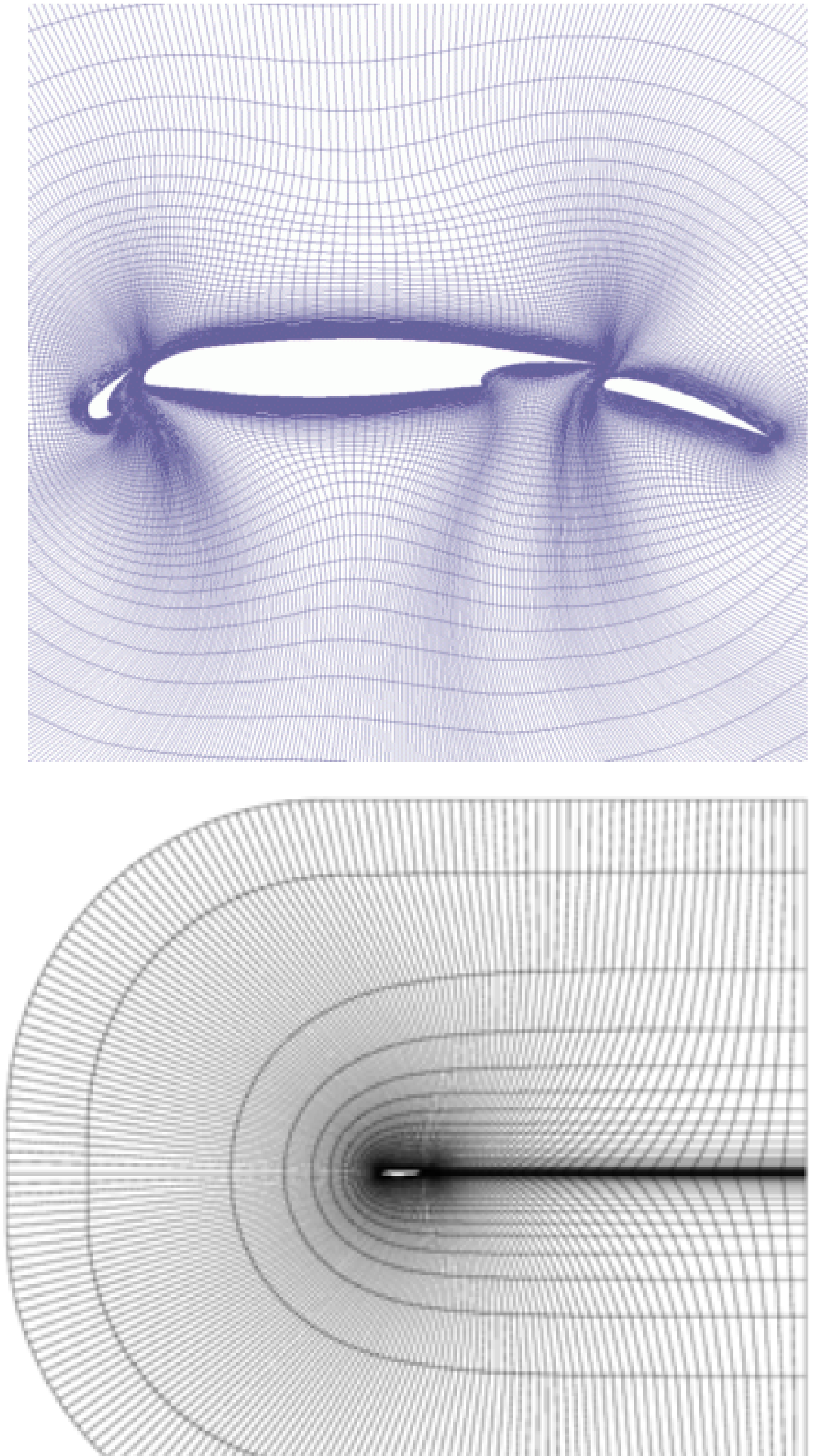
- Generally tri / tetra.
- Can also mix different shapes (hybrid mesh) to achieve better resolution and alignment where needed (with quad / hex) and still use resources efficiently. Often used for boundary layers.



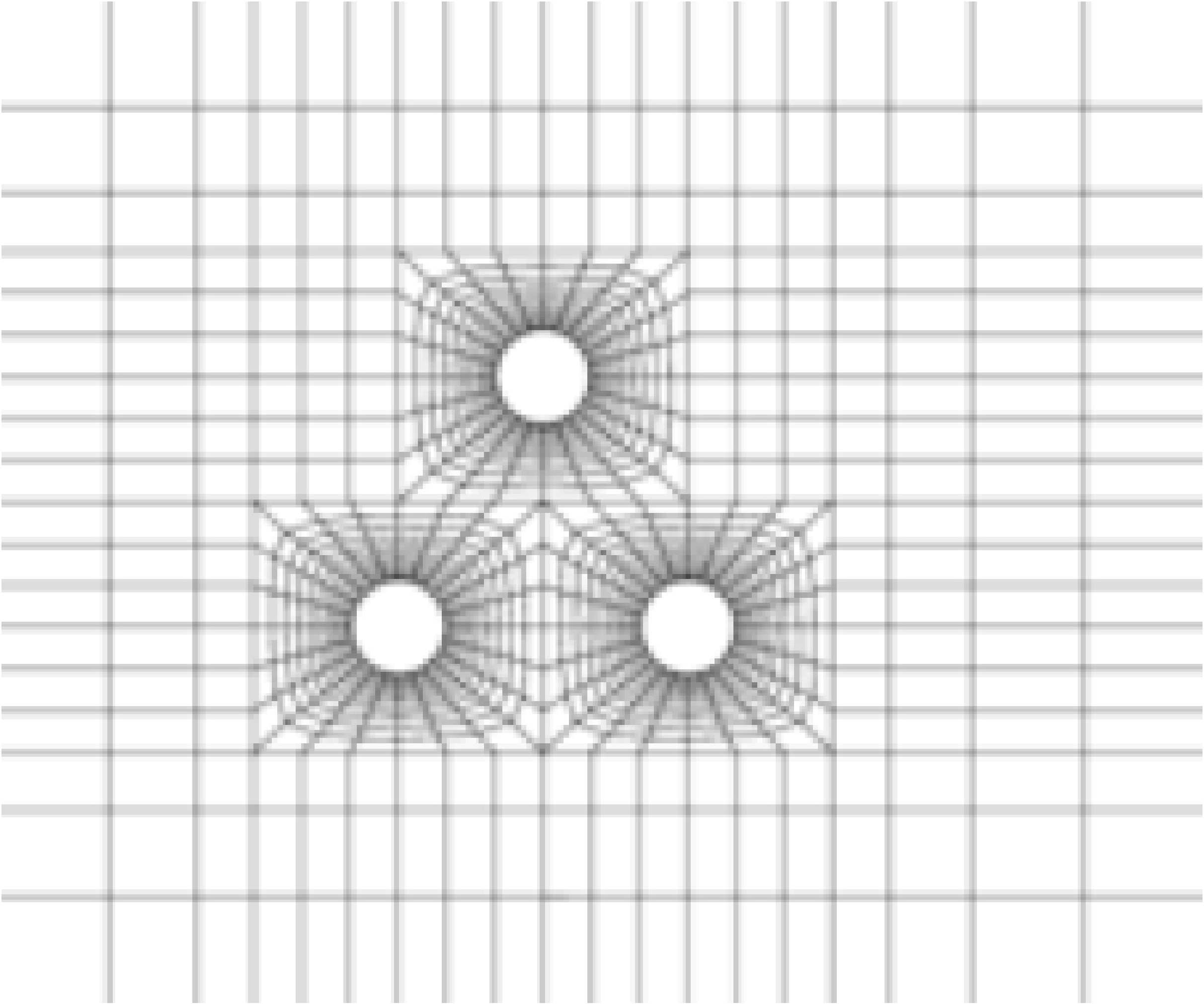
- Can mesh very complex geometries.
- Very good control of local refinement (including solution-based semi-automatic refinement).

Some 2D examples

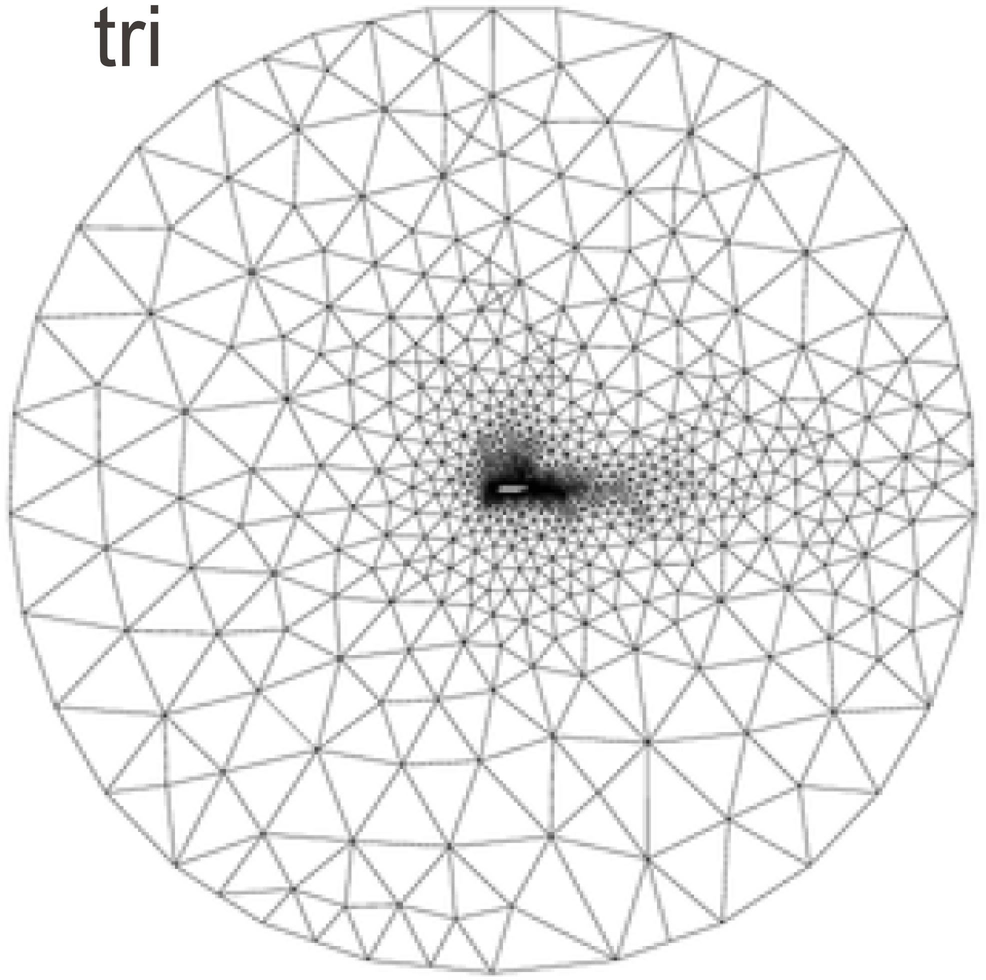
Structured, quad



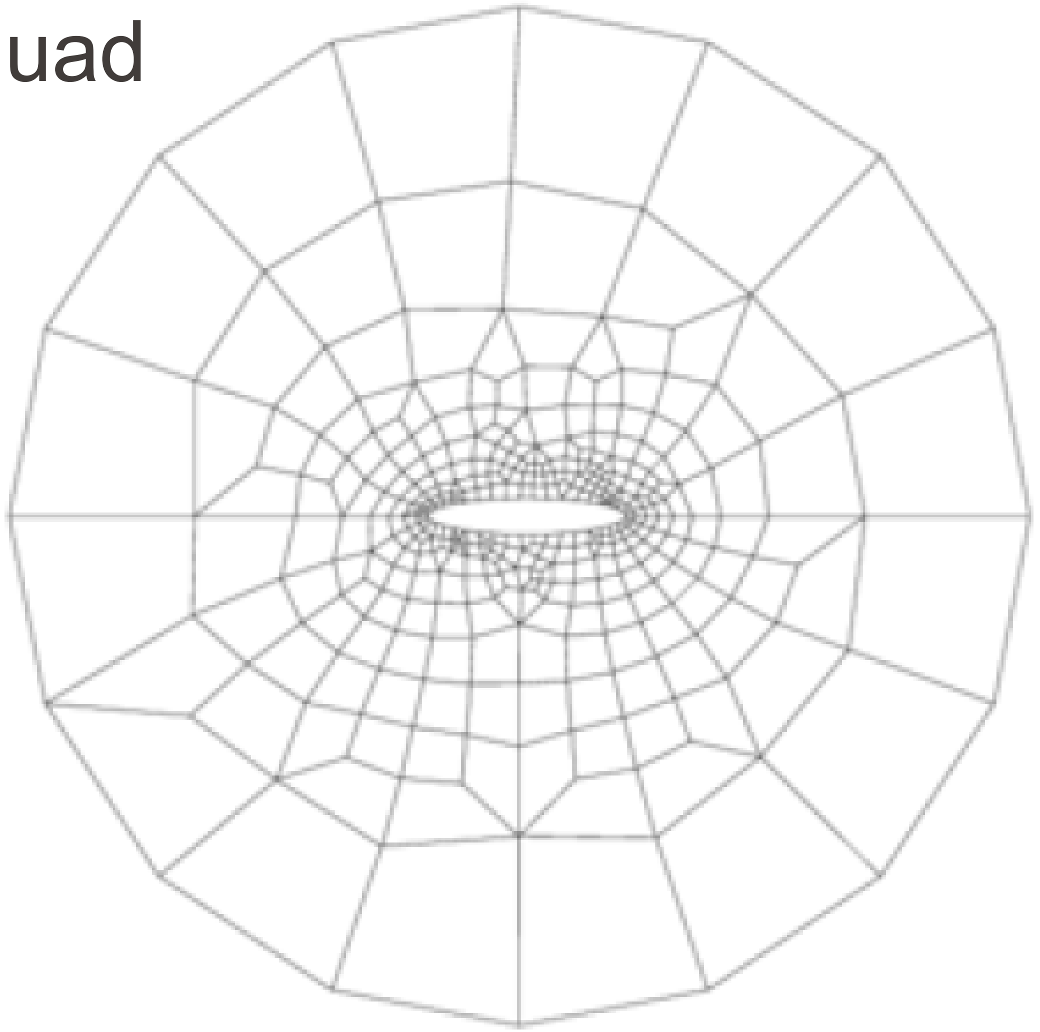
Block-structured, quad



Unstructured, tri

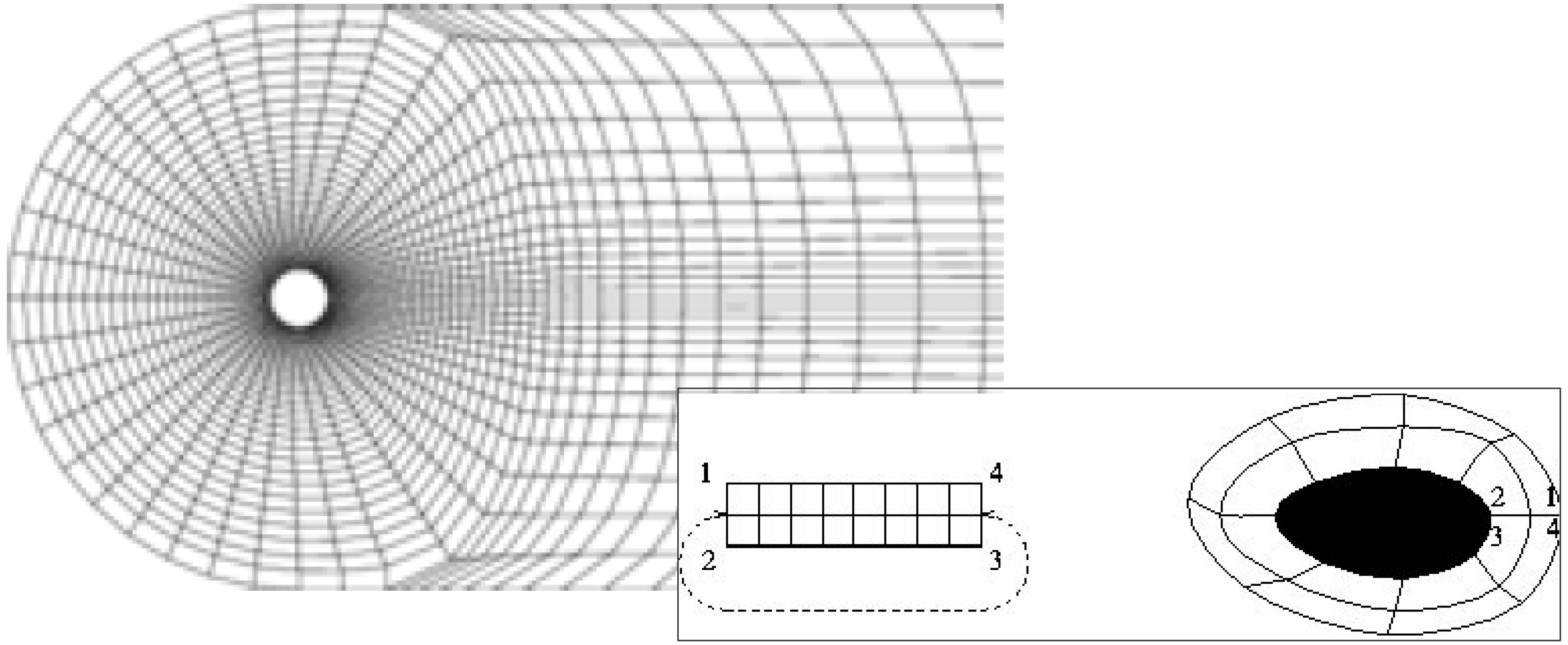


Unstructured, quad



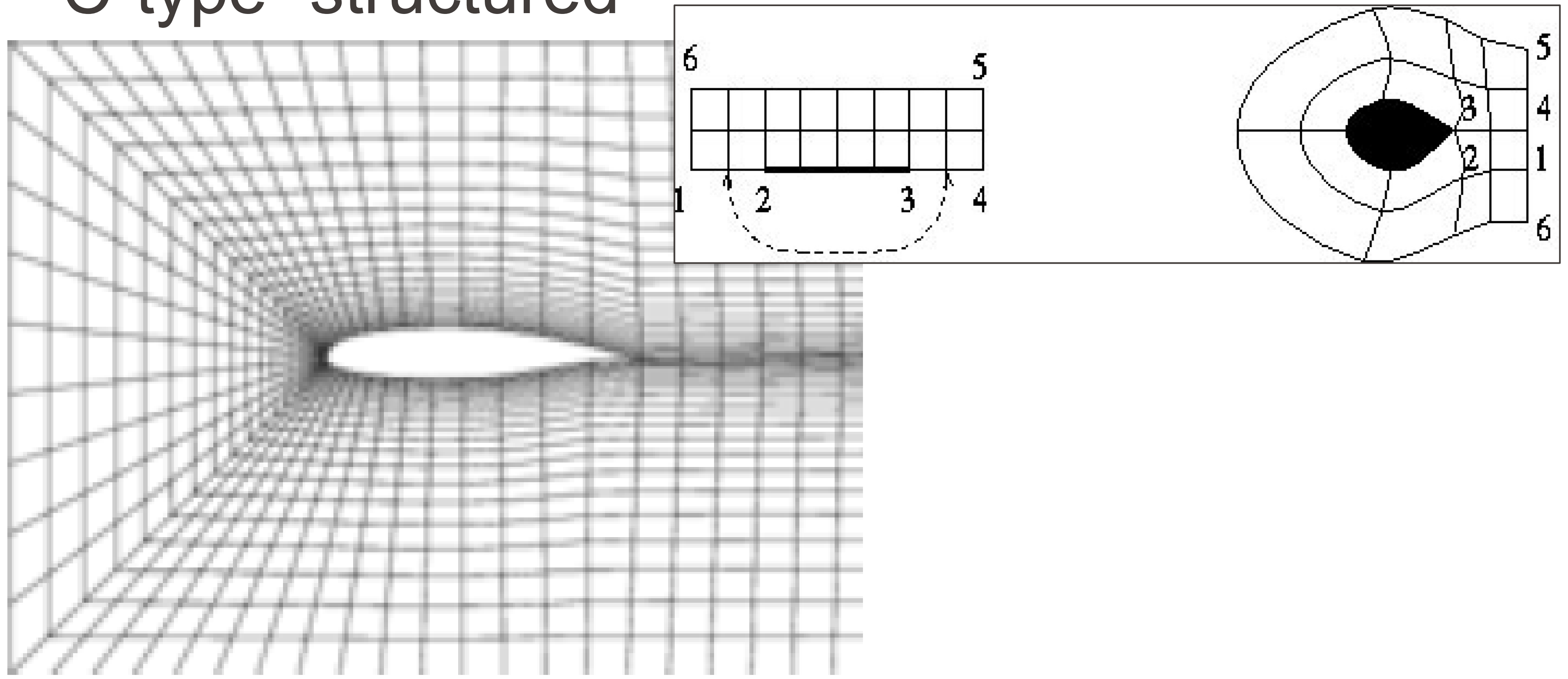
Some 2D examples

“O-type” structured

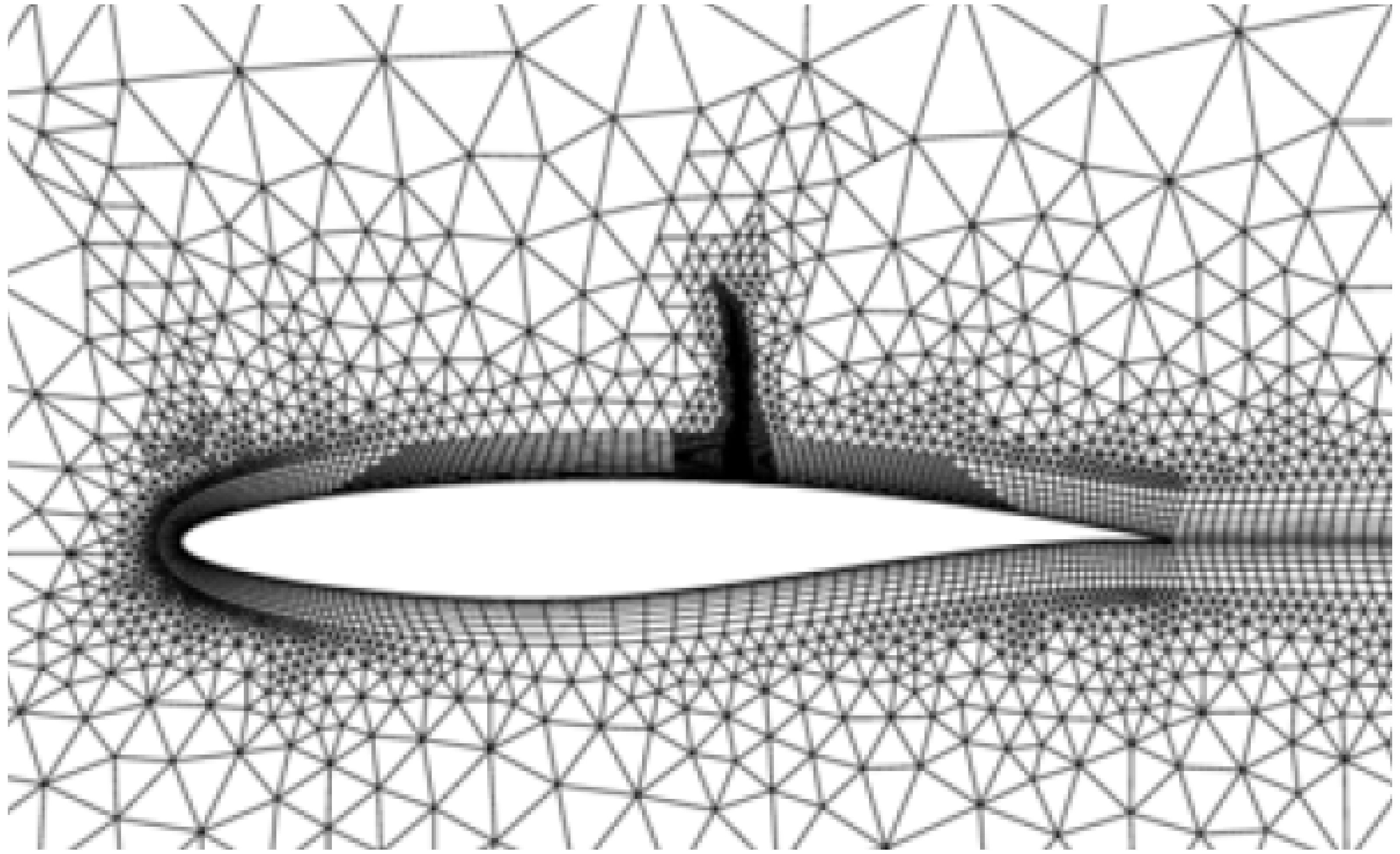


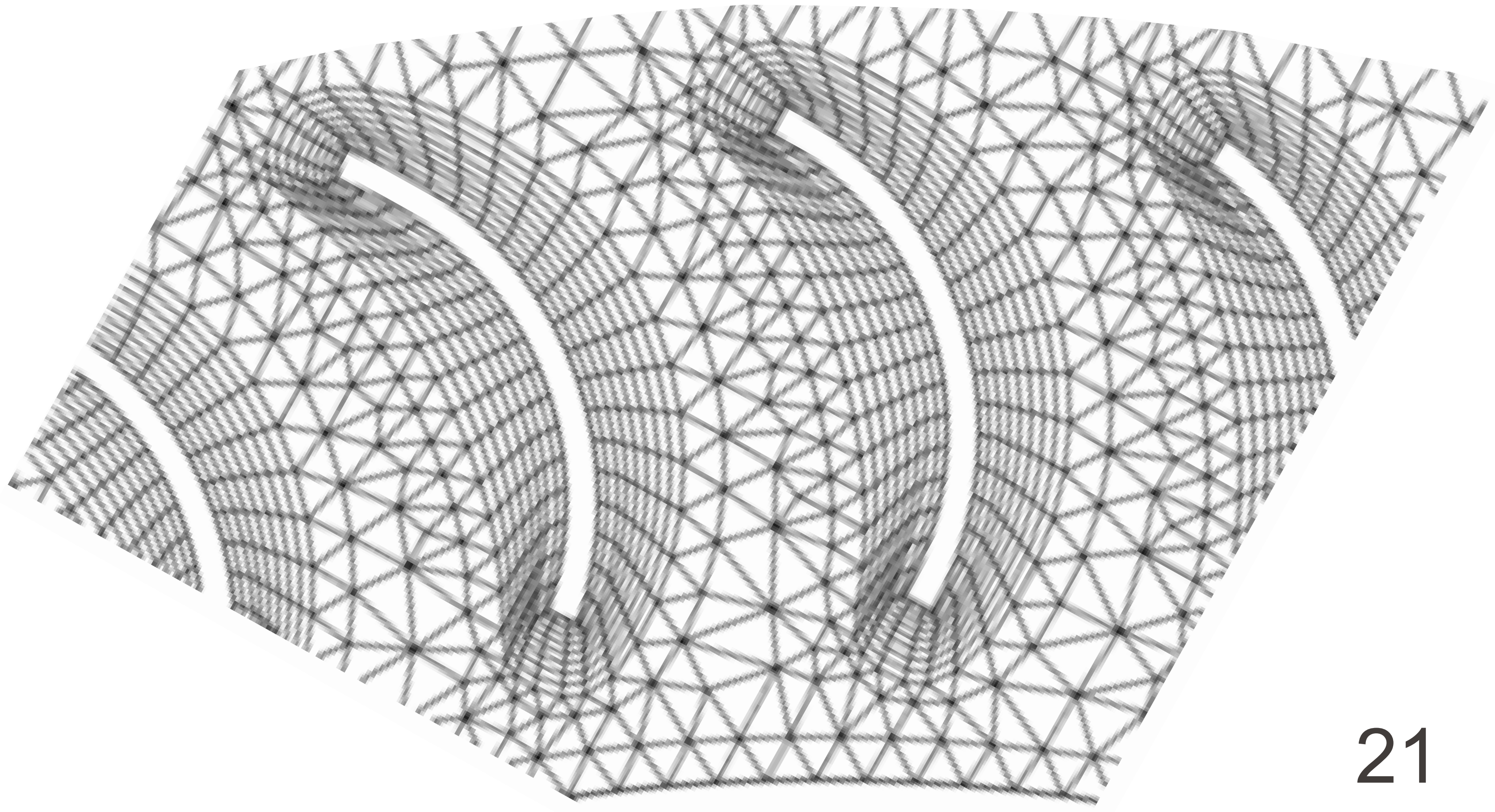
Different topologies
(different mappings
from Cartesian mesh)

“C-type” structured



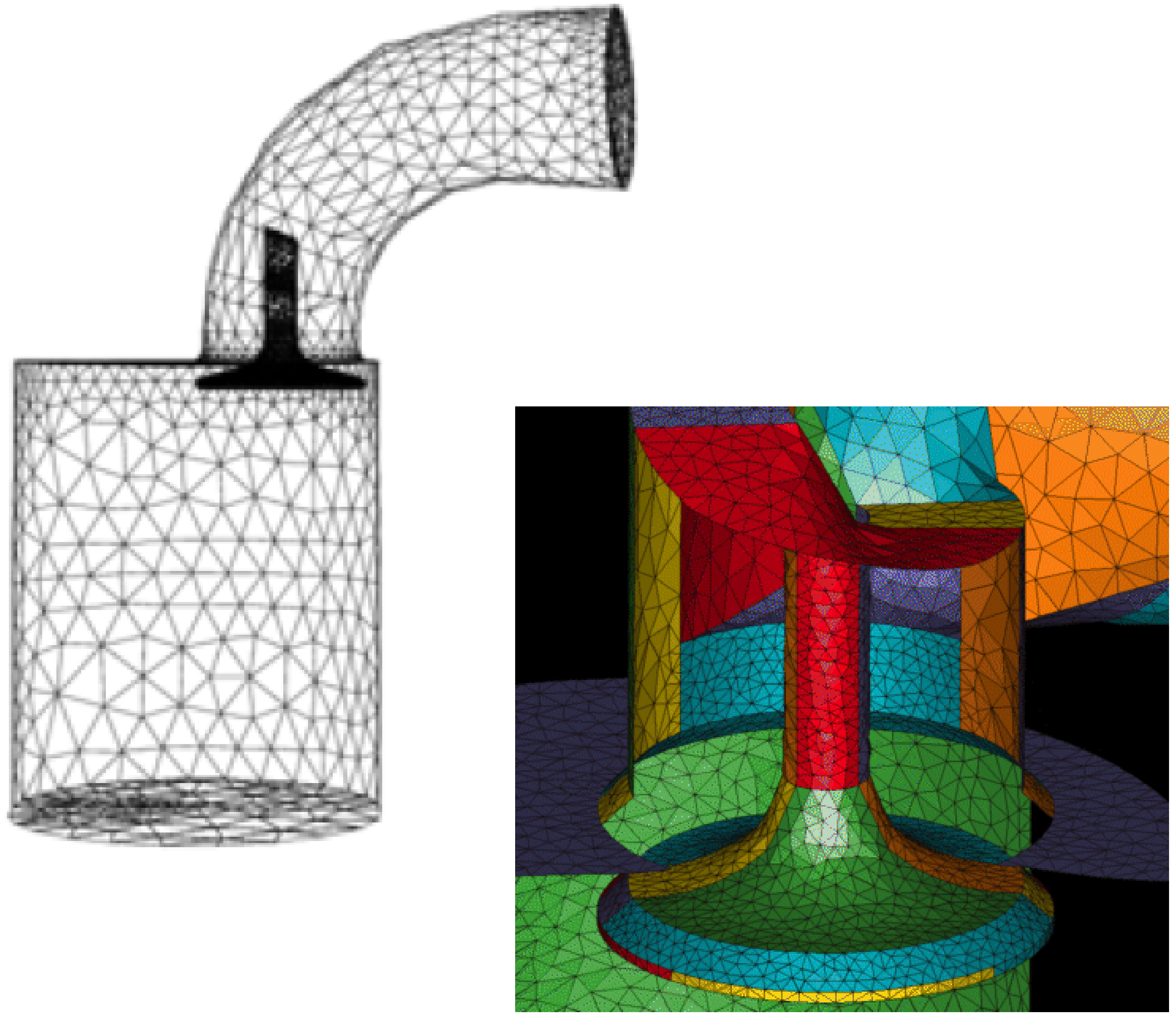
Hybrid tri/quad



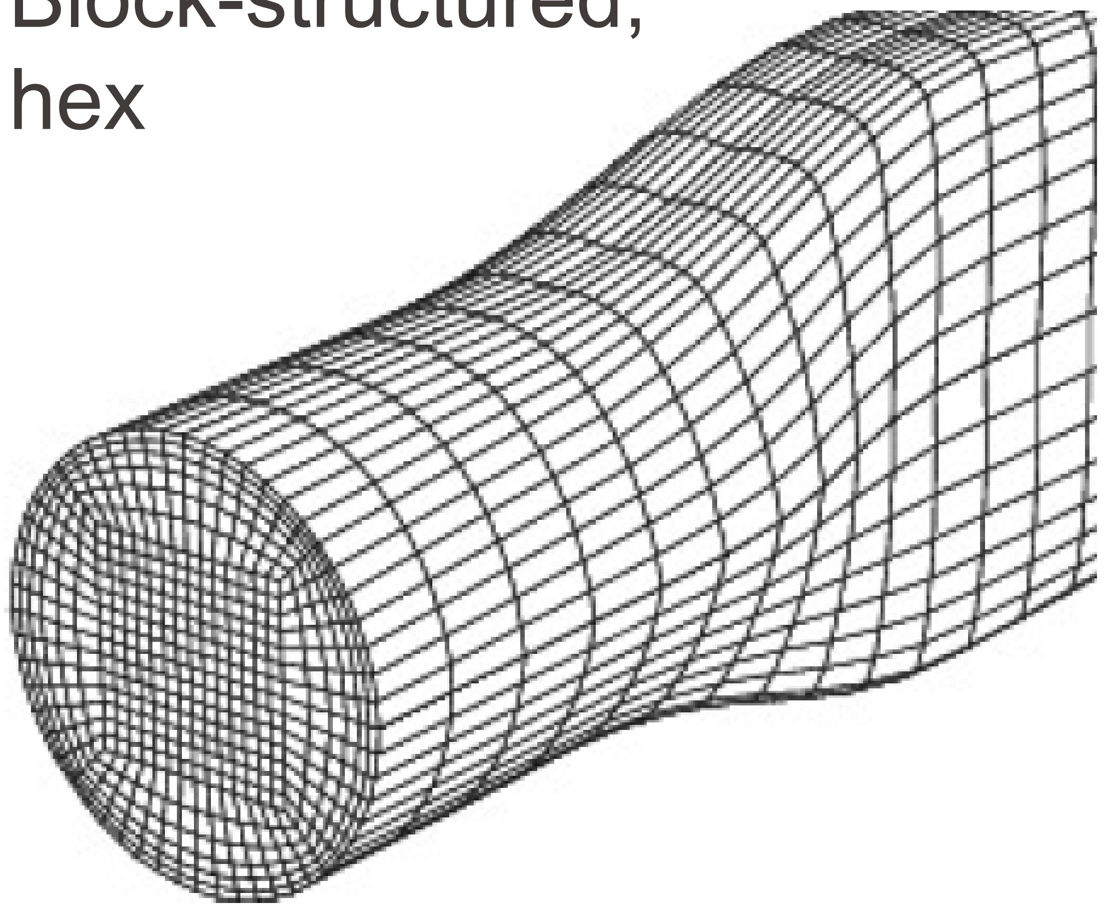


Some 3D examples

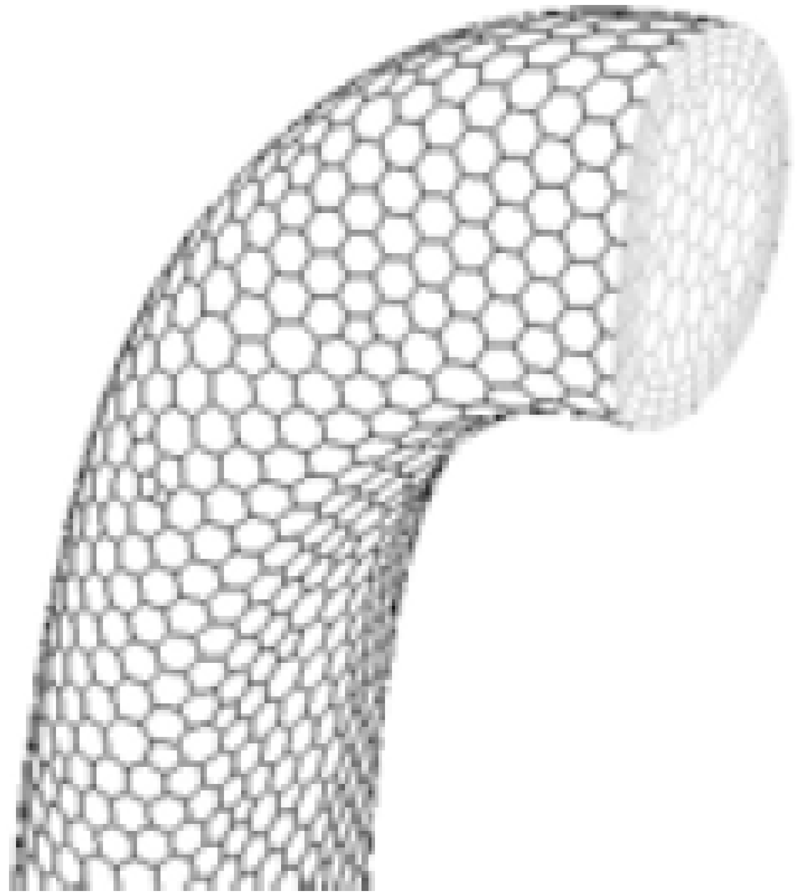
Unstructured, tetra



Block-structured, hex

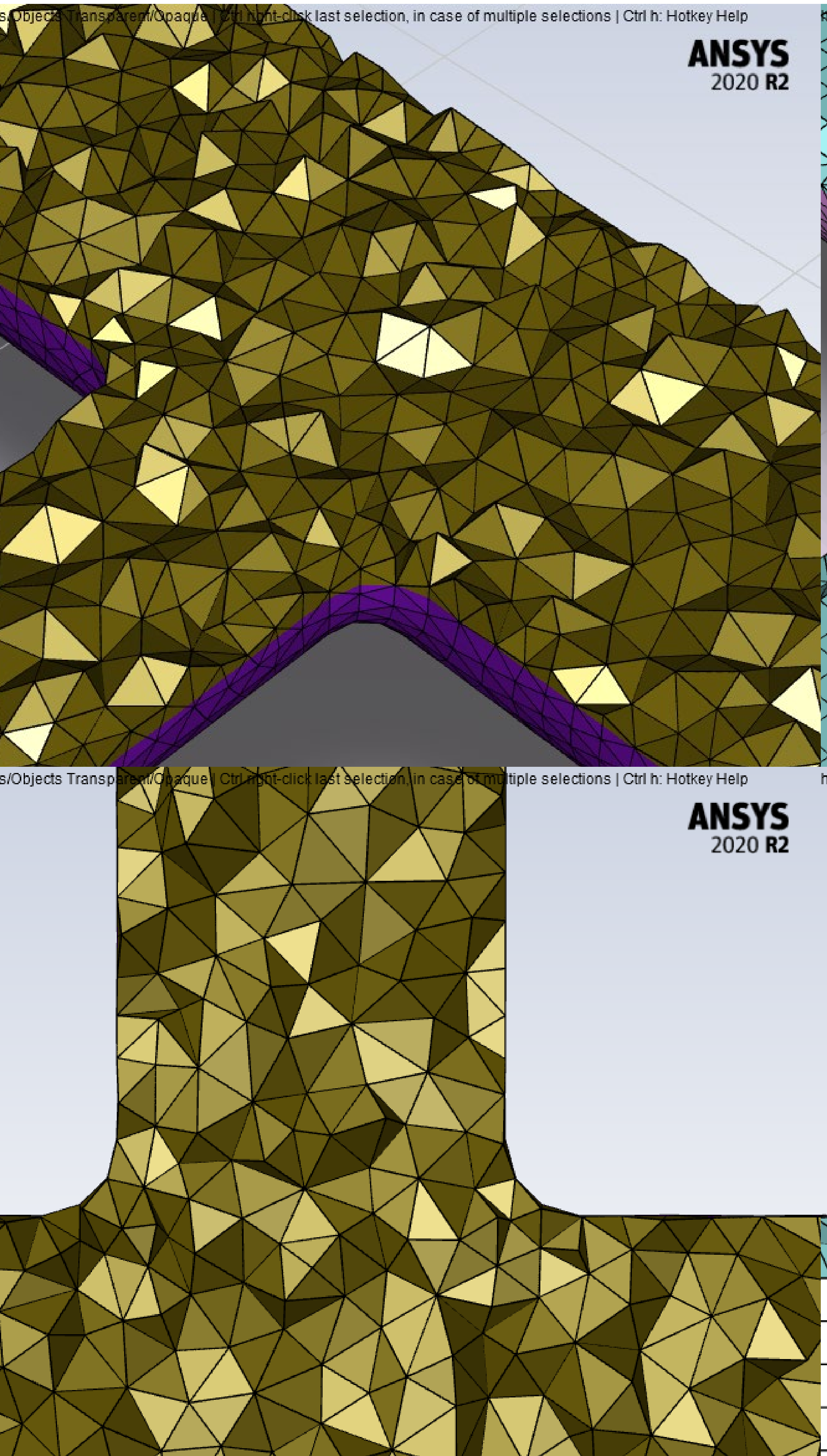


Polyhedral

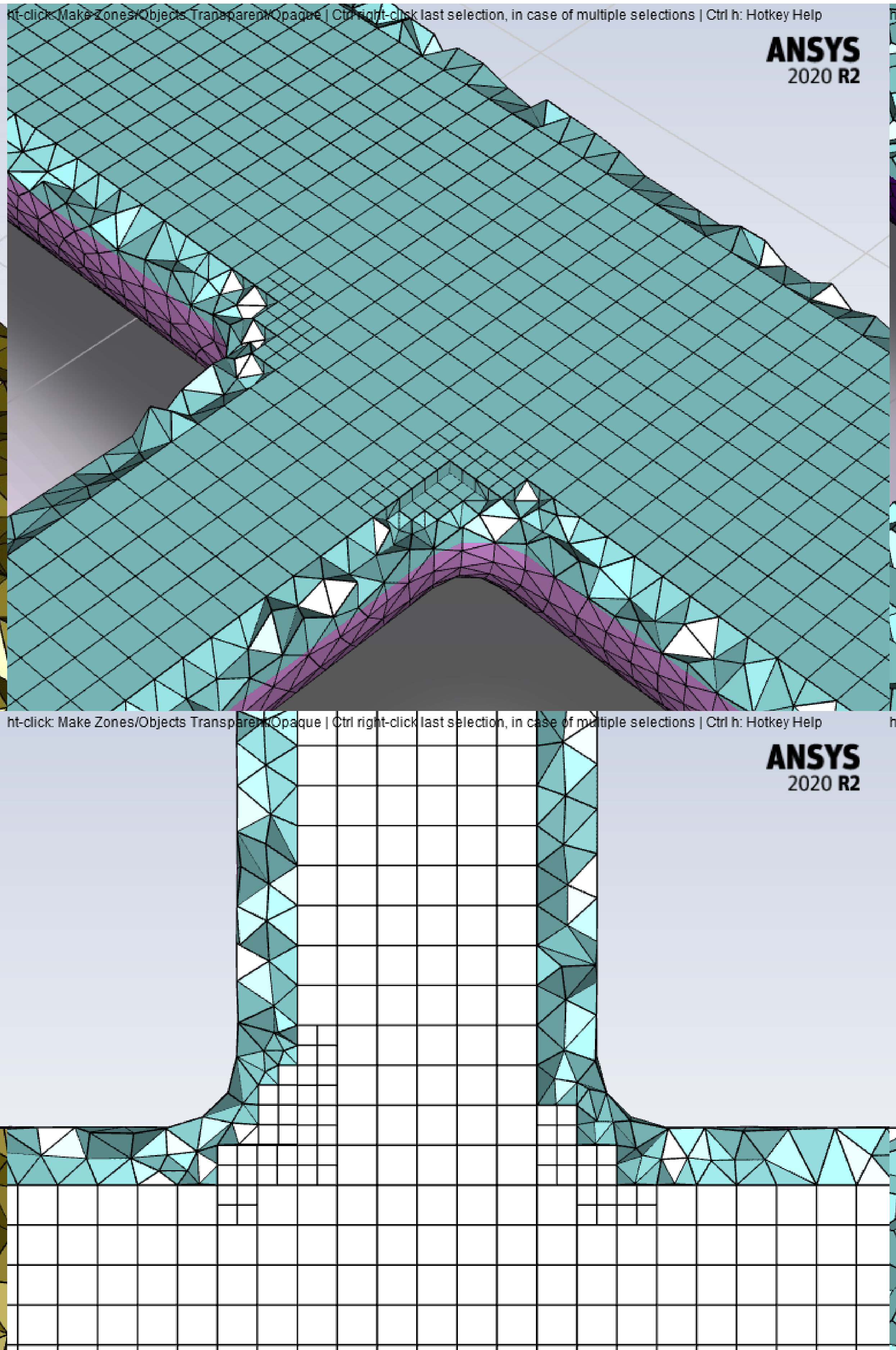


Some 3D examples

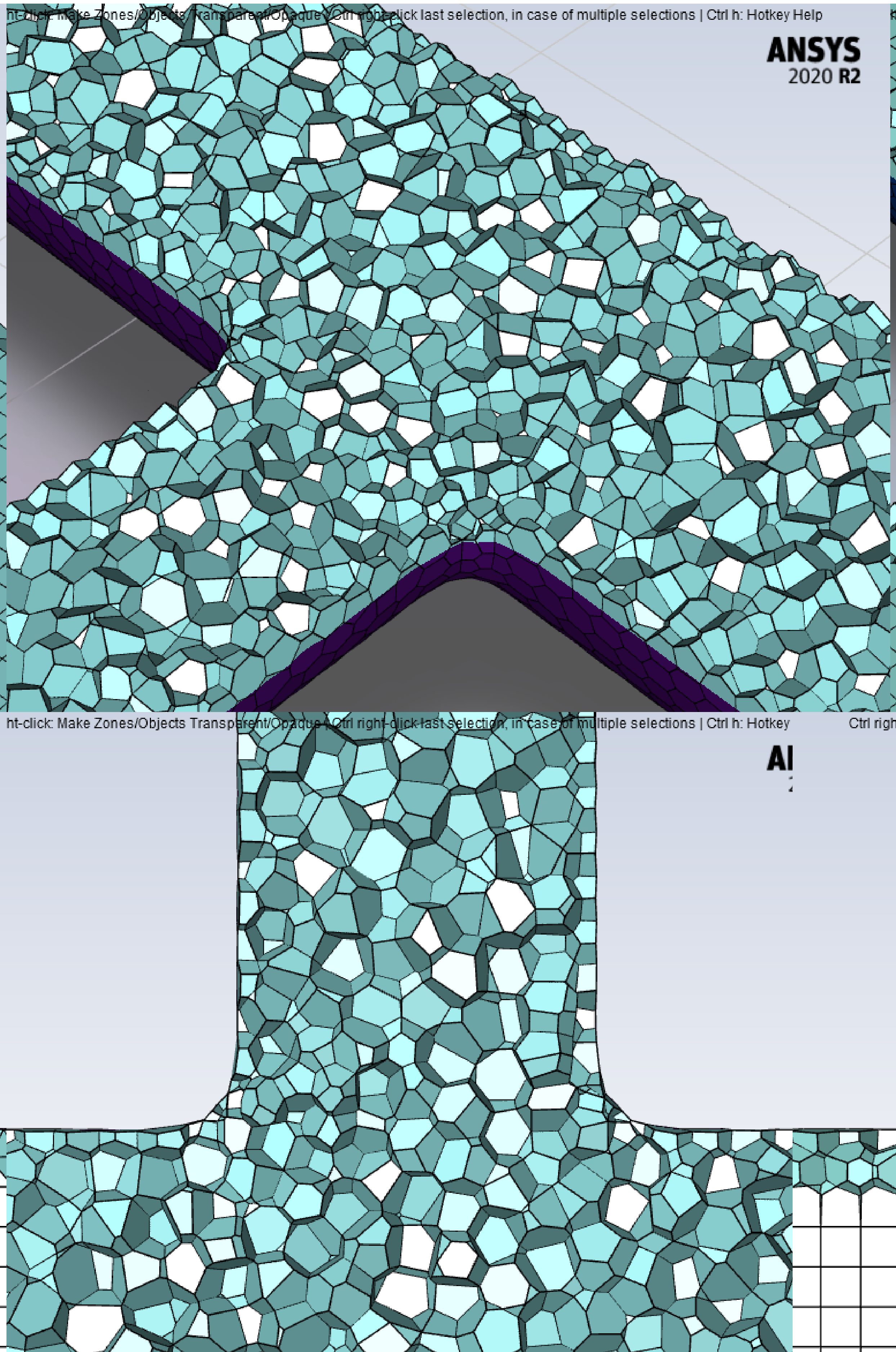
Unstructured,
tetrahedra



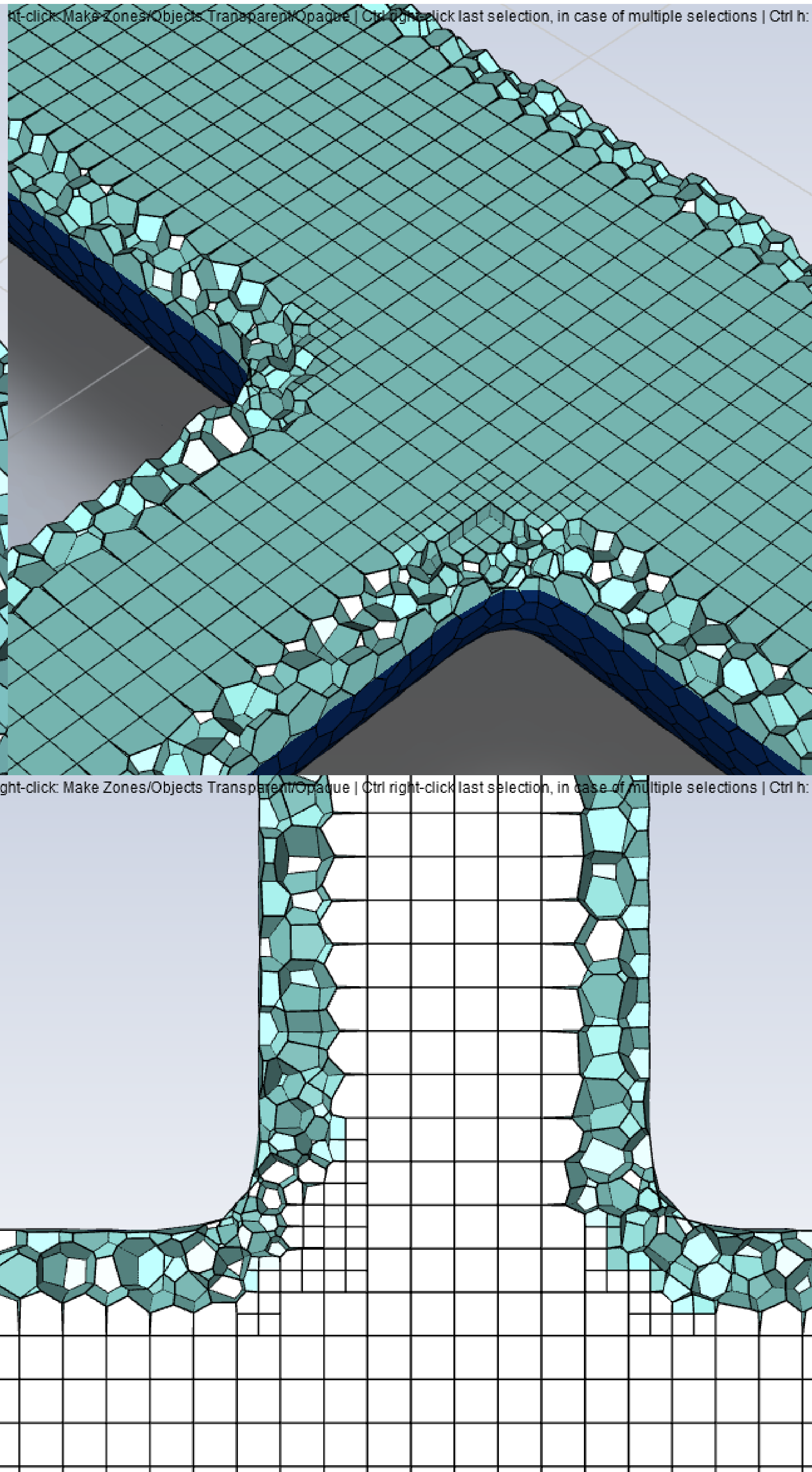
Hybrid, tetra/hexa
("hexcore")



Unstructured,
polyhedra



Hybrid, poly/hexa
("poly-hexcore")



What is a good mesh?

- Importance of:
  - Elements size: trade-off between accuracy and computational cost (time, memory).
  - Elements distribution: not all regions need the same level of details. For ex., large velocity gradients in shear layers (wake, jet, separation), boundary layers, shocks.
  - Elements shape: direct and strong impact on the solution accuracy.

- A “good mesh” should:
  - Be as coarse as possible, but as fine as necessary.
  - Use physically/numerically suitable element shapes (may differ in different regions).

- No written theory about mesh generation, no universally accepted definition of a good mesh. Rather a set of good standard practices.
- Meshing requires experience.

What is a good mesh?

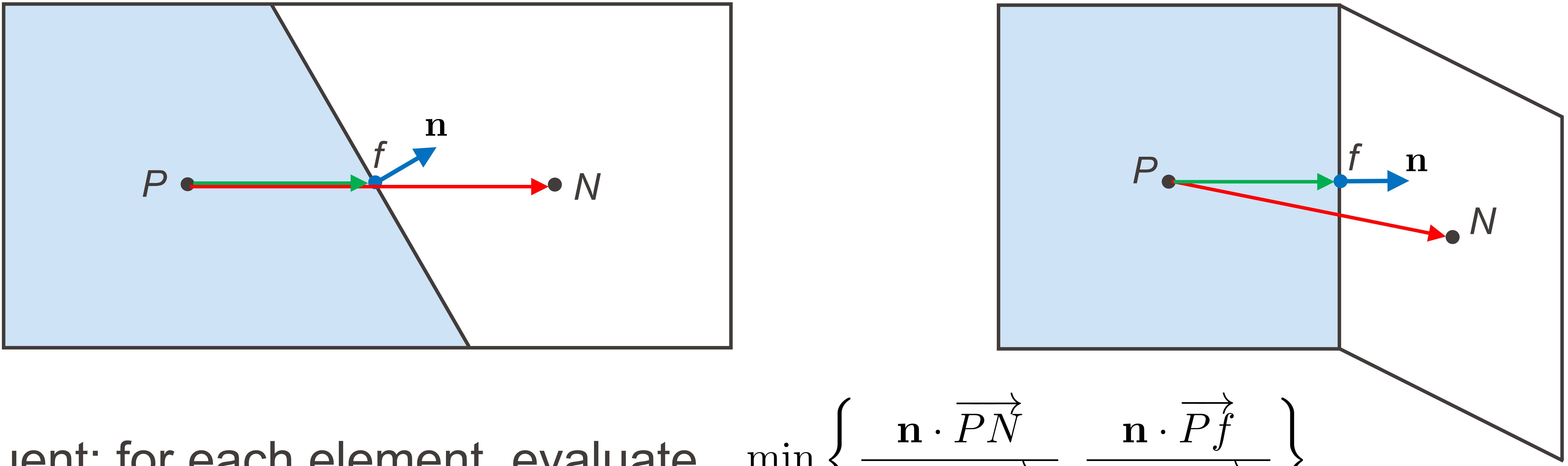
- Qualitative (subjective) rule of thumb: elements shape and distribution should be pleasing to the eye. (Strong element distortion and spatial variation to be avoided.)

- Quantitative criteria: mesh quality metrics. Significant role in accuracy and stability of the computation. For example:
    - Size
    - Orthogonality
    - Skewness
    - Aspect ratio
    - Smoothness
    - …

- Should always evaluate these metrics to assess the mesh quality. (If not to aim for an exceptionally good mesh, at least to avoid a bad mesh.)

Mesh quality metrics: orthogonality

- For each face, alignment between face normal vector **n** and vector *PN* (from node to neighbor node) or vector *Pf* (from node to face center).



- Fluent: for each element, evaluate

$$\min_{\text{faces}} \left\{ \frac{\mathbf{n} \cdot \overrightarrow{PN}}{||\mathbf{n}||\;||\overrightarrow{PN}||}, \frac{\mathbf{n} \cdot \overrightarrow{Pf}}{||\mathbf{n}||\;||\overrightarrow{Pf}||} \right\}$$

  (0: worst, 1: best)

- Non-orthogonality affects the convective and diffusive terms, and adds numerical diffusion.

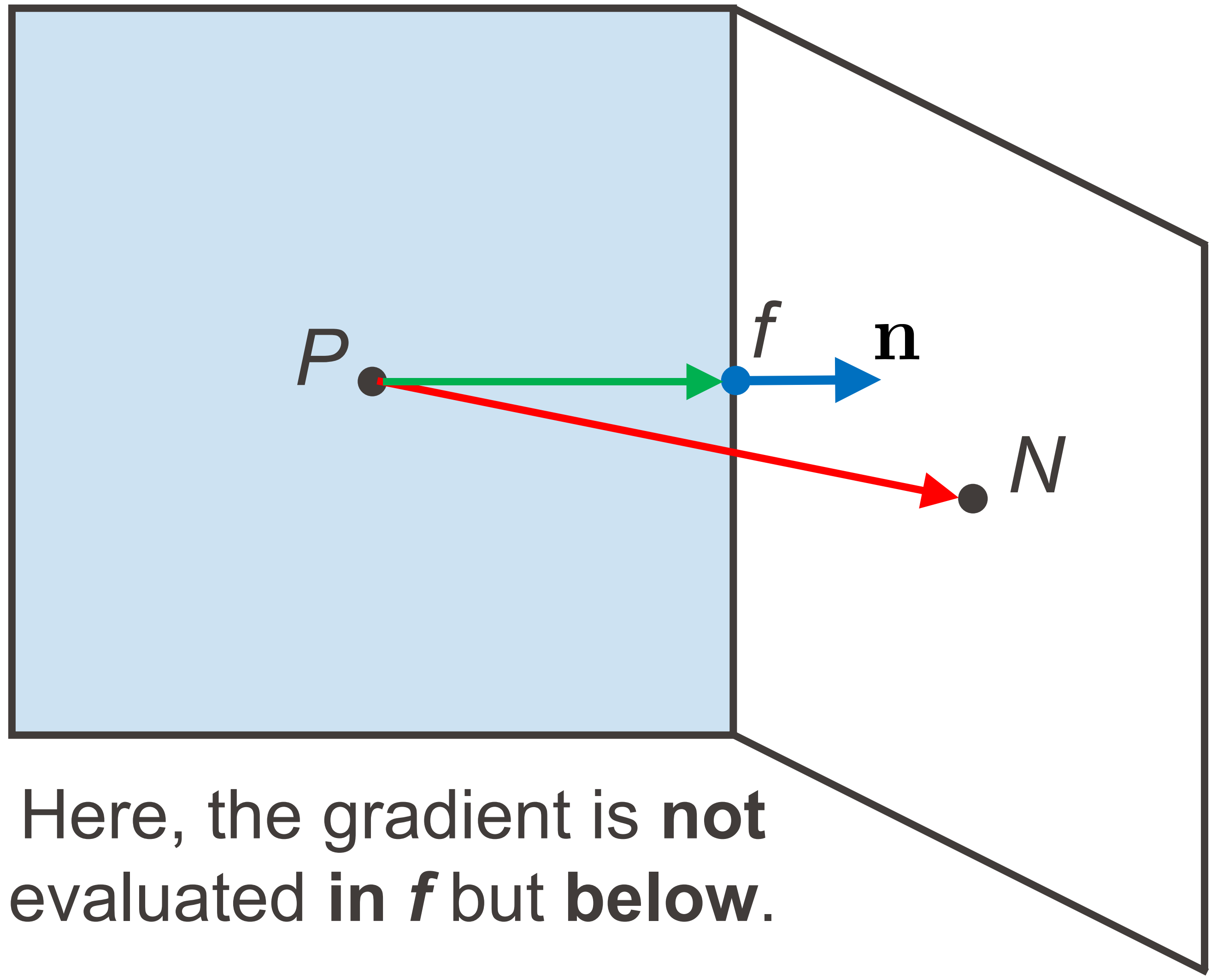
Mesh quality metrics: orthogonality

- For instance, the diffusive terms can be discretized with central differencing as:

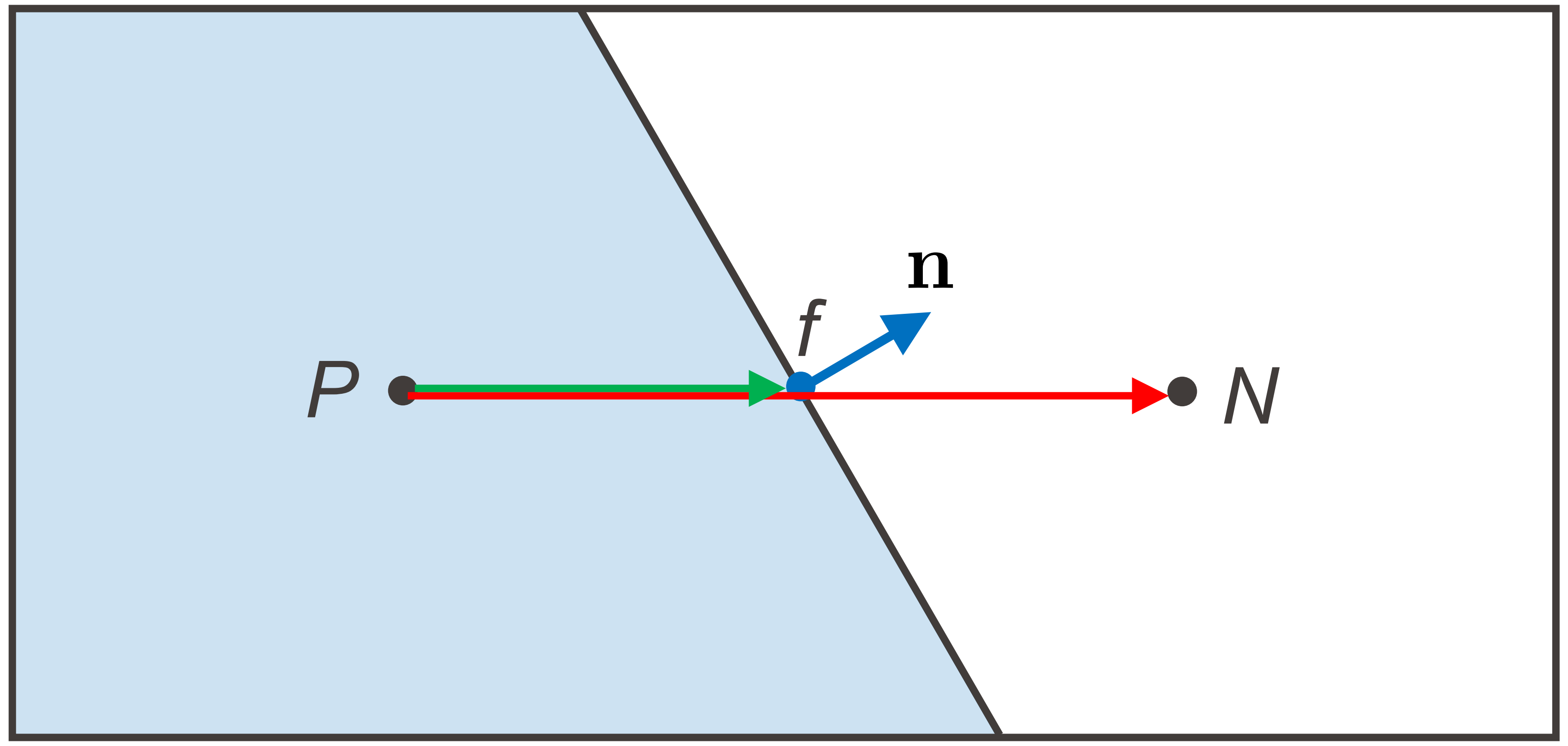
$$\int_{A_i} grad(\phi)\cdot \mathbf{n}\, dA \approx grad(\phi)|_f \cdot \mathbf{n}\, A_i \approx \frac{\phi_N - \phi_P}{||\overrightarrow{PN}||} A_i$$

2nd-order midpoint rule: accurately represented by this CD scheme only if *PN* intersects face at *f*

This CD scheme accurately represents normal gradient only if **n** aligned with *PN*



Here, the gradient is **not** evaluated **in *f*** but **below**.



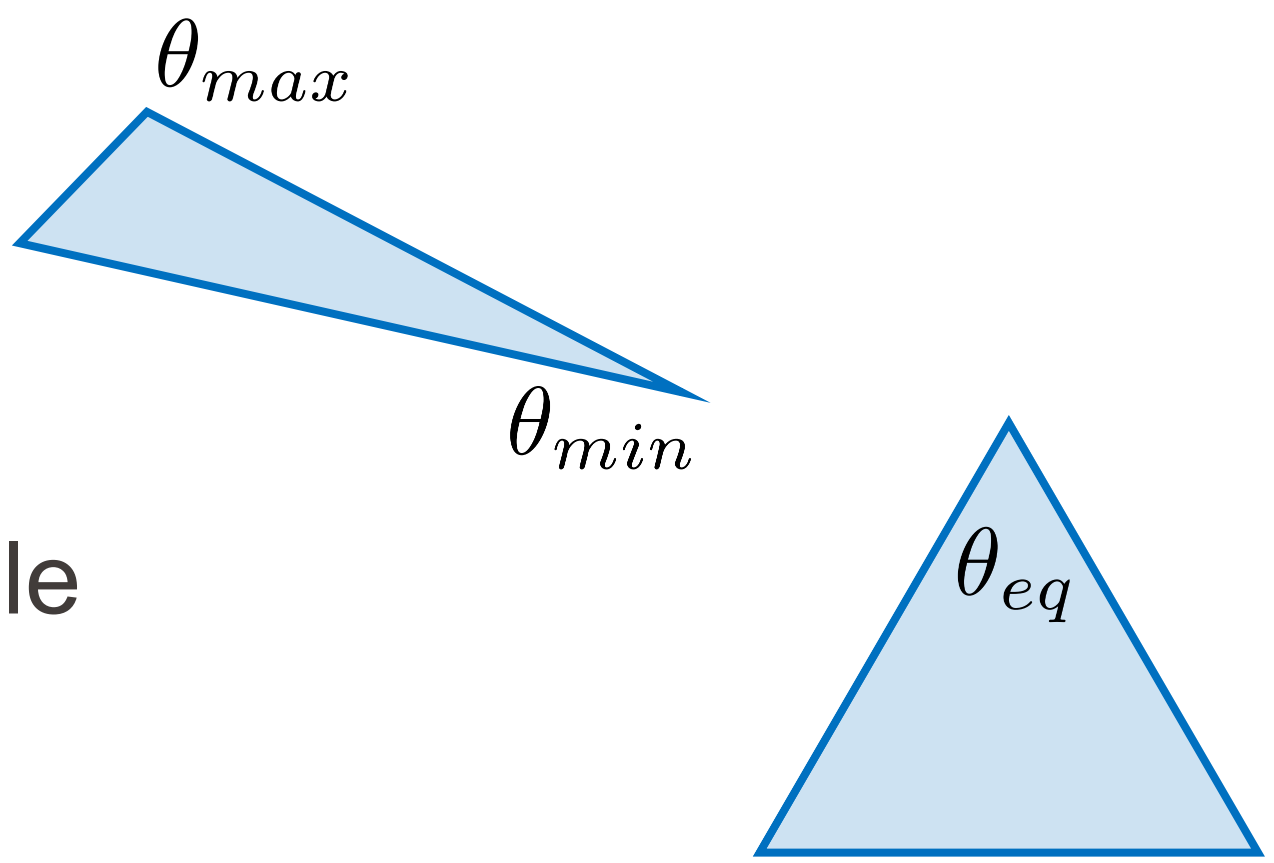
Here, the evaluated gradient is **not the normal gradient**.

Mesh quality metrics: skewness

- Deviation from equilateral element. For example:

$$\max\left\{\frac{\theta_{max}-\theta_{eq}}{180^\circ-\theta_{eq}}, \frac{\theta_{eq}-\theta_{min}}{\theta_{eq}}\right\}$$

where θ_{eq} is the characteristic equilateral angle (90° for quad / hex, 60° for tri / tetra)



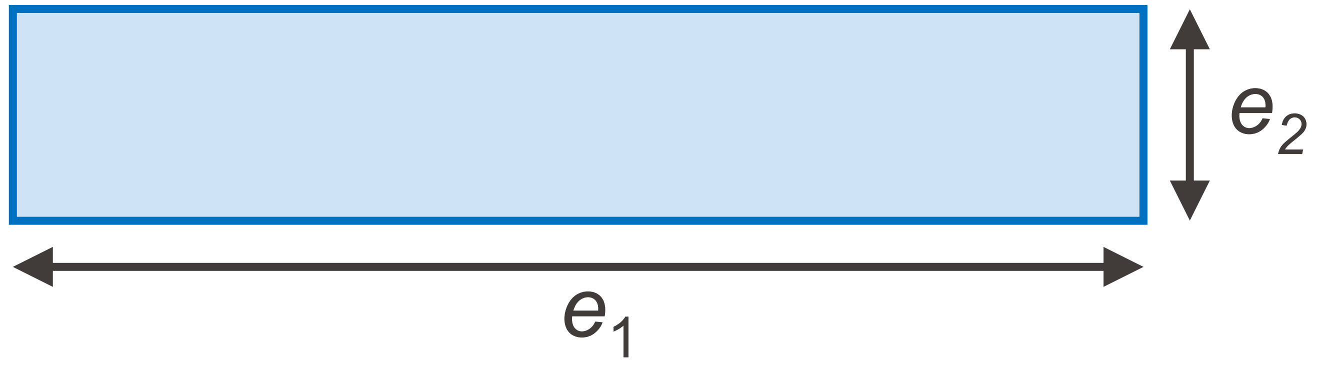
(0: best, 1: worst)

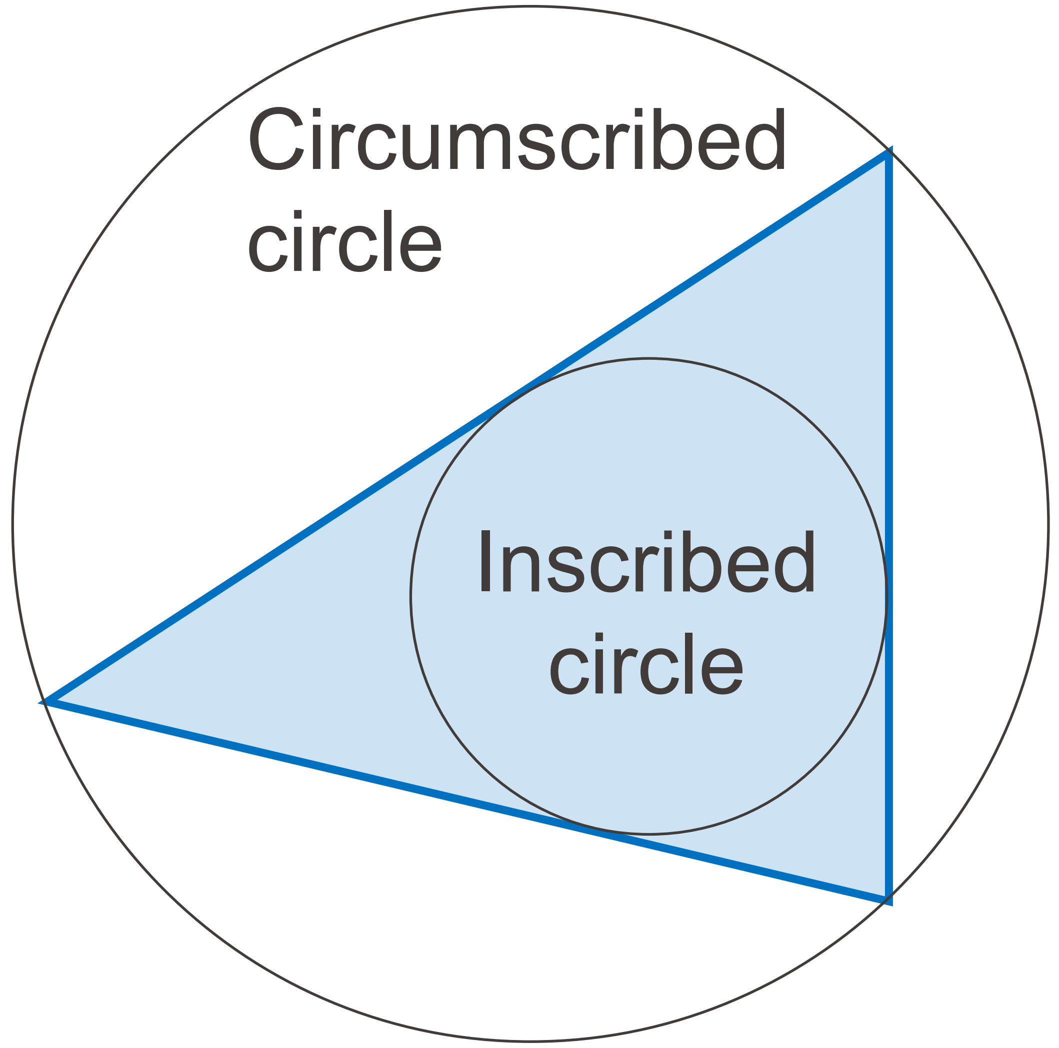
- Large skewness can lead to convergence difficulties.

Mesh quality metrics: aspect ratio (AR)

- Measure of element stretching.
  - Quad / hex: ratio of longest to shortest side $\frac{\max(e_i)}{\min(e_i)}$
  - Tri / tetra: ratio of circumscribed/inscribed circles radii $\propto \frac{R}{r}$

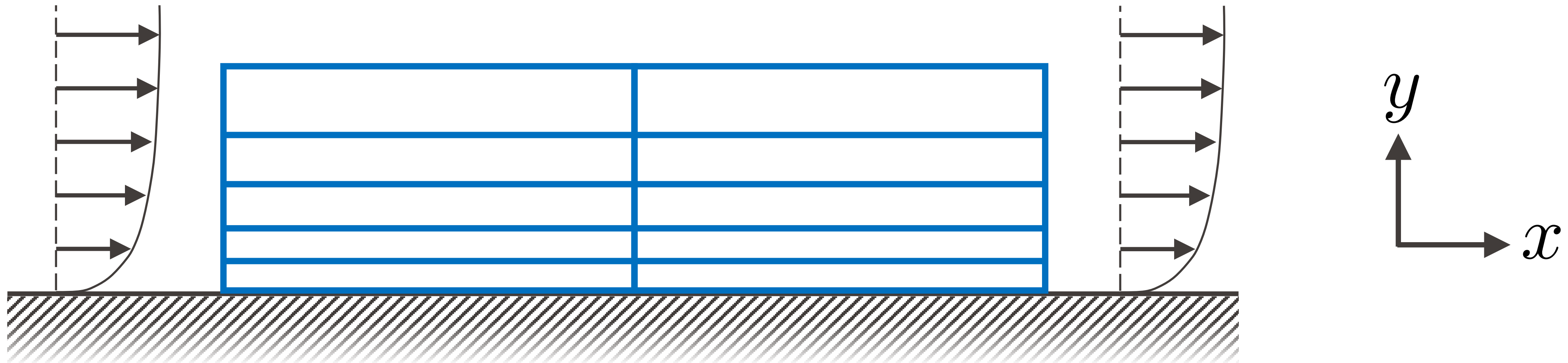
  (>>1: poor, 1: best)





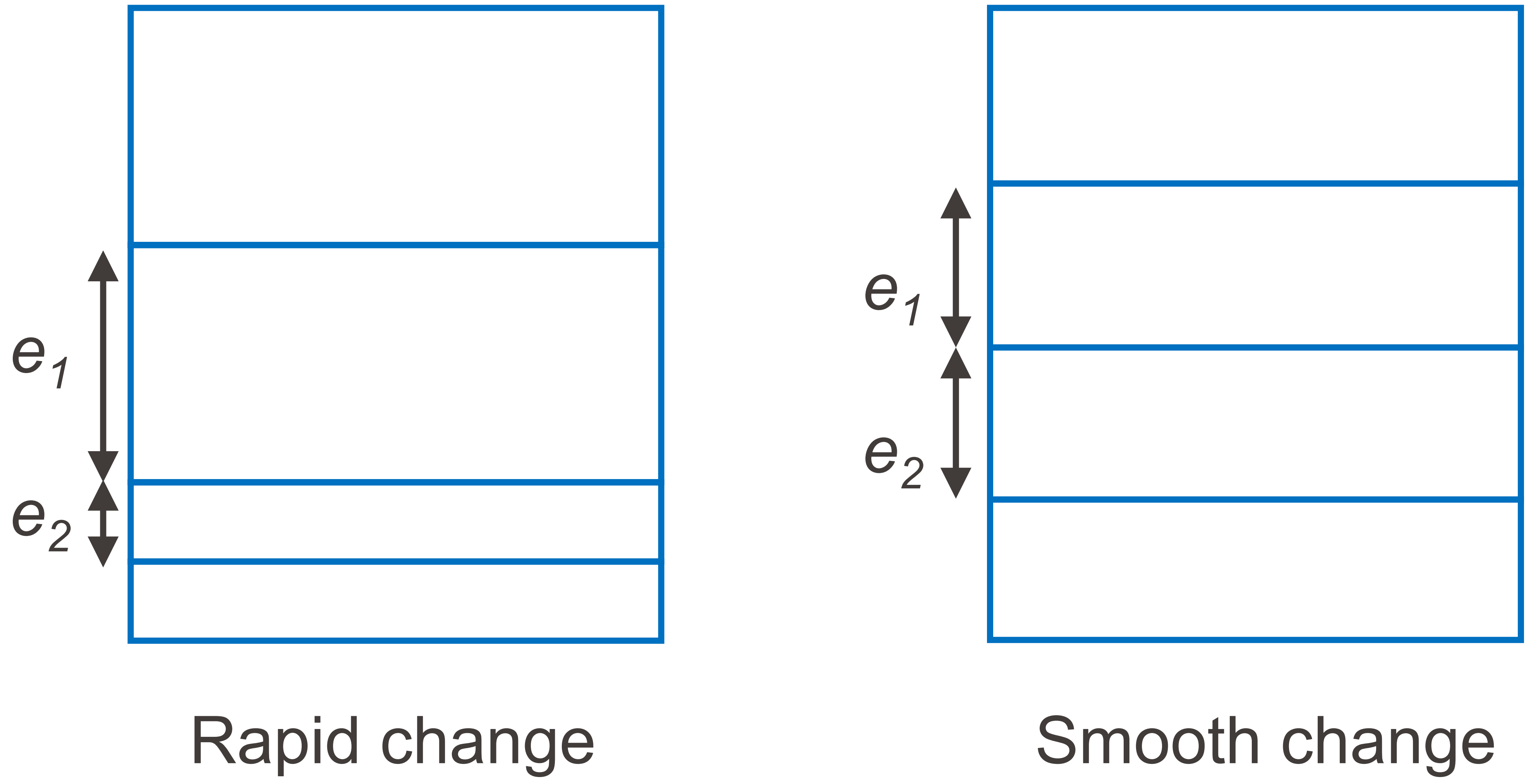
- Large AR smear gradients.
- Large AR good if small gradient in the long direction
  → good to use stretched quad / hex / prism elements aligned with the flow direction for highly anisotropic flows (e.g. boundary layers).

$$\phi_f = \phi_P + \frac{\partial \phi}{\underset{\underset{\text{small}}{\uparrow}}{\partial x}}\Delta x + \frac{\partial \phi}{\partial y}\underset{\underset{\text{small}}{\uparrow}}{\Delta y} + O(\Delta^2)$$



Mesh quality metrics: smoothness

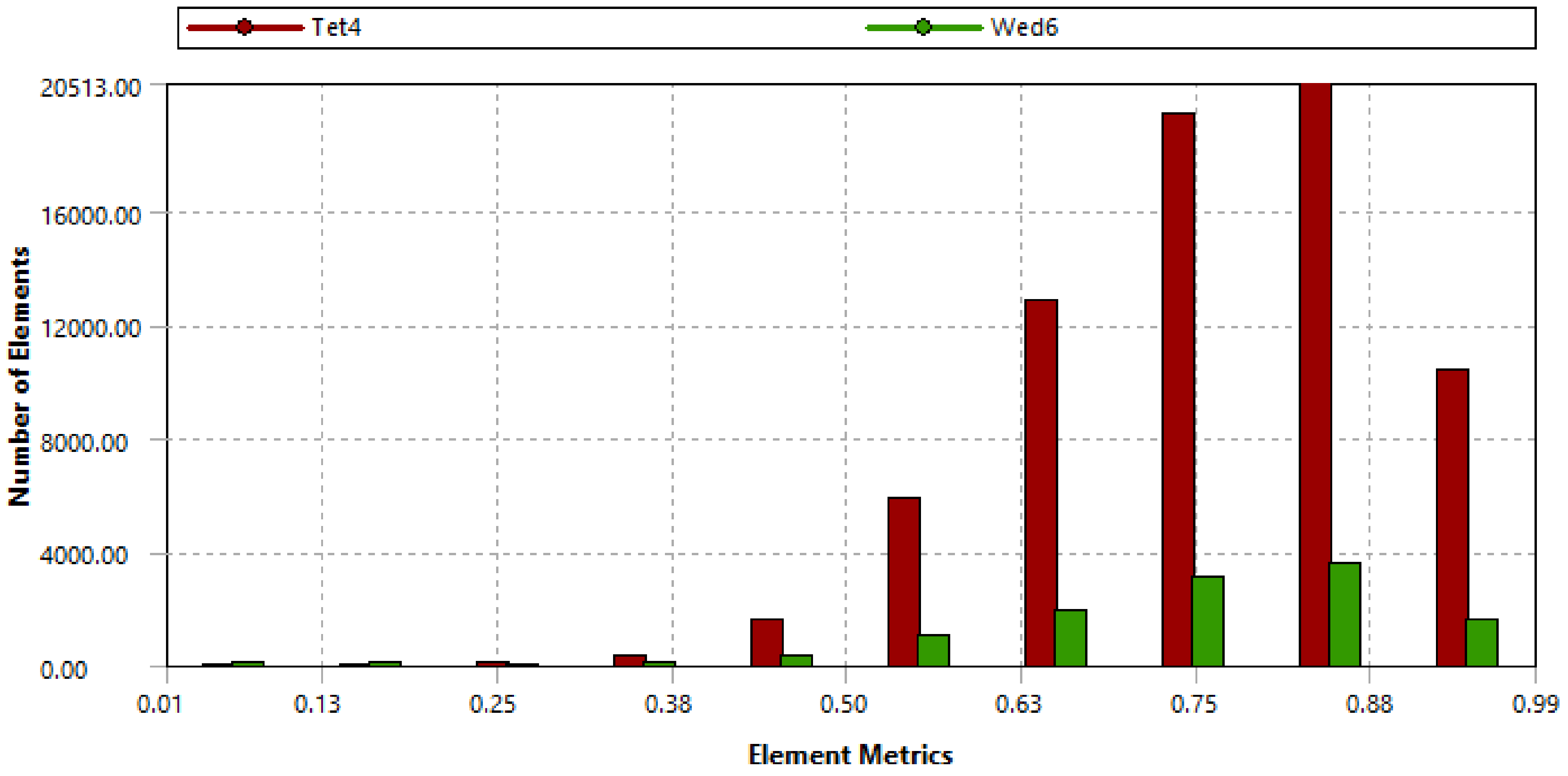
- Or “expansion rate”, “growth factor”, “uniformity”…
- Measure of the size variation between neighbor elements. For example: $\frac{e_1}{e_2}$. (>>1: poor, 1: best)



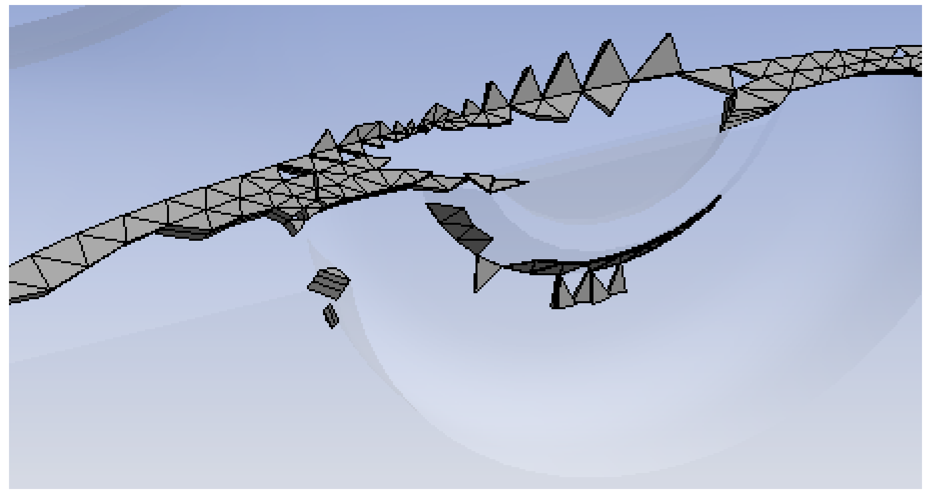
- Rapid changes lead to larger truncation errors.

Mesh quality metrics

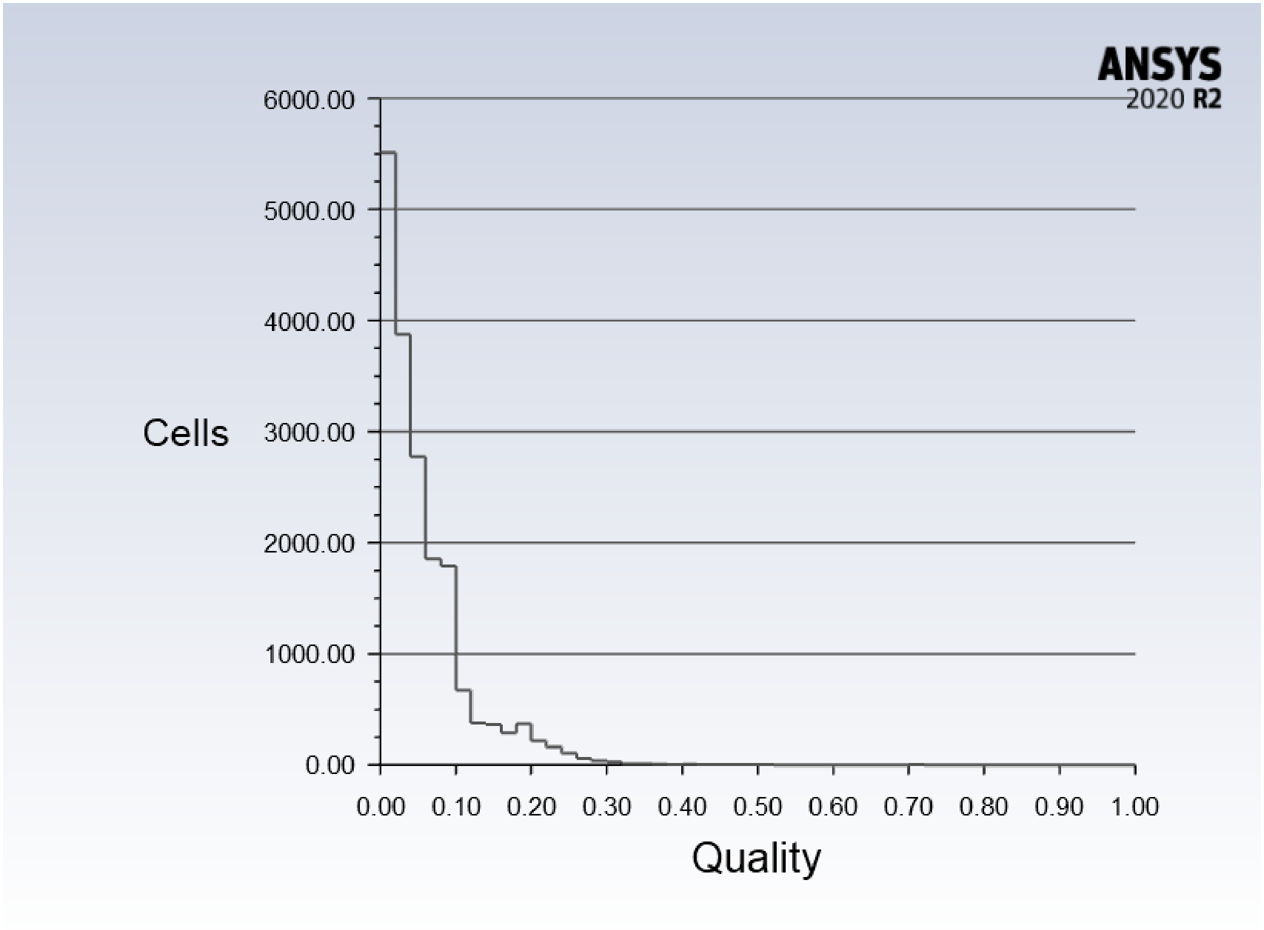
- **In Workbench meshing:**
  - Can compute min, max, average, and plot a distribution histogram (Details of Mesh > Quality > Mesh metric).



  - Can also display faces / cells in each quality range.



- **In Fluent (meshing mode):**
  - Can compute min, max, average (Report > Face / Cell Limits), and plot a distribution histogram (Display > Plot > Face / Cell Distribution).



  - Cannot display faces / cells in each quality range.

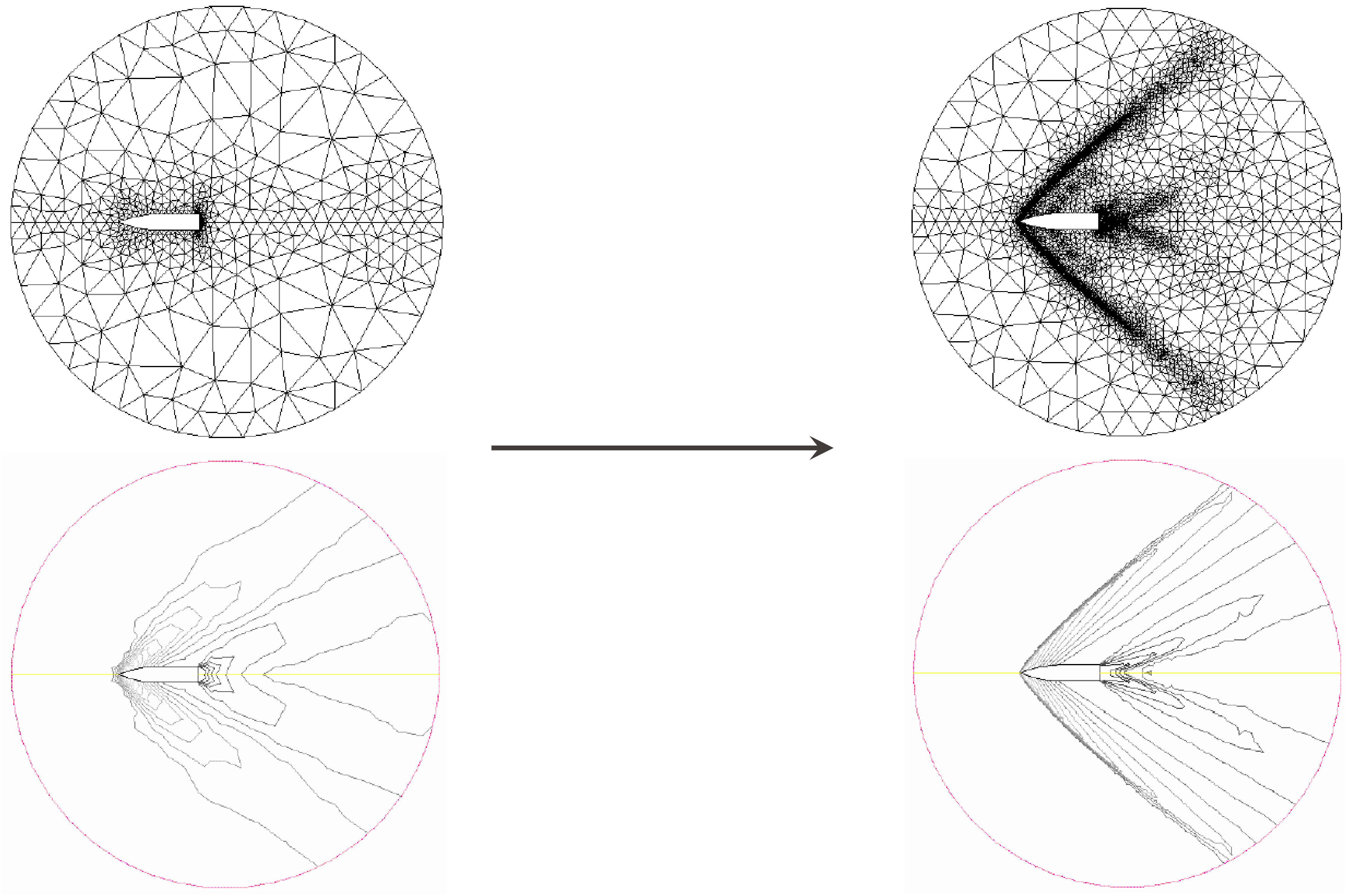
Mesh adaption

- Can improve the mesh by refining/coarsening based on the geometry and/or the flow solution.

- For ex., Fluent provides mesh adaption based on different criteria:
  - Gradient (velocity for shear layers, pressure for shocks…)
  - Iso-value (high-velocity jets, low-pressure wakes, reaction rate for combustion…)
  - Region
  - Element size or size change
  - Wall y^+ or y^* (turbulent flows)
  - Volume fraction (multiphase flows with Volume of Fluid method)

Mesh adaption: example

- 2D supersonic flow around a projectile, 5 refinement cycles



Initial

Refined

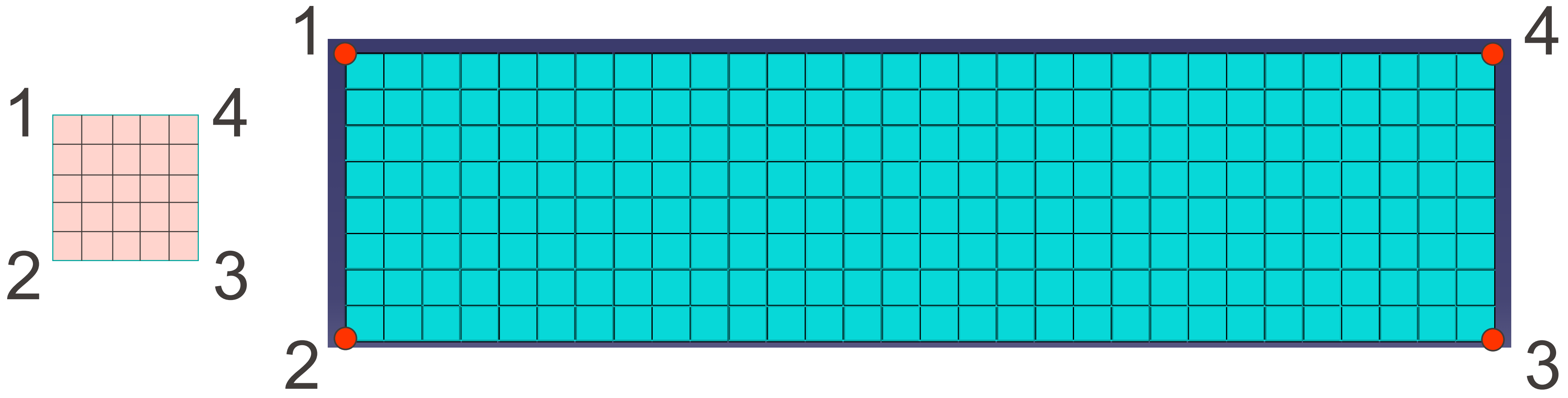
Mesh

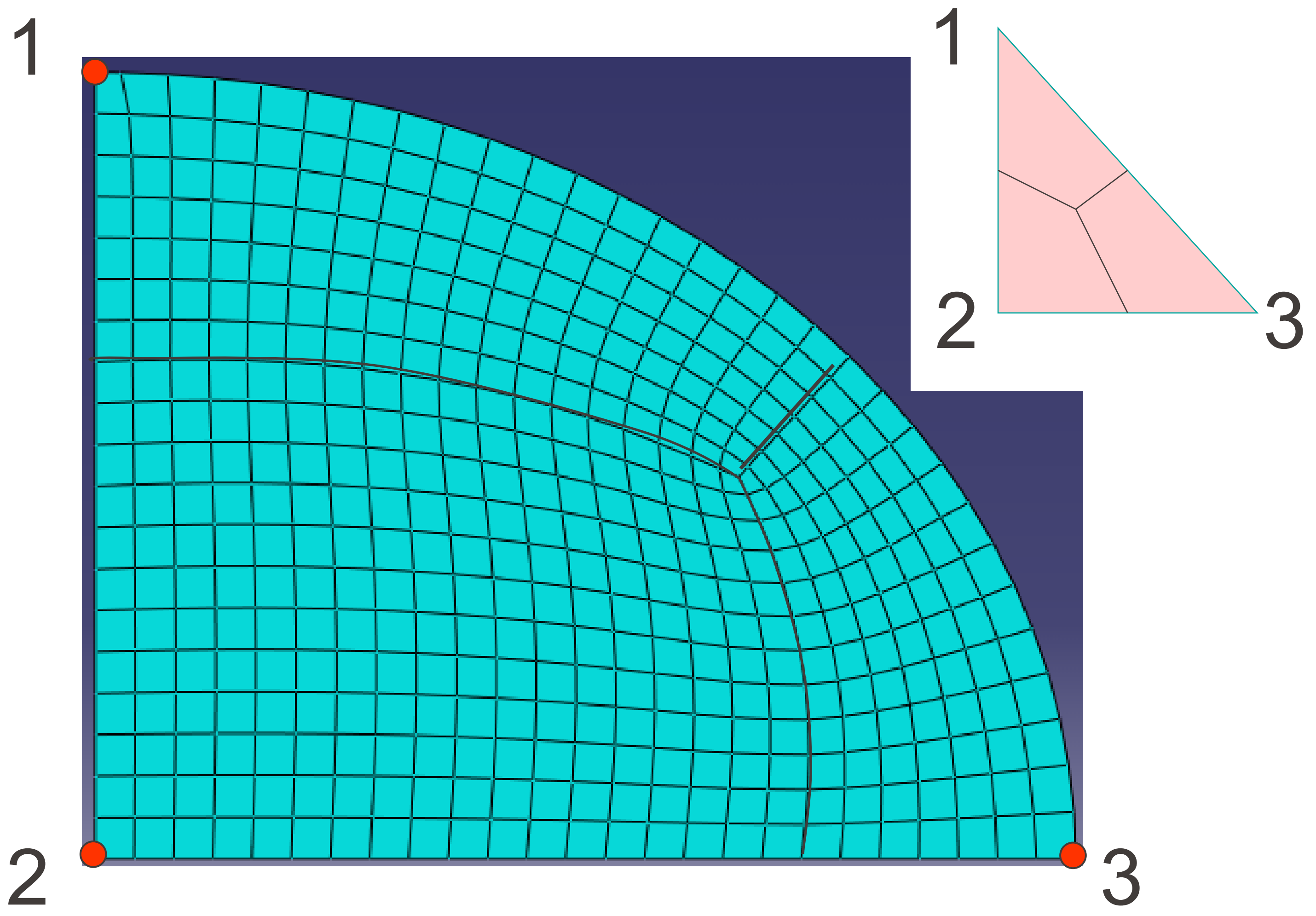
Solution (pressure contours)

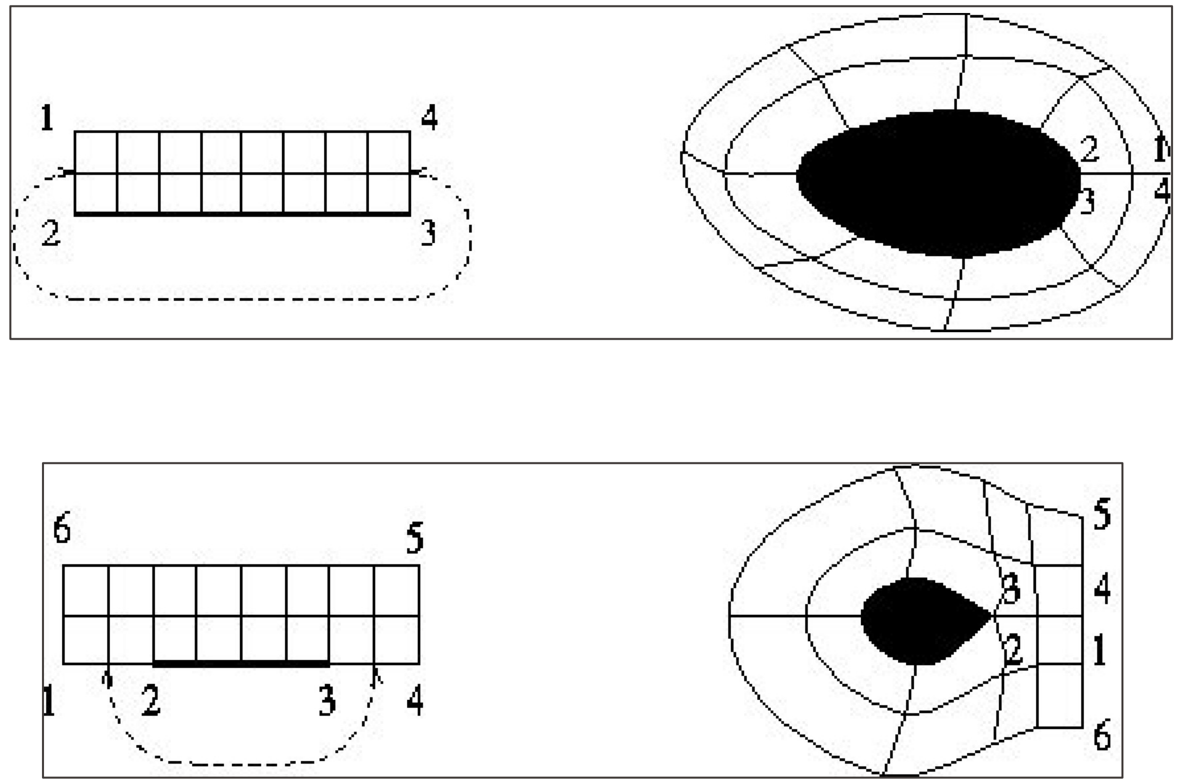
- May need to re-adapt for each flow condition.

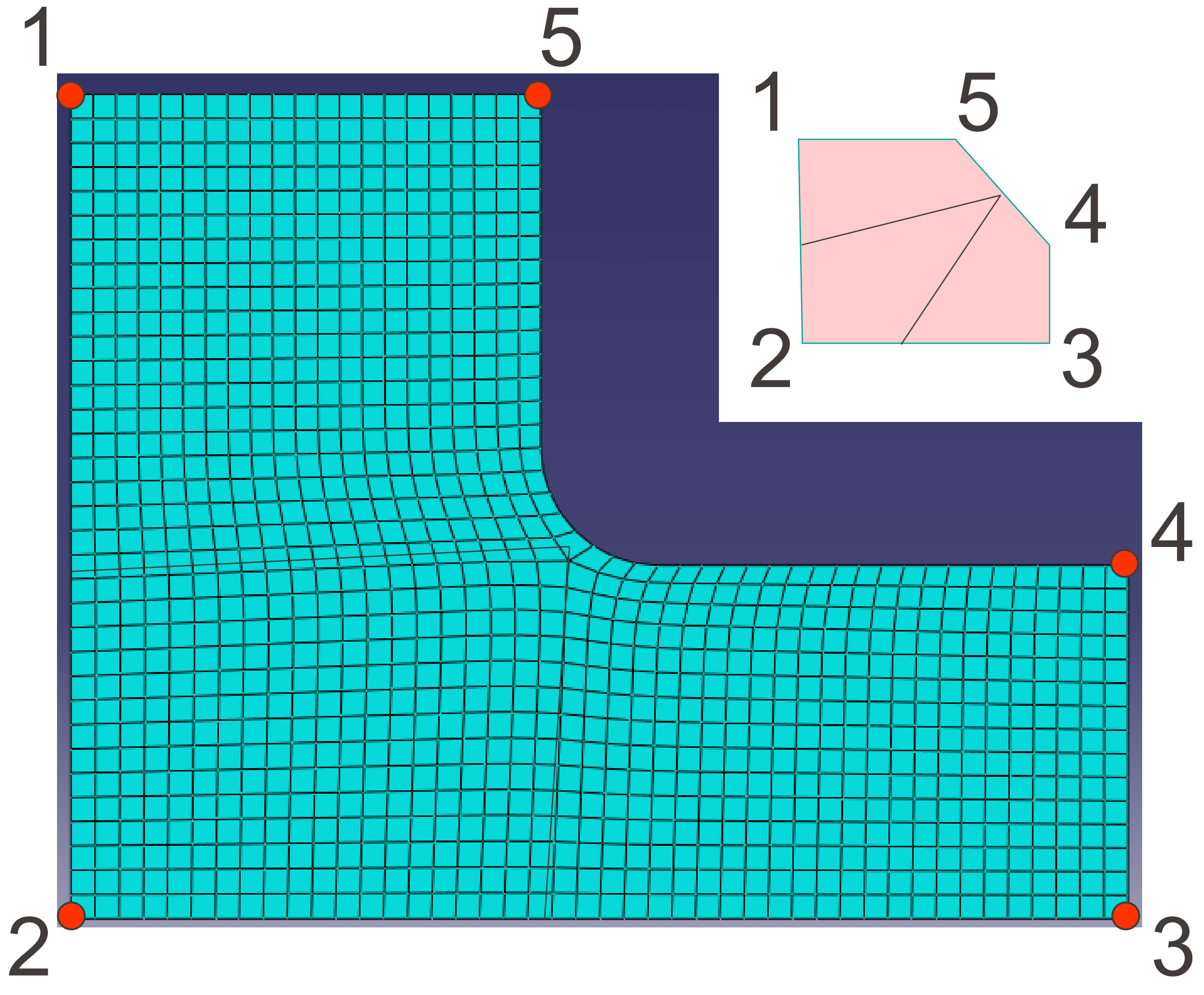
Many different meshing algorithms

- 2D structured (quad) mesh: map/deform a simple polygon onto the actual surface.





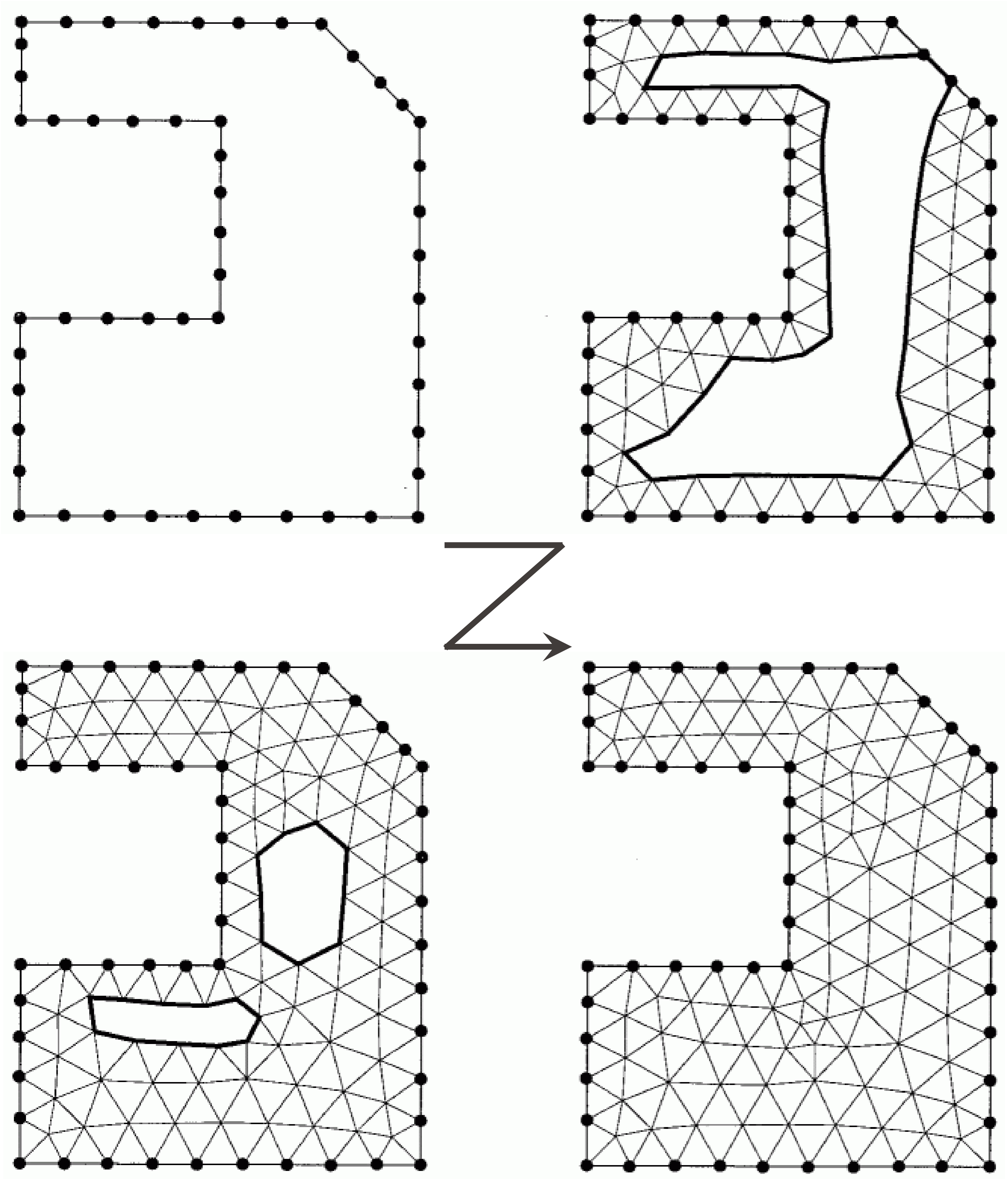




Many different meshing algorithms

- 2D unstructured (tri) mesh:

Advancing front



Delaunay

A collection of points

A Delaunay triangle

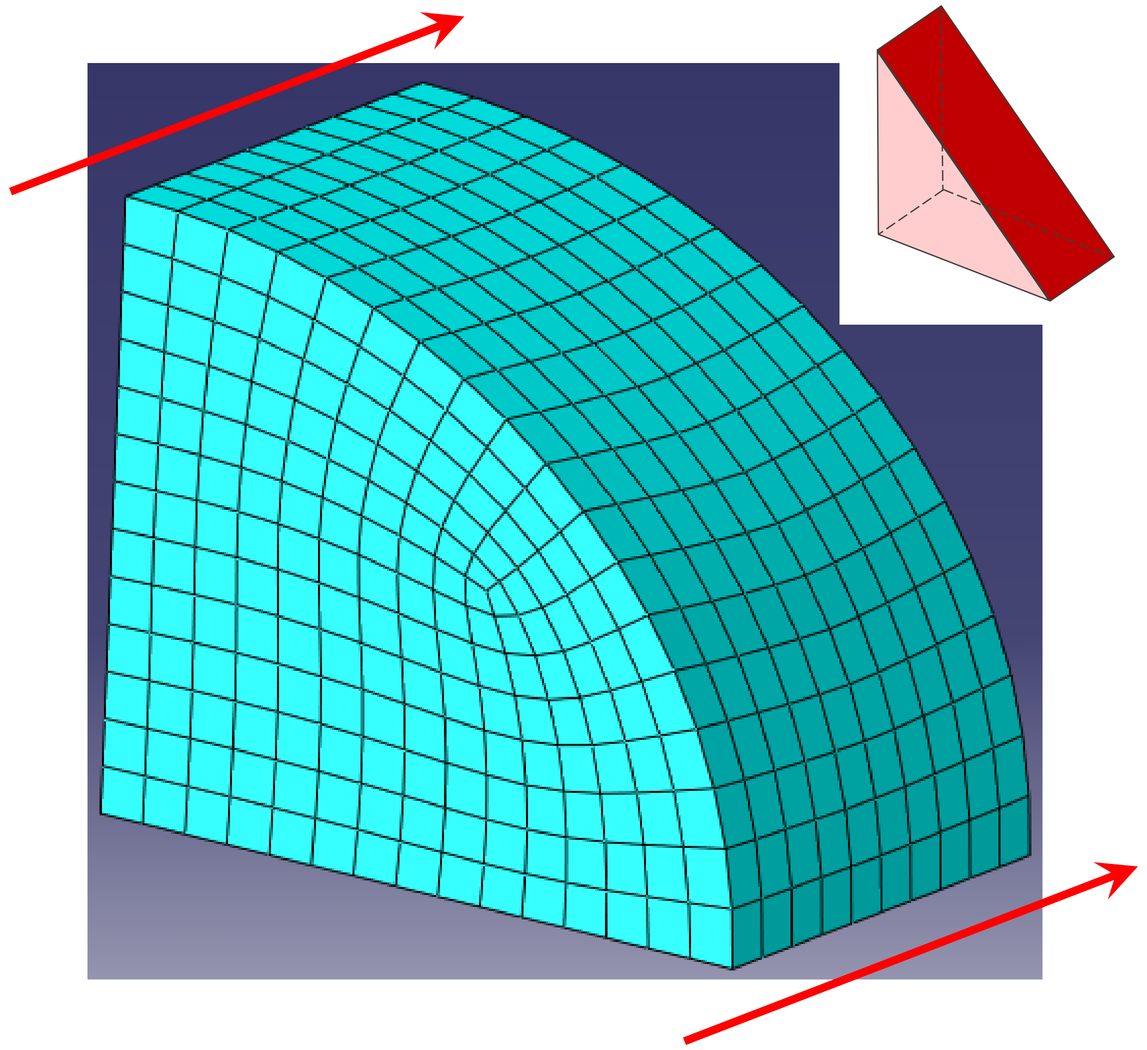
A non-Delaunay triangle

A Delaunay triangulation

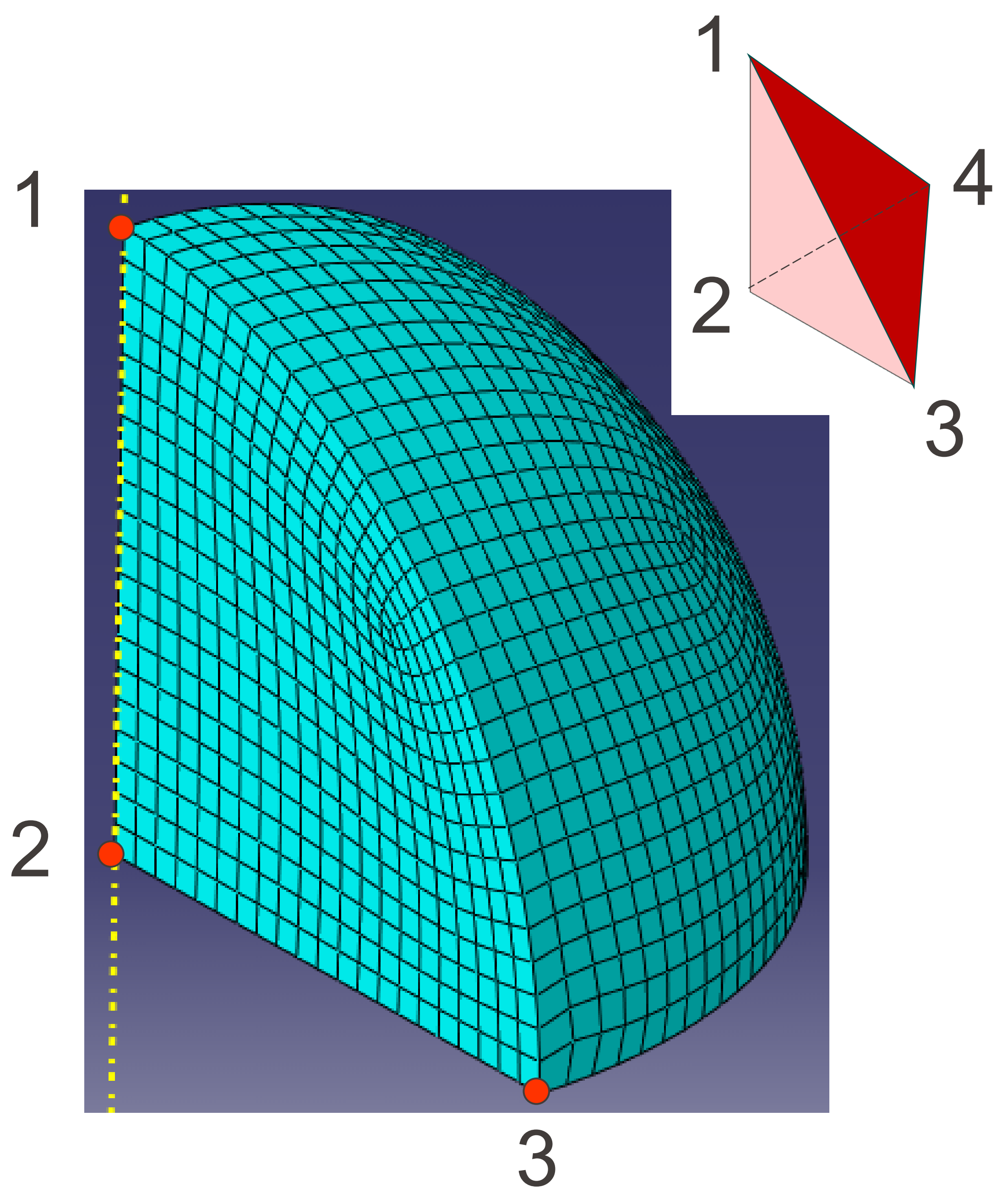
Many different meshing algorithms

- 3D structured mesh (hex):

Extrude a structured 2D (quad) mesh.

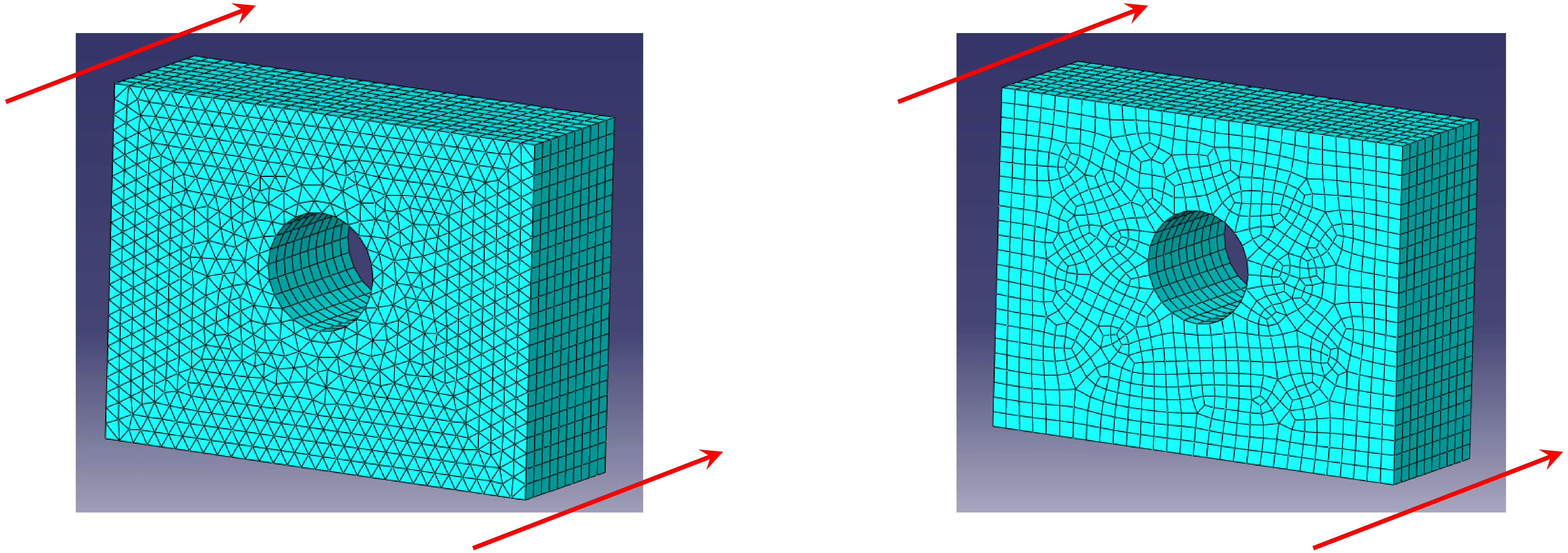


Map/deform a simple polyhedron onto the actual volume



Many different meshing algorithms

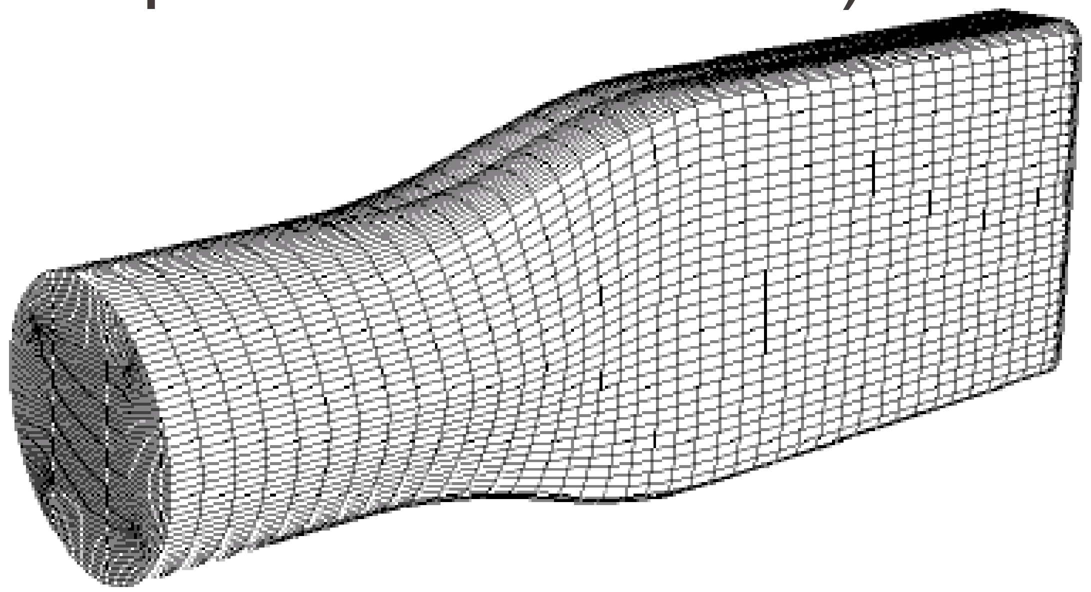
- 3D swept mesh: extrude unstructured 2D mesh (tri→prism / quad→hex)



- 3D unstructured mesh: advancing front / Delaunay
- Other algorithms: partitioning method, grid method, paving method…

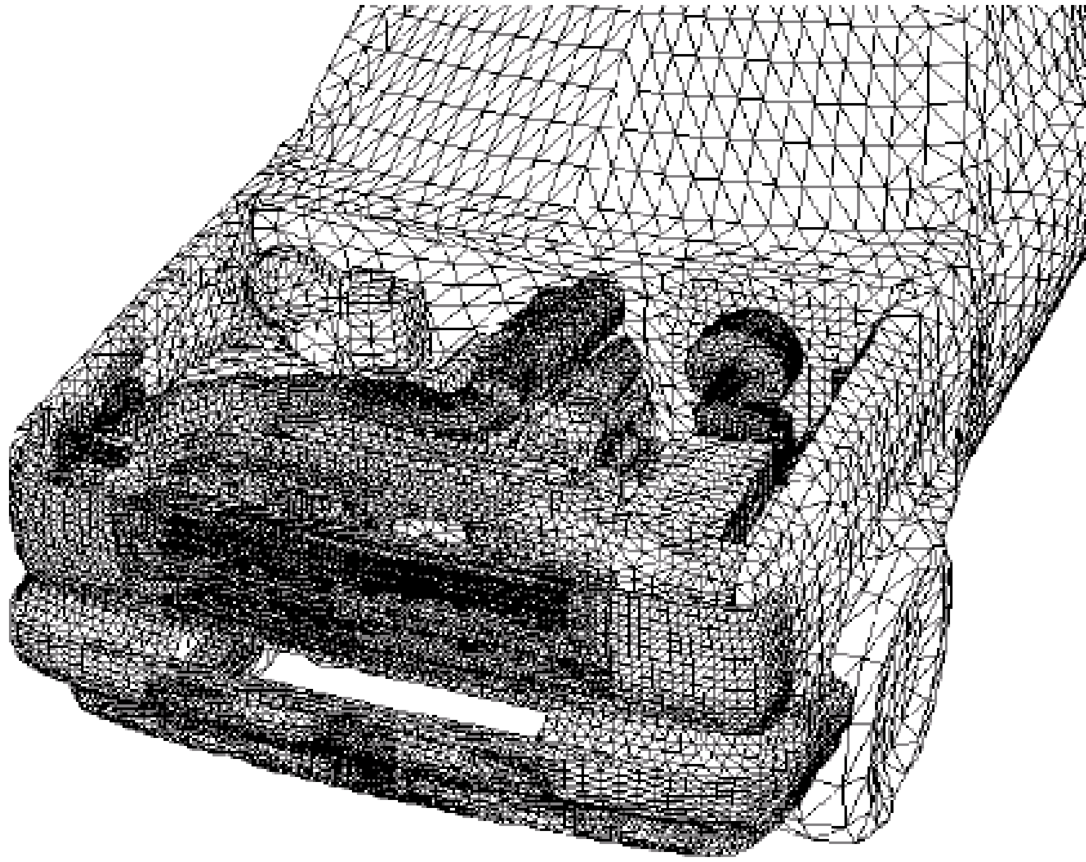
Some guidelines: choice of mesh guided by…

- Geometry
  - Some elements better adapted to some simple geometries (e.g. quad / prism for channels).
  - Automatic unstructured meshing easier for complex geometries.



- Flow characteristics: large gradients require special attention.

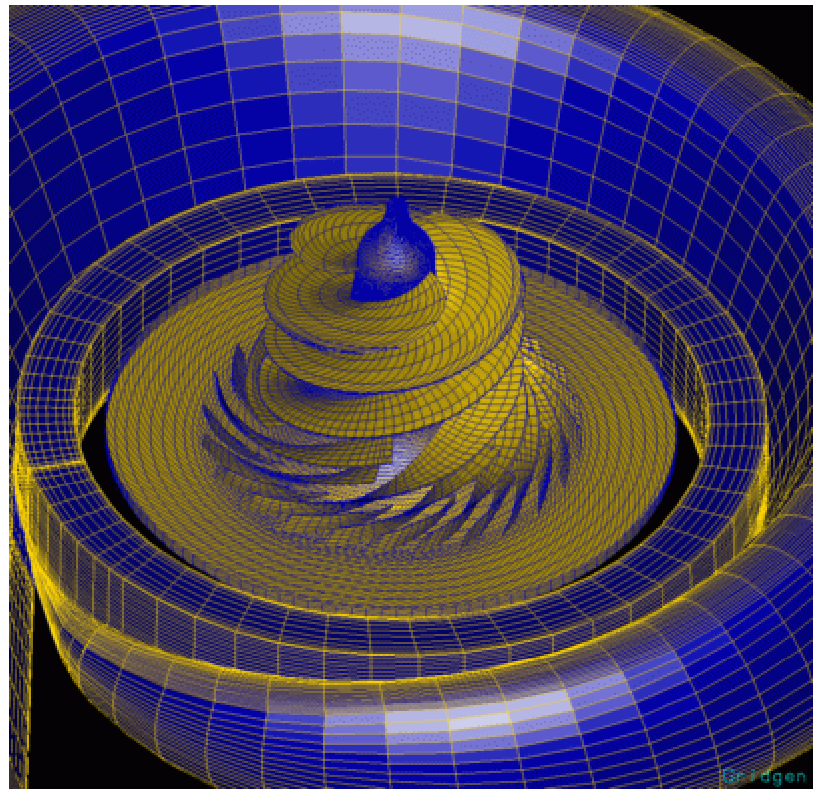
- Meshing time
  - Mesh generation extremely time consuming for complex geometries.
  - Automatic unstructured mesh generation faster.



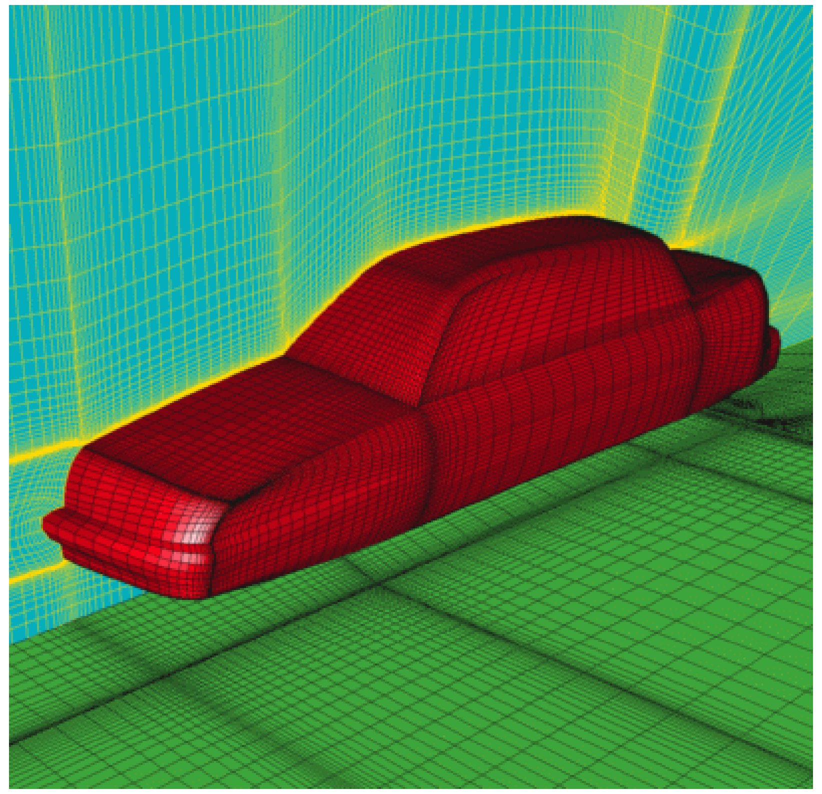
- Computational resources
  - Simple geometries / boundary layers: quad / hex may use fewer cells.
  - Complex geometries / different length scales: tri / tetra may be better.

- Solution accuracy
  - Less numerical diffusion when flow aligned with the mesh.
  - For simple flows, quad / hex are preferred. For complex flows, no preferred element.

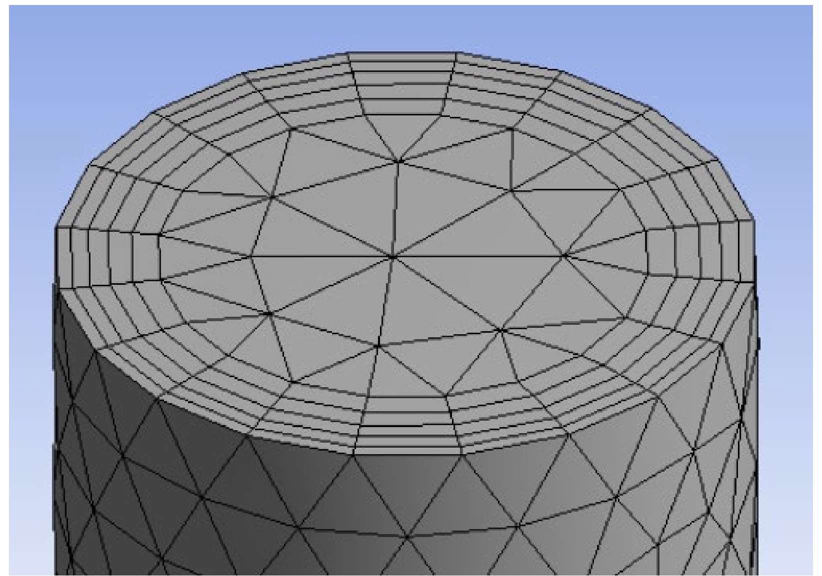
Some guidelines for mesh generation



- Minimize mesh complexity
  - Use structured mesh when appropriate.
  - Use quad / hex elements when possible.
  - Use tri / tetra elements for complex geometries.



- Optimize number of mesh cells
  - Don’t use too many / too few elements. Refine where needed, coarsen where possible.
  - Use quad / hex when possible (e.g. boundary layers, long pipes).
- Maximize solution accuracy
  - Concentrate elements in critical regions (boundary layers, wakes, jets, shocks).
  - Align quad / hex elements with flow direction.
  - Avoid poor quality elements.
  - Maximize mesh continuity: rapid size variations should be avoided (e.g. edge of boundary layers). Sometimes poor transition with automatic mesh generation / adaption.



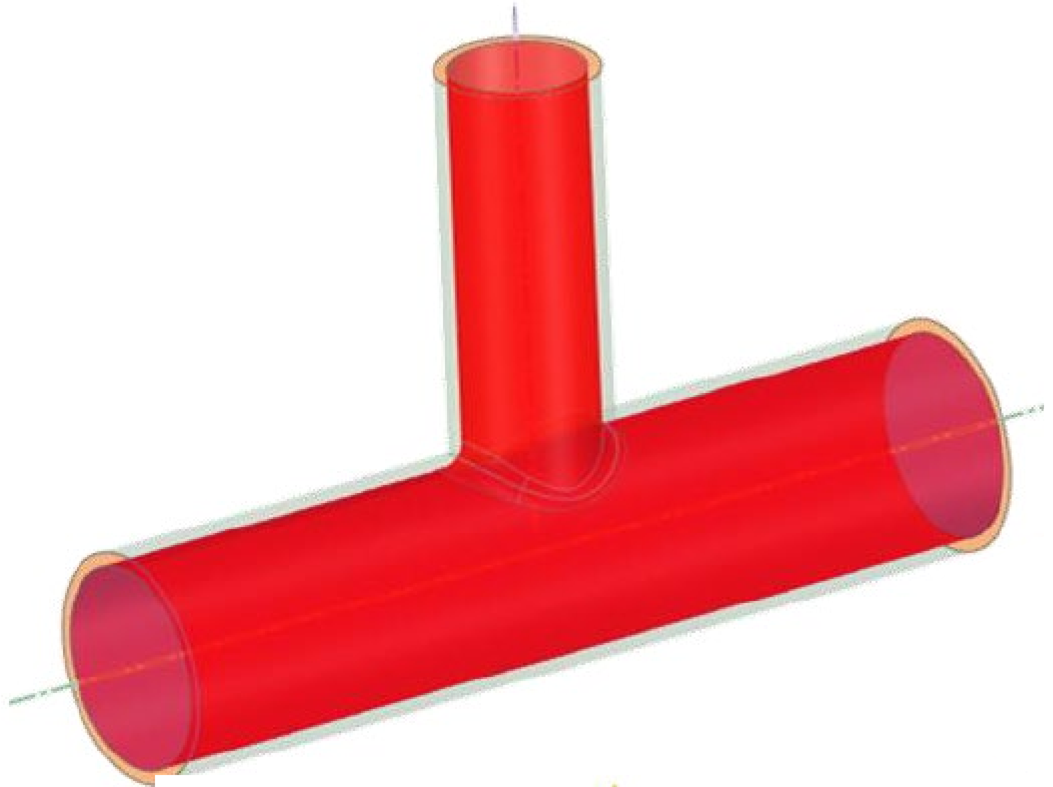
Summary

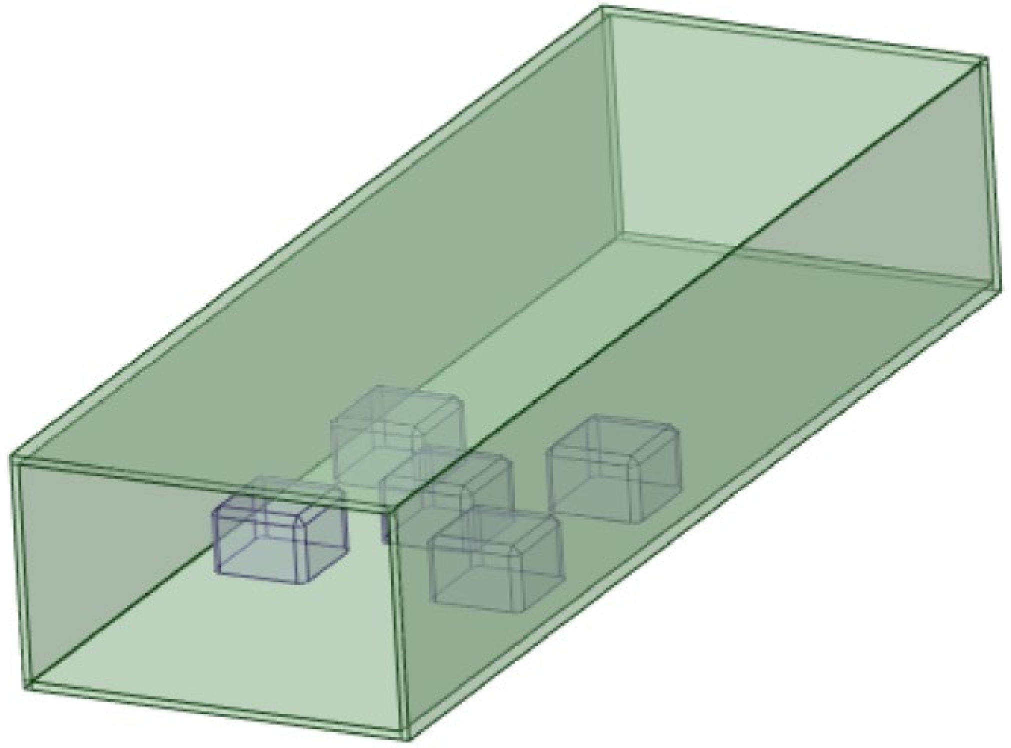
- Geometry modeling:
  - Define a geometry suitable for CFD before meshing.
  - Clean geometry of unwanted features.
  - Make sure the geometry is closed.

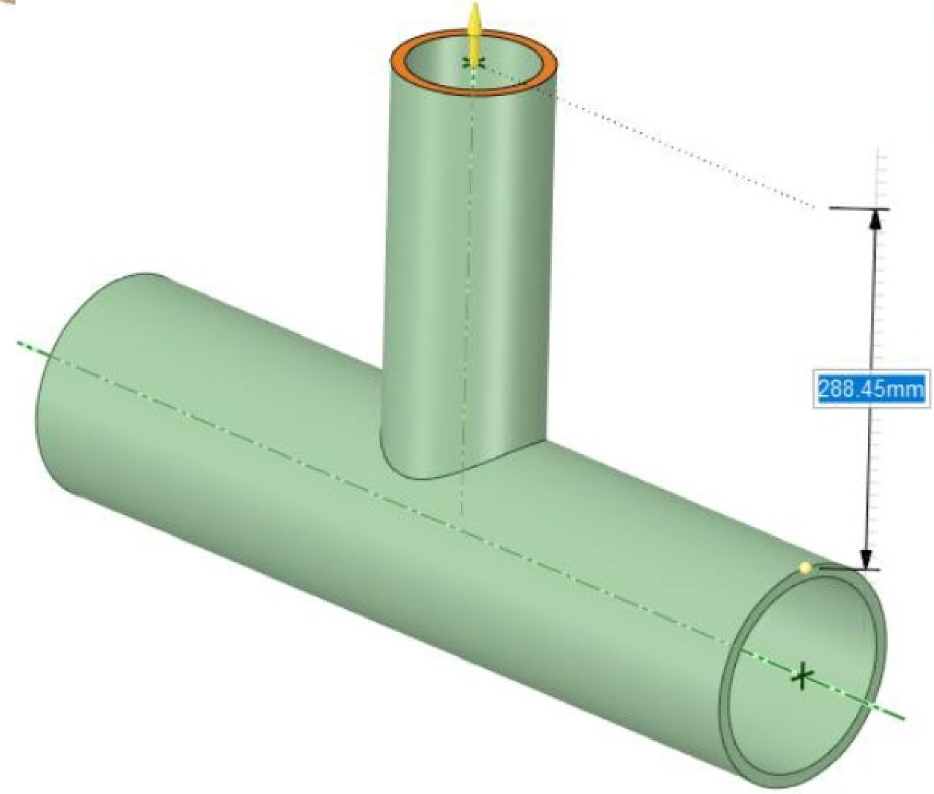
- Meshing:
  - Many different mesh elements and mesh types.
  - Trade-off between resources (setup time, computation time, memory) and accuracy.
  - Convergence and accuracy depend on mesh size / quality.
  - Strive for mesh quality. Refine in regions of large gradients.

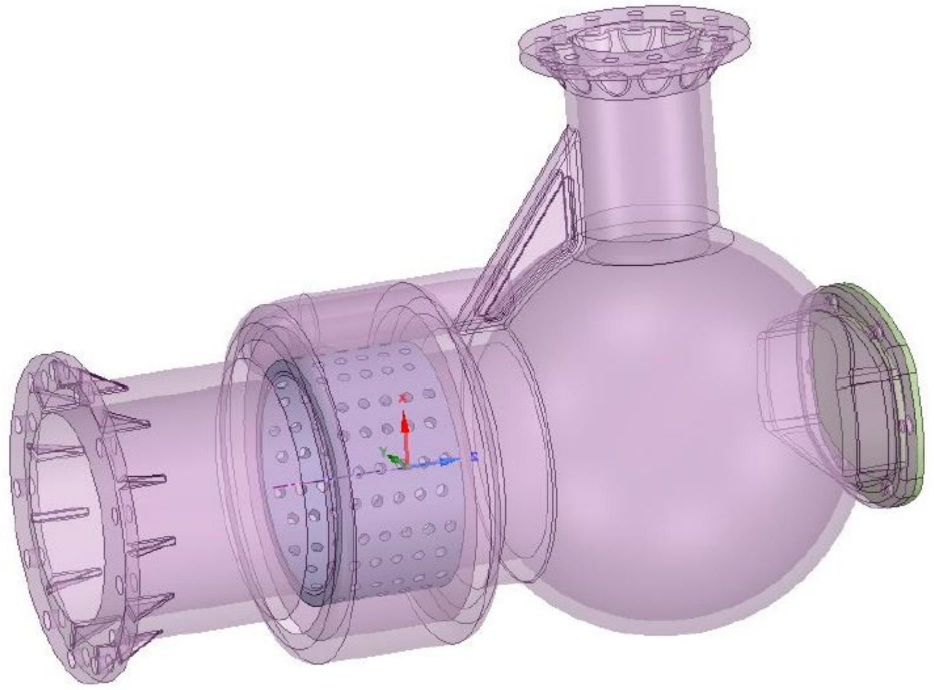
Tutorials: geometry modeling with SpaceClaim

1. Extracting a fluid volume
2. Repairing an existing geometry; using a symmetry plane to split
3. Creating a geometry from scratch
4. Named selections; bodies of influence





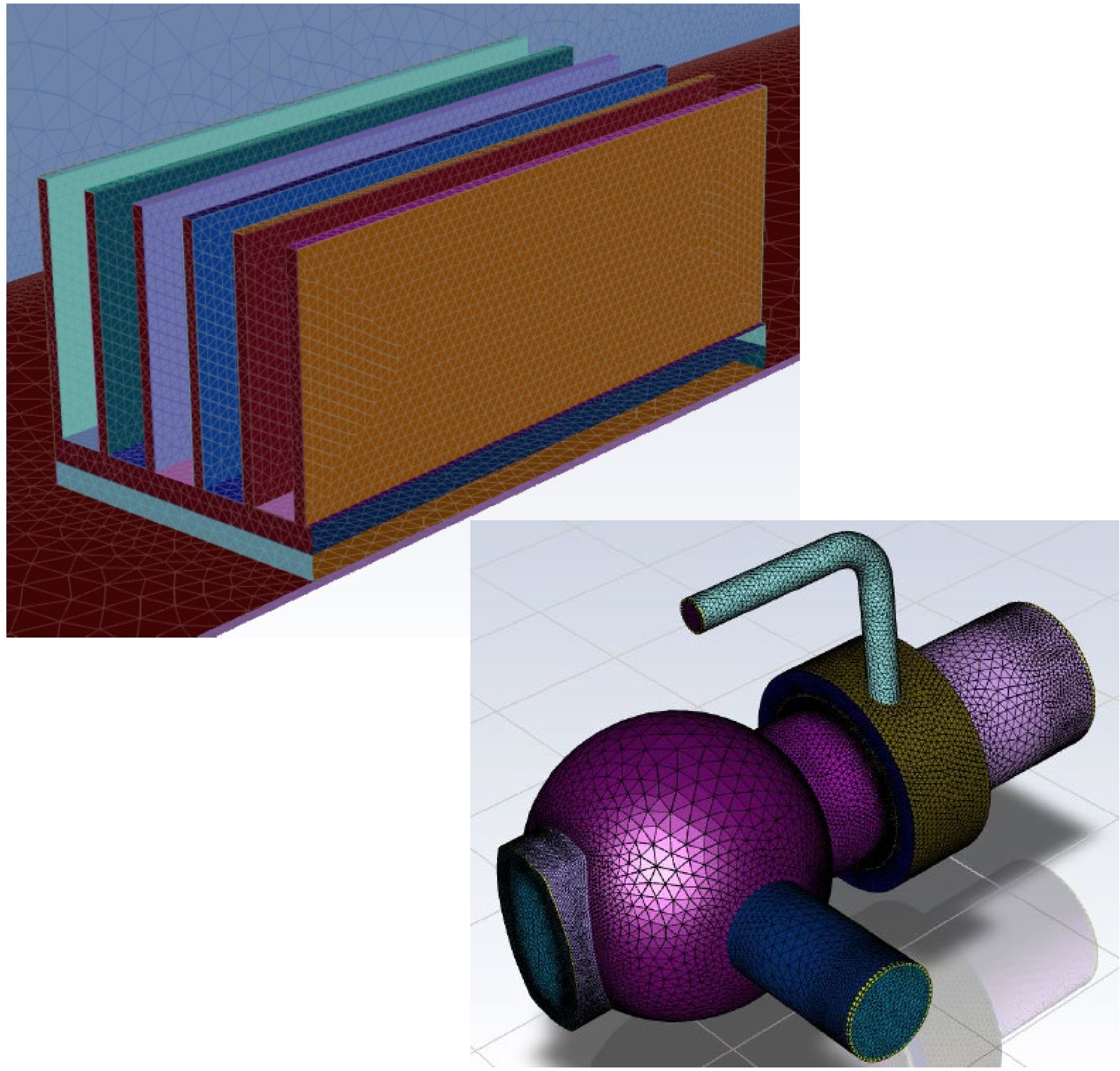




- Consider how you would perform these examples using alternative CAD software that you may be familiar with (e.g. Catia, Solidworks).

Tutorials: meshing with Fluent meshing mode

1. Overview of the “Watertight Geometry” workflow (mesh generation of a heat sink)
2. Overview of the “Watertight Geometry” workflow (mesh generation of a mixer)



Numerical Flow Simulation

Tutorials: meshing with Workbench Meshing

1. Meshing basics
   (mesh generation in a T-junction)

2. Meshing methods
   (review of different meshing methods)

3. Global mesh controls
   (sizing and inflation)

4. Local mesh controls
   (hybrid mesh on a multi-body part)