Challenges in visualizing results from more modern finite element formulations: high-order, DG, H(div), H(curl)...

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Based on open source tools
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100% employee-owned

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6 offices across USA/Europe

65% staff with PhD or Master
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20+ years of expertise
Kitware USA, 1998
Kitware Europe, 2010

Revenue 2020
$39M consolidated

Kitware / Services

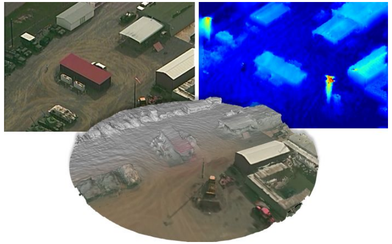
TRAINING

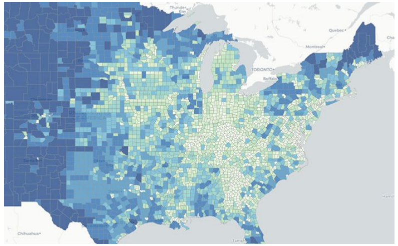
SUPPORT

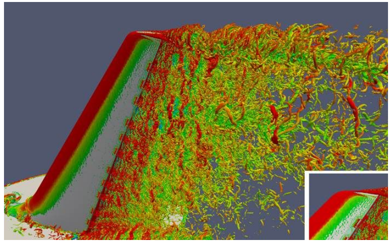
DEVELOPMENT

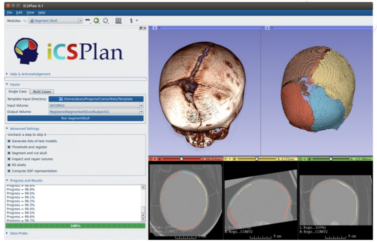
GRANT COLLABORATION

Areas of expertise / Built on open source









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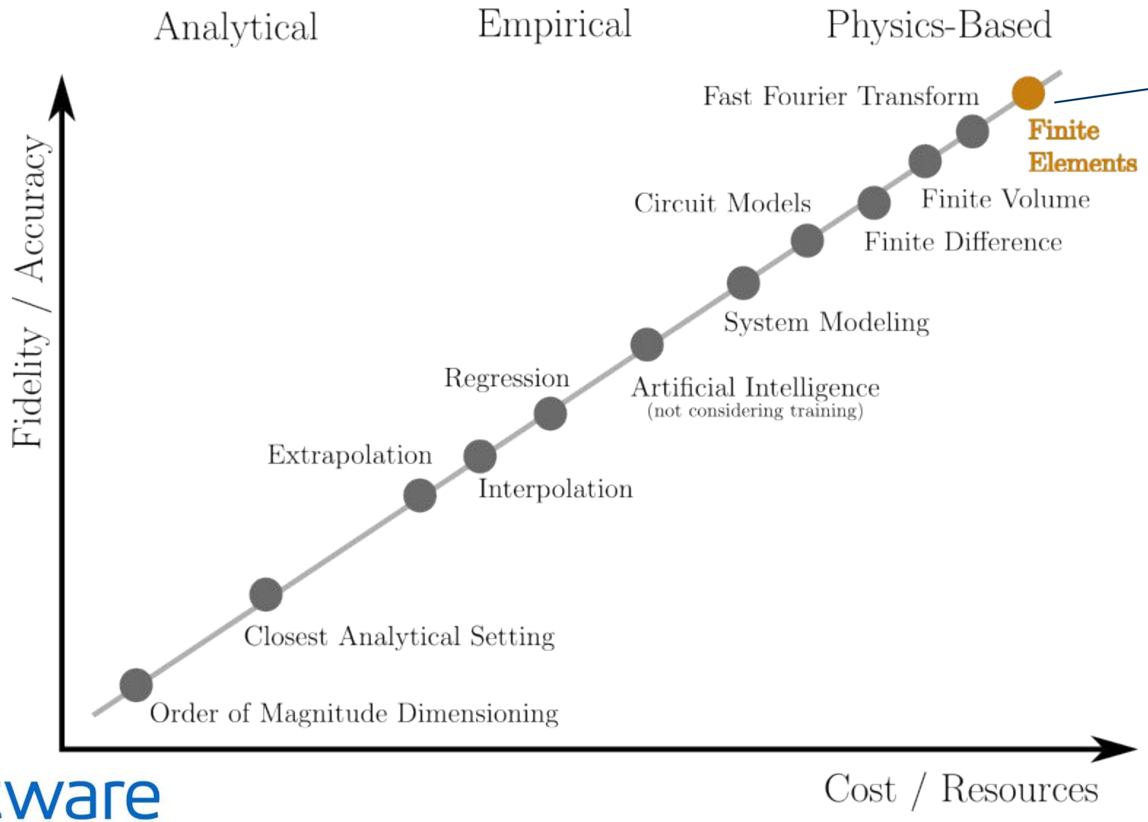
Numerical Methods: a cost/accuracy balancing act



A whole lot of other things that can affect this balance:

- Stability considerations
- Model choice
- Numerical schema
- Linear system solver
- Mesh resolution
- …

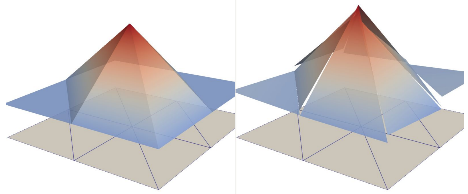
What do we mean by "modern" finite elements?

*Anything that is **not classical** finite elements.*

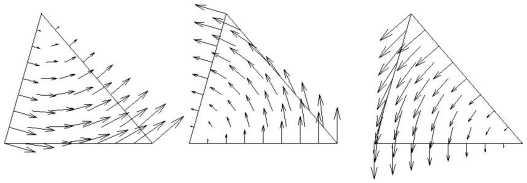
Classical finite elements methods usually have the following properties:

- Piecewise linear per element solutions
- At least C^0 Continuity between elements
- Nodal degrees of freedom
- Scalar basis functions

High-Order



Discontinuous



Conforming

Jacobsson, Per. “Nedelec elements for computational electromagnetics.” (2007).

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Reasons for using more complex formulations

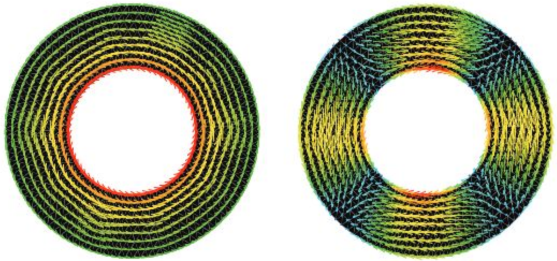


FIGURE 2.4. Approximation of the vector Laplacian on an annulus. The true solution shown here on the right is an (accurate) approximation by a mixed method. It is orthogonal to the harmonic fields and satisfies the differential equation only modulo harmonic fields. The standard Galerkin solution using continuous piecewise linear vector fields, shown on the left, is totally different.

Arnold, Douglas, Richard Falk, and Ragnar Winther. "Finite element exterior calculus: from Hodge theory to numerical stability." *Bulletin of the American mathematical society* 47.2 (2010): 281-354.

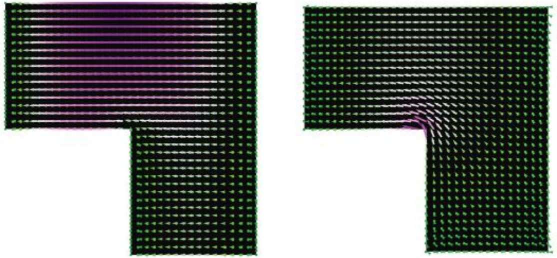
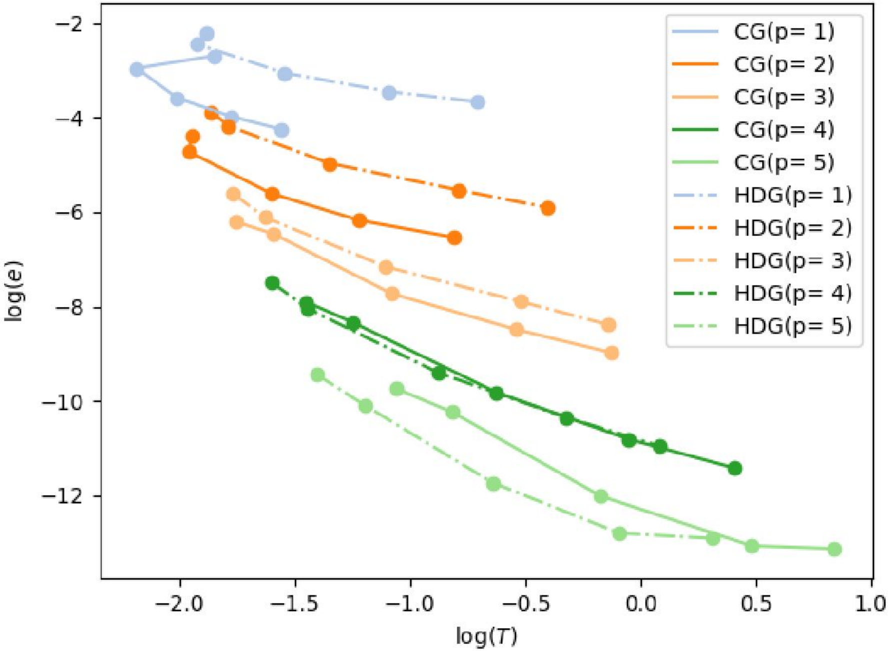


FIGURE 2.3. Approximation of the vector Laplacian by the standard finite element method (left) and a mixed finite element method (right). The former method totally misses the singular behavior of the solution near the reentrant corner.

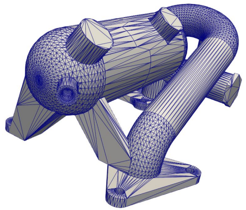


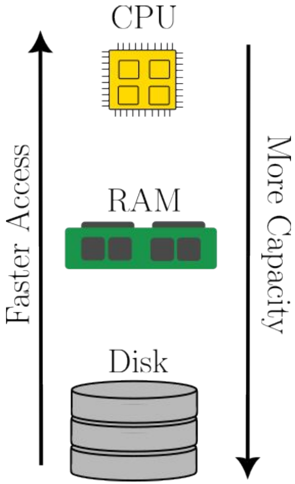
Logarithmic evolution of the error as a function of computational time for an analytical parabolic test case: a comparison between Continuous Galerkin (CG) and Hybrid Discontinuous Galerkin (HDG) approaches at high orders

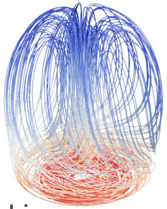
The big steps from simulation to visualization

Simulation → I/O → Processing → Rendering

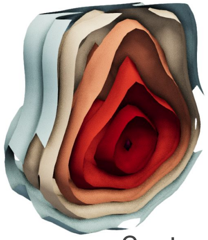
$$\begin{cases} \int_\Omega F(u,\phi)d\Omega = \int_{\partial\Omega} b(\phi)d\partial\Omega \\ \int_{\partial\Omega} B(u,\phi)d\partial\Omega = \int_{\partial\Omega} f \cdot \phi d\partial\Omega \end{cases}$$







Stream Lines



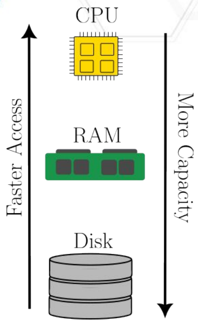
Contouring

The OpenFoam Motorbike, rendered with the NVIDIA OptiX path tracer in ParaView.

Formalizing the Challenges

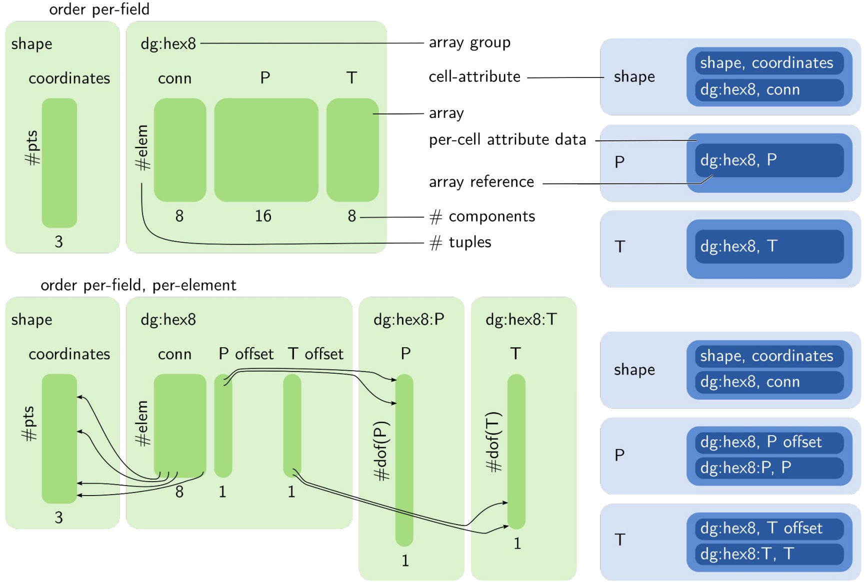
I/O: formatting and interfacing

What format can solutions from modern finite element codes use to describe themselves?



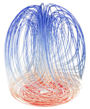
Characteristics of solutions from more modern formulations breaking the mould:

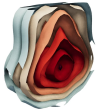
- A zoology of element types
  - Modal vs. nodal degrees of freedom
  - Non-standard interpolation primitives
- Discontinuous point data



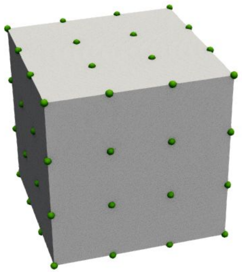
Design for discontinuous galerkin data structure taken from:
https://discourse.vtk.org/t/discontinuous-galerkin-elements-and-other-novel-cell-types-function-spaces/9209

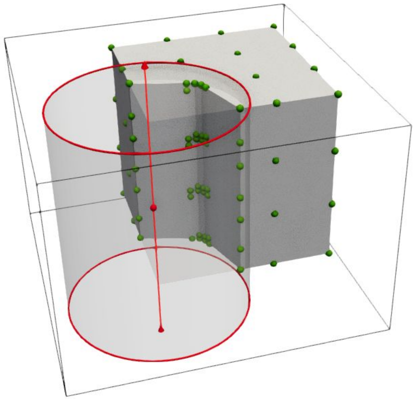
Post-processing: reducing and transforming data





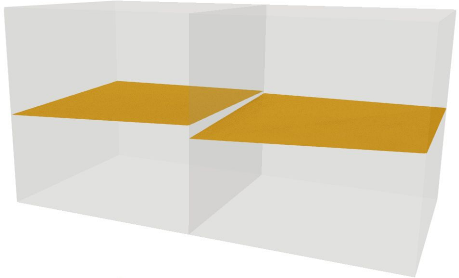
Do basic processing operations have the same implementations for more complex data?

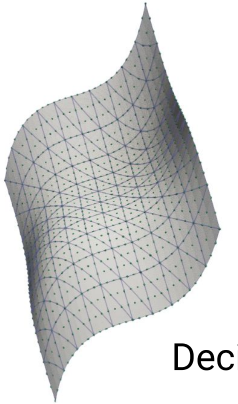


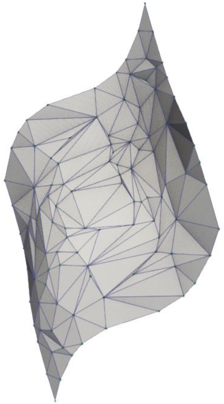


Clipping

Contouring







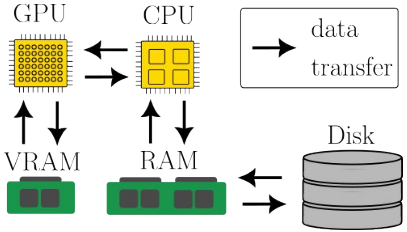
Decimation

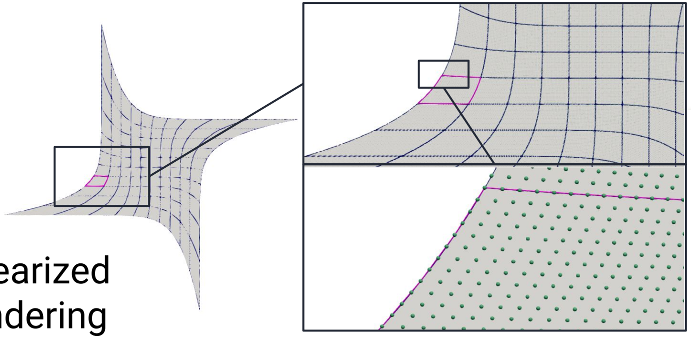
Rendering: from data to image

How do we implement graphics primitives based on user formulations? How should graphics primitives behave in discontinuous settings?

2 main challenges:

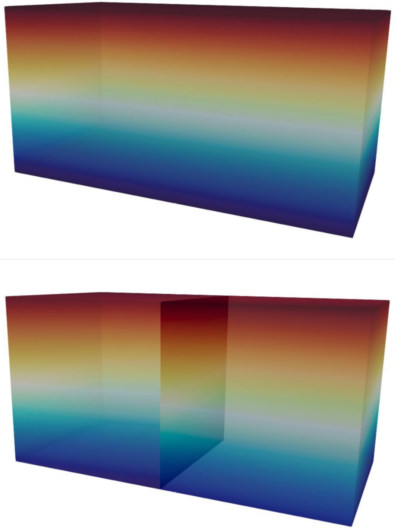
- Translating special interpolation primitives to the GPU
- Rendering discontinuous data





Linearized Rendering

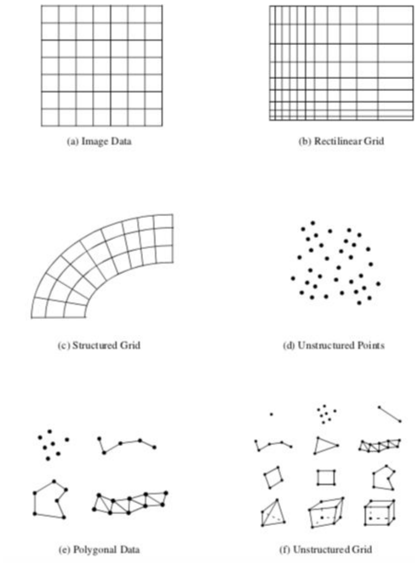
Discontinuous Rendering Artifacts



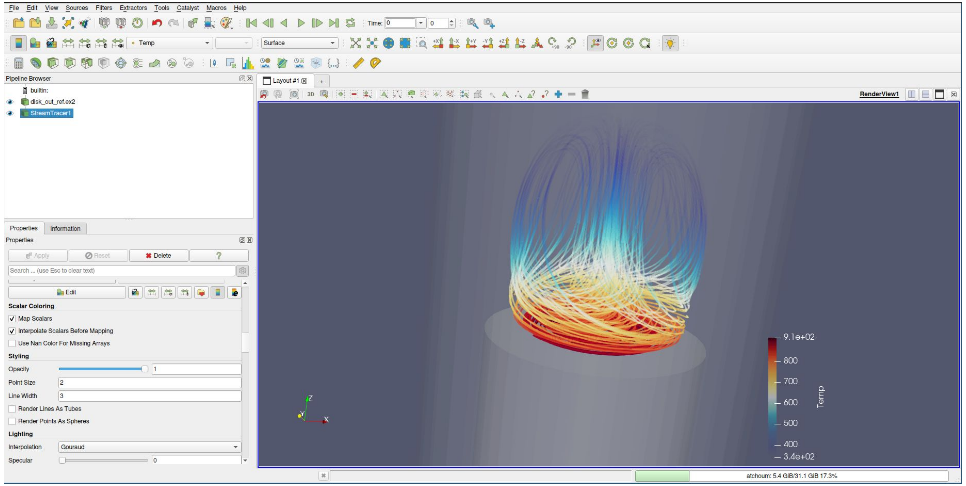
Infrastructure: refactoring tools for new applications

How do we migrate existing visualization tools towards supporting these new data models?

These more modern finite element formulations necessitate fundamental design changes in existing APIs, formats and computational kernels.



VTK Dataset model taken from: https://examples.vtk.org/site/VTKBook/05Chapter5/



ParaView Screenshot

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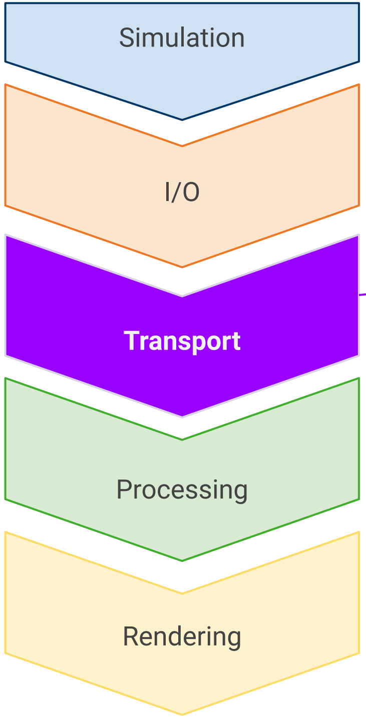
Promising Solutions

Intermediate solution framework



Extra step to project the high-order / exotic data onto a linear mesh dedicated to visualization

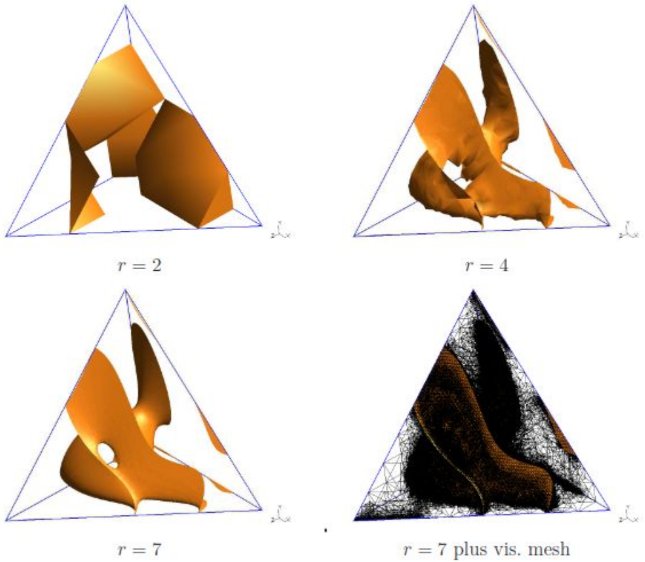


Figure 5. Visualization of one 4th order function on one single tetrahedron. Figures show one iso-surface using different error thresholds. The last Figure (bottom-right) show the visualization mesh together with the iso-surface.

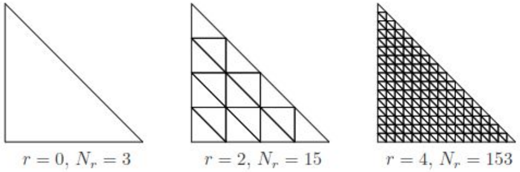


Figure 3. Some AMR refinement templates for triangles at different resolution levels.

J.-F. Remacle, N. Chevaugeon, E. Marchandise, and C. Geuzaine. Efficient visualization of high-order finite elements. International Journal for Numerical Methods in Engineering, 69(4):750–771, 2007.

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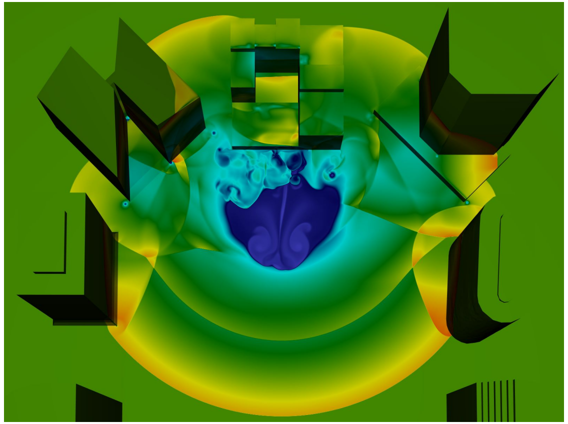
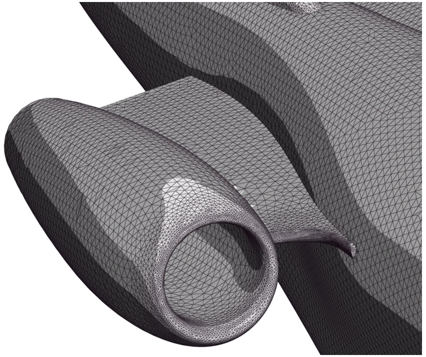
Long-term solution framework

B. Nelson, E. Liu, R. M. Kirby, and R. Haimes. Elvis: A system for the accurate and interactive visualization of high-order finite element solutions. IEEE transactions on visualization and computer graphics, 18(12):2325–2334, 2012.

Pixel exact approaches using appropriate computational primitives on the GPU.



ViZiR: https://pyamg.saclay.inria.fr/images/vizir/city_blast_sol.png



ViZiR: https://pyamg.saclay.inria.fr/images/vizir/falconP3_zoom.png

Loseille, Adrien & Feuillet, Rémi. (2018). Vizir: High-order mesh and solution visualization using OpenGL 4.0 graphic pipeline. 10.2514/6.2018-1174.

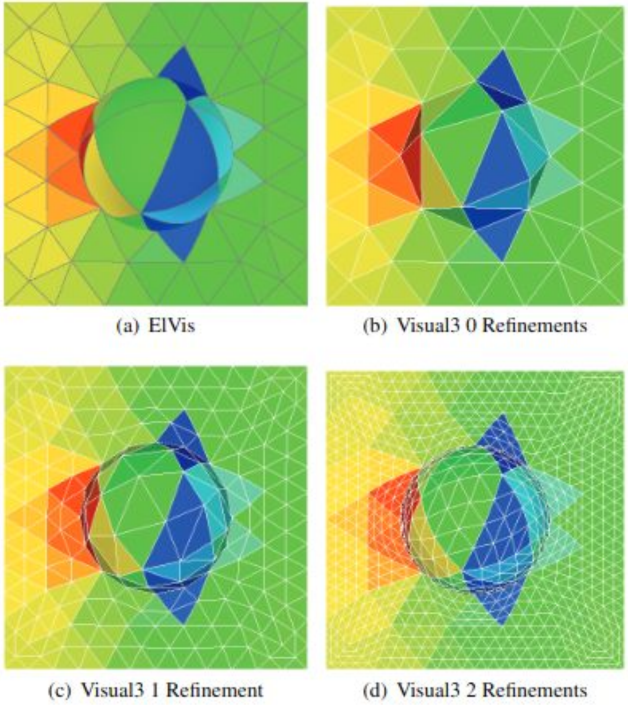


Fig. 7. A top-down view of the hemisphere from Case 3. The mesh plotting tools of Visual3 and ElVis are enabled.

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Conclusion and Outlook

Conclusions:

- Modern finite element formulations are becoming more mainstream (with good reason)
- Challenges in visualizing these kind of datasets can be divided into 4 categories:
  - Absence of existing standard for **I / O** formatting and design
  - Classical **post-processing** transformations do not behave correctly for more complex data
  - **Rendering** primitives need to be re-designed for these types of datasets
  - Porting current **infrastructure** is not trivial
- 2 generic approaches to these problems stand out: linear projections and native support

Outlook:

- A clear and iterative roadmap needs to be elaborated at the community level
- Best to source dedicated project financing for affecting coherent change

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More Info: https://www.kitware.eu/paraview-user-day-europe-2023/

Thank you for your attention!

Questions?

Or/and contact us at kitware@kitware.fr or julien.fausty@kitware.com