Unstructured Grid Adaptation: Status, Potential Impacts, and Recommended Investments Toward CFD Vision 2030

Michael A. Park[1] Joshua A. Krakos[2] Todd Michal[2]
Adrien Loseille[3] Juan J. Alonso[4]

[1]NASA Langley Research Center

[2]The Boeing Company

[3]INRIA Paris-Saclay

[4]Stanford University

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Motivation

Finding 3 of the CFD Vision 2030 Study[1]

Mesh generation and adaptivity continue to be significant bottlenecks in the CFD workflow, and very little government investment has been targeted in these areas.

[1] Slotnick et al. CFD Vision 2030 Study: A Path to Revolutionary Computational Aerosciences NASA CR-2014-218178

Outline

Impacts of Mature Grid Adaptation Technology

Accurate solutions with error estimates on smaller meshes

- Reduce time required for initial grid generation
- Asymptotic convergence rates for AIAA Prediction Workshop Series
- Verify numerical methods and increase confidence
- Set the stage for rigorous validation and certification by analysis

Eliminate discretization error as a concern

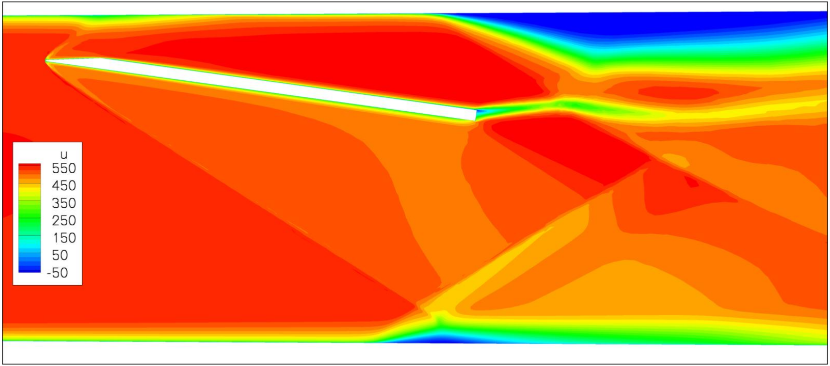
- Construction of aerodynamic databases
- Development and adoption of improved modeling techniques
- Uncertainty quantification and design optimization
- Multidisciplinary analysis

Outline

Status: Grid Adaptation Mechanics

Primary focus on unstructured tetrahedral methods

- High Reynolds number turbulent flows with discontinuities
- Arbitrary alignment and aspect ratio for complex flow simulations
- Lack of grid regularity in high gradient regions degrade solver and error estimation performance



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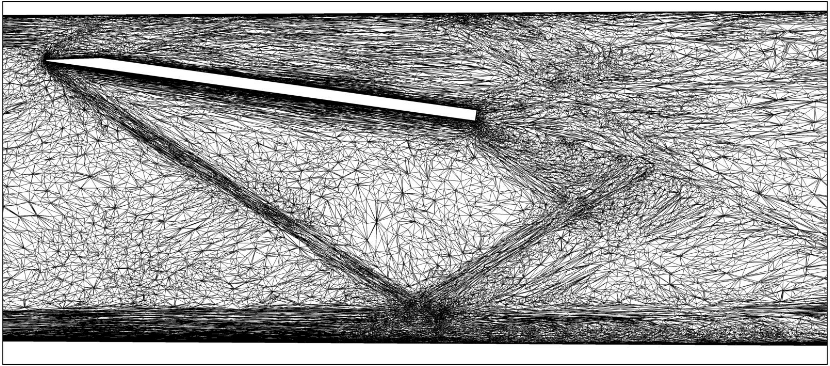


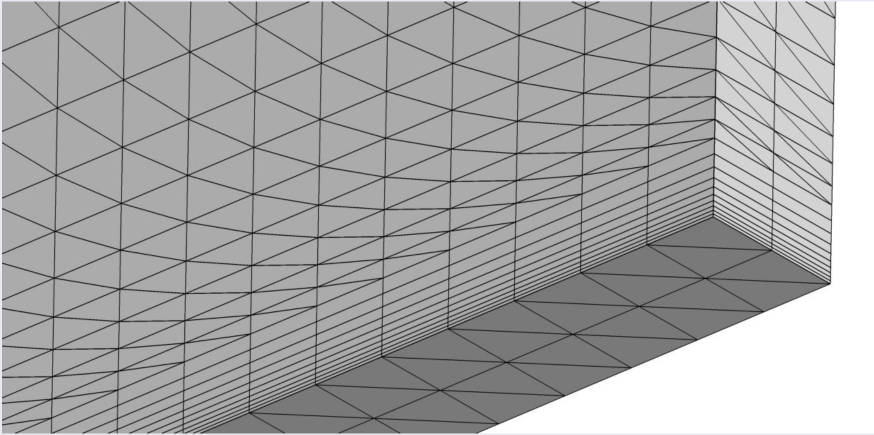
Status: Grid Adaptation Mechanics

Structured and Cartesian subdivision

- More mature for schemes that permit hanging nodes
- Alignment is limited by topology and potentially difficult to generate
- Viscous Cartesian adaptation uses alternative boundary layer methods
- Collaboration opportunities for other aspects of grid adaptation

Status: Grid Adaptation Mechanics

Semistructured prism stacks and tetrahedral grids



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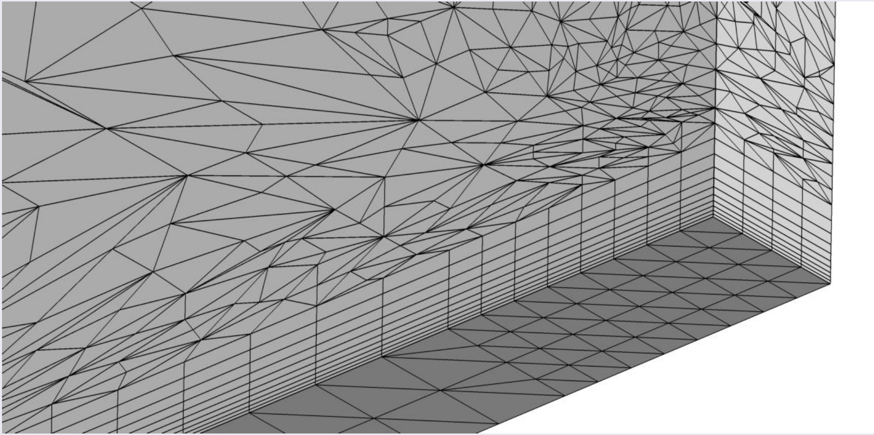
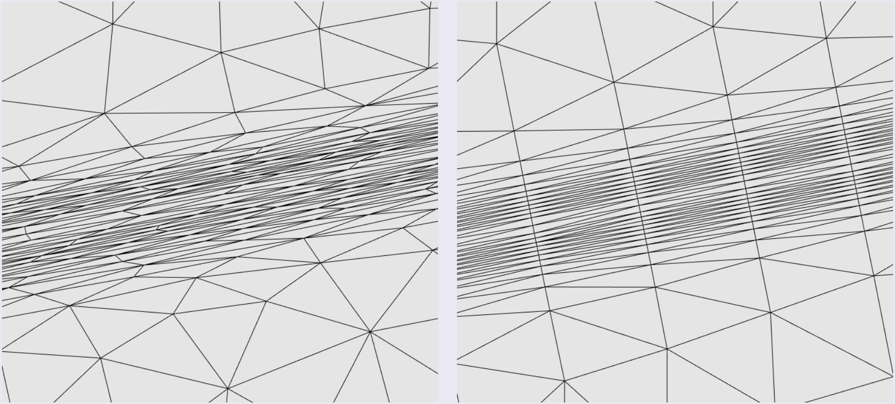


Status: Grid Adaptation Mechanics

Tetrahedral elements orthogonal to spacing request



Status: Error Estimation

Central to the implementation of any solution-adaptive scheme is the ability to detect and assess solution error. The construction of a suitable refinement criterion represents the weakest point of most adaptive strategies.[2]

Available methods

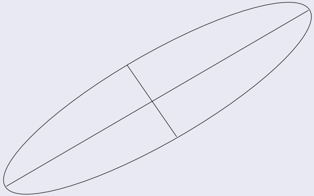
- Output based adaptation is used where the adjoint is available and a functional can be targeted (adjoint weighted residual)
- Entropy adjoint
- Interpolation error estimates are used in other cases, but ignore the transport of errors impacting the solution
- Feature-based methods are popular, but lack guarantees that features are in correct location or functionals are improved
- Complicated by multiple solutions, hysteresis, and chaotic flows

[2] Mavriplis, Unstructured Grid Techniques, Annual Review of Fluid Mechanics, 1997

Status: Error Estimation

Anisotropy

- Optimized metric based on surrogate error-cost models
- Continuous mesh model and metric approach
- Orientation in the next higher solution derivative direction, aspect ratio evaluated in orthogonal plane
- Hessian for second-order methods
- Metric regularity aids grid mechanics



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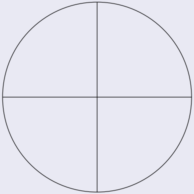
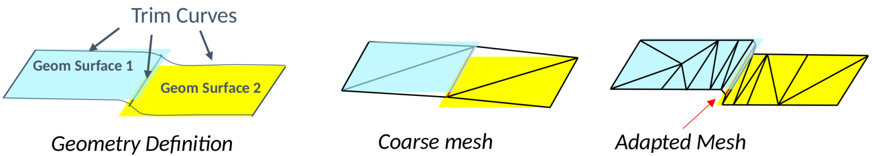


Status: Geometry

Geometry for grid adaptation

- Parallel and client-server access available but infrequently used
- Surrogate or implicit representations for parallel access and small gaps
- Adaptation places more stringent needs on geometry than a fixed-grid approach



Status: Higher Order Boundaries

Curved Meshes

- Required for many high-order schemes
- Displacement of linearly generated and adapted grids
- Few examples of directly adapting curved grid
- May increase geometry requirements (e.g., surface normal)
- High-order methods may allow larger elements

Outline

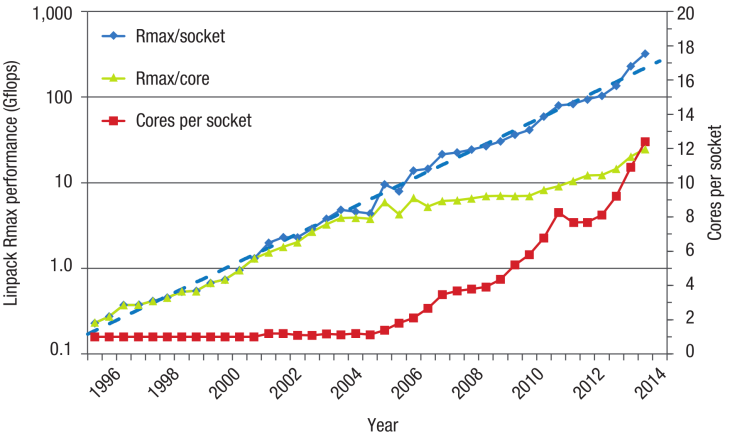
Forecast: HPC

Architecture shift underway

- Traditional gains in single core performance no longer available
- Sequential and per core speed stagnate and forecast to drop
- Parallel *and hybrid* decomposition of application work and memory
- Concurrency requirements will accelerate
- A given implementation may execute slower on new hardware without software investment

Forecast: HPC

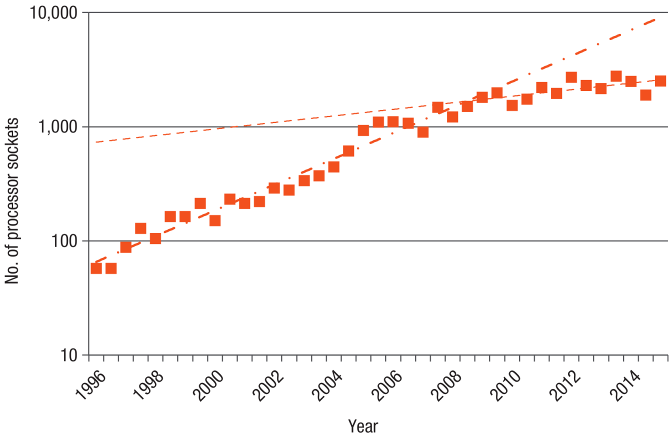
Reduction in single core performance gains[3]



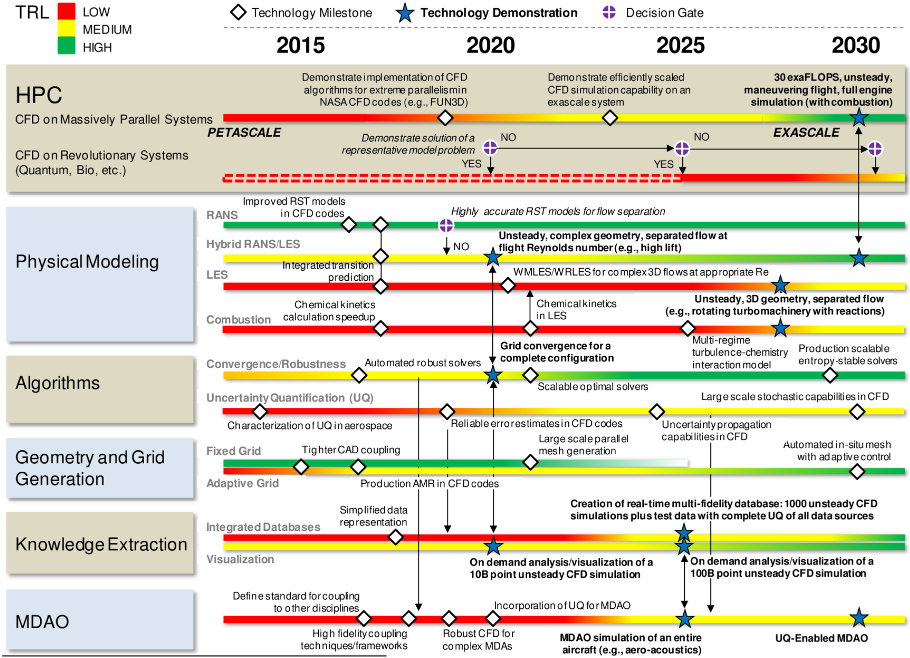
[3] Strohmaier et al., The TOP500 List and Progress in High-Performance Computing, Computer, 2015

Forecast: HPC

Assume 10x speed up per five years (post 2010 observations)[4]



[4]Strohmaier et al., The TOP500 List and Progress in High-Performance Computing, Computer, 2015



[5] Slotnick et al. CFD Vision 2030 Study: A Path to Revolutionary Computational Aerosciences NASA CR-2014-218178

In Five Years: 2020

Forecast

- Error estimation and metric construction mature for CFD
- Orthogonality of adaptive grid elements improves
- Research includes 2D and 3D methods

Recommendations

- Improve solver automation to impact all disciplines
- Evaluate mesh and geometry databases (e.g., MOAB, PUMI), which include linkages to CAD and CAD surrogates
- Improve error estimation for CFD
- Improve anisotropic initial grid generation and adaptation
- Sequential algorithms become parallel

In Ten Years: 2025

Forecast

- Reliable error estimation extensions will include other disciplines, coupling terms, and turbulent eddy resolving methods
- Design optimization and uncertainty quantification based on adapted grid solutions with comparable or superior efficiency to fixed grids
- Accurate Common Research Model (DPW) solution with reliable error estimate verified by asymptotic convergence rate demonstration
- Customers will require the option of adaptive methods and error estimates from vendors easing the initial grid generation task

Recommendations

- Robustness also be incorporated into higher levels of the system
- Shift in emphasis from pre-deployment testing to monitoring the application in production due to high complexity and throughput
- All research in parallel, application includes heterogeneous hardware

In Ten Years: 2025

System Level Robustness

- Completely testing all aspects of the integrated CFD process during development will no longer be possible
- Shift to monitoring the application in production and statistically evaluating failures
- Intentionally failing components in production to harden system (Netflix Chaos Monkey)
  - Failure to evaluate a CAD geometry query
  - Rebooting a server
  - Network failures
  - Flow solver divergence

In Fifteen Years: 2030

Forecast

- Adaptive grid computations displace fixed grids as the default
- Practitioner will rarely visualize the grid directly
- Verification databases provide high confidence in discrete solutions
- Modeling, coupling, and manufacturing errors will be quantified, controlled, and balanced to increase design robustness
- Error estimation and adaptation is a clear competitive advantage

Recommendations

- Embrace adaptive execution and fault tolerance on heterogeneous and throttling architectures
- Define standards for analysis certification and certification by analysis

Outline

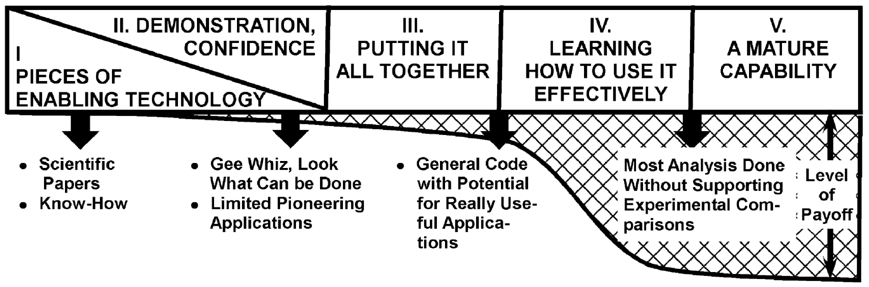
Grid Adaptation Technology Diffusion Strategy

> In industry, CFD has no value of its own. The only way CFD can deliver value is for it to affect the product. To affect the product, it must become an integral part of the engineering process for the design, manufacture, and support of the product.[6]

[6] Johnson, Tinoco, and Yu, Thirty Years of Development and Application of CFD at Boeing Commercial Airplanes, Seattle, Computers and Fluids, 2005

Grid Adaptation Technology Diffusion Strategy

Phases of the CFD development process.[7, 8]



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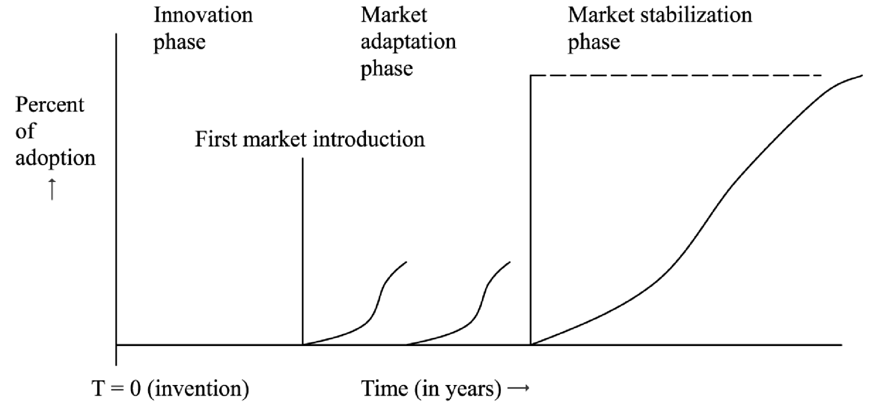
[7]Johnson, Tinoco, and Yu, Thirty Years of Development and Application of CFD at Boeing Commercial Airplanes, Seattle, Computers and Fluids, 2005

[8]National Research Council, Current Capabilities and Future Directions in Computational Fluid Dynamics, NASA CR-179946, 1986

Grid Adaptation Technology Diffusion Strategy

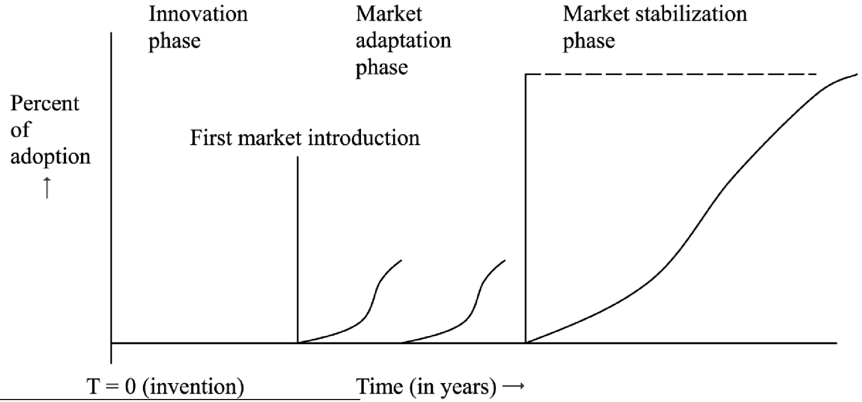
Phases in the technology diffusion process[9]



[9] Ortt and Schoormans, The Pattern of Development and Diffusion of Breakthrough Communication Technologies, European Journal of Innovation Management, 2004

Grid Adaptation Technology Diffusion Strategy

It is important to establish the position of the technology in the pattern of development and diffusion and that strategies should be tailored to this position.[10]



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Grid Adaptation Technology Diffusion Strategy

The choice being made is not a choice between adopting and not adopting but a choice between adopting now or deferring the decision until later.[11]

Adoption should not take place the instant that benefits equal costs, but should be delayed until benefits are somewhat above costs.[11]

Take-off is caused by outward shifting supply and demand curves.[12] [Number of grid adaptation implementations is a more important factor than the efficiency of a particular implementation to trigger rapid adoption.]

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[11] Hall and Khan, Adoption of New Technology, National Bureau of Economic Research, Working Paper 9730, 2003

[12] Agarwal and Bayus, The Market Evolution and Sales Takeoff of Product Innovations, Management Science, 2002

Outline

Summary and Conclusions

Summary

- Impact, status, and roadmap synergies with the CFD Vision 2030
- Recommended investments are provided for fifteen year forecast

Conclusions

- HPC trends in single core performance stagnate, go heterogeneous
- Many items are dependent on other disciplines
- Adoption is critical to impacting production workflows (success)
- Robust participation of government, university, industry, and commercial vendor researchers is potentially the best way forward

In AIAA Paper 2016-3323

- Detailed description of unstructured grid methods
- Partial bibliography of the previous fifteen years to support the forecast