

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

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Finding 3 of the CFD Vision 2030 Study¹

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

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

Outline

- 1 Motivation
- 2 Impacts of Grid Adaptation
- 3 Status of Unstructured Methods
- 4 Fifteen Year Forecast
- 5 Technology Diffusion
- 6 Summary and Conclusions

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

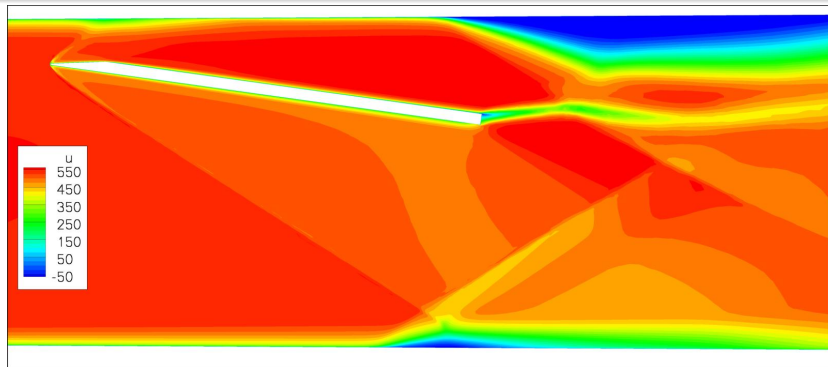
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Status: Grid Adaptation Mechanics

Primary focus on unstructured tetrahedral methods

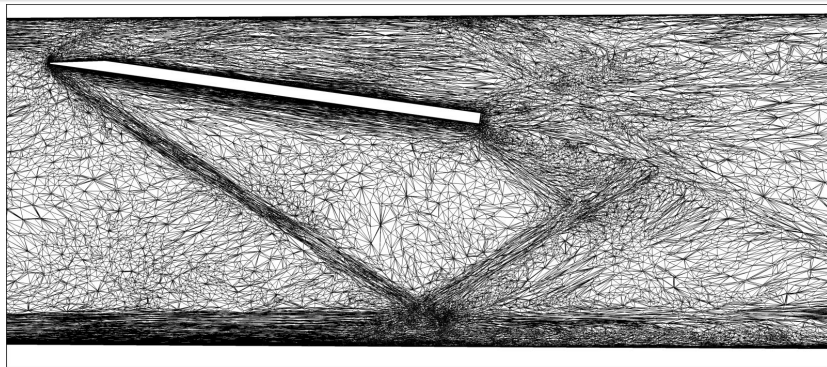
- High Reynolds number turbulent flows with discontinuities
- Arbitrary alignment and aspect ratio for complex flow simulations
- Lack of grid regularity in high gradient regions degrade solver and error estimation performance



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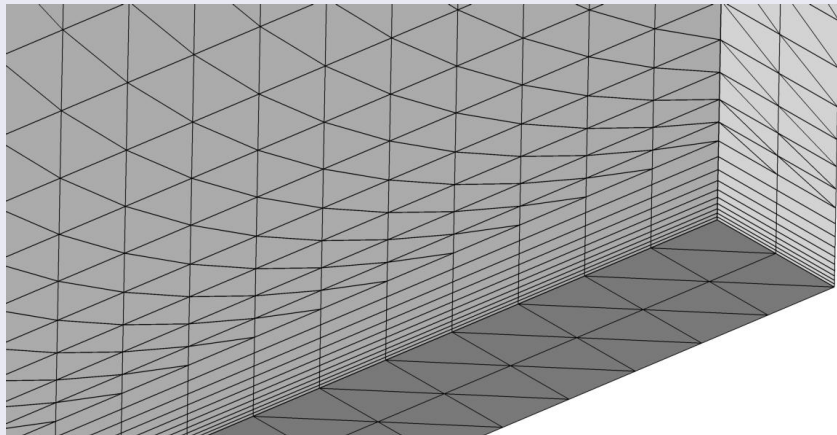
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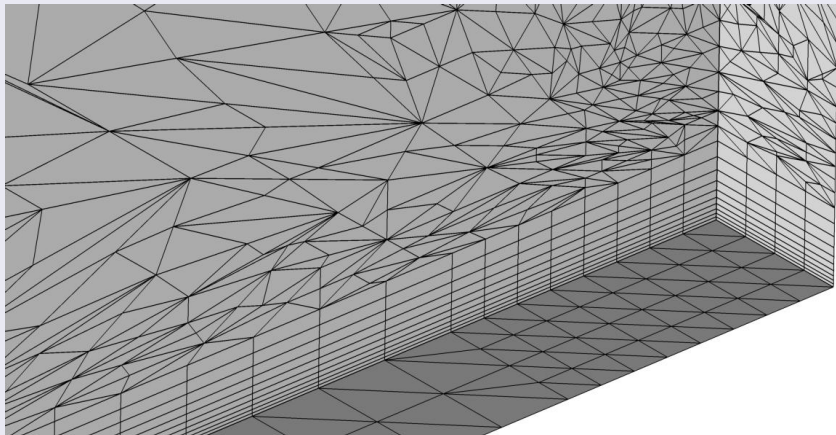
Structured and Cartesian subdivision

- 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

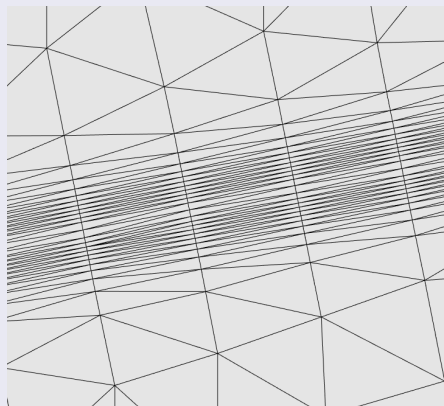
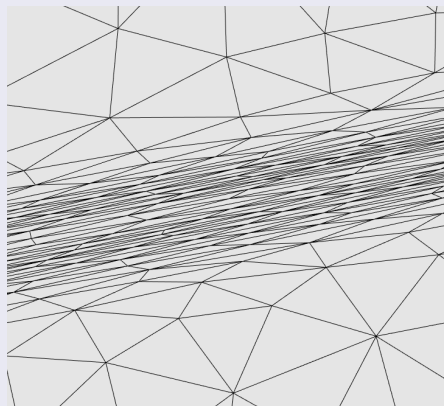
Semistructured prism stacks and tetrahedral grids



Semistructured prism stacks and tetrahedral grids



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

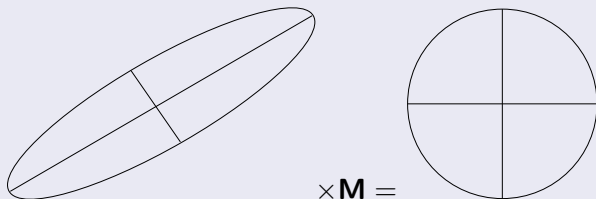
Available methods

- 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

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

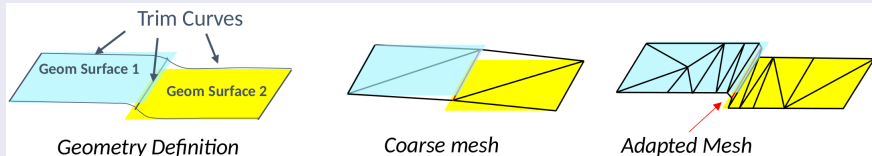
Anisotropy

- 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



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



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

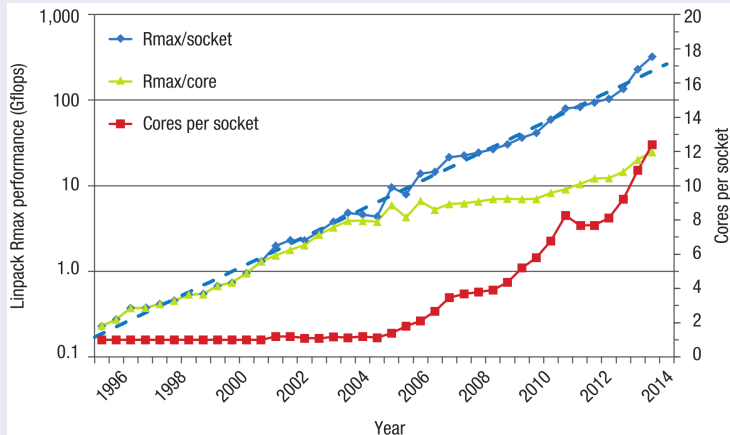
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Architecture shift underway

- 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

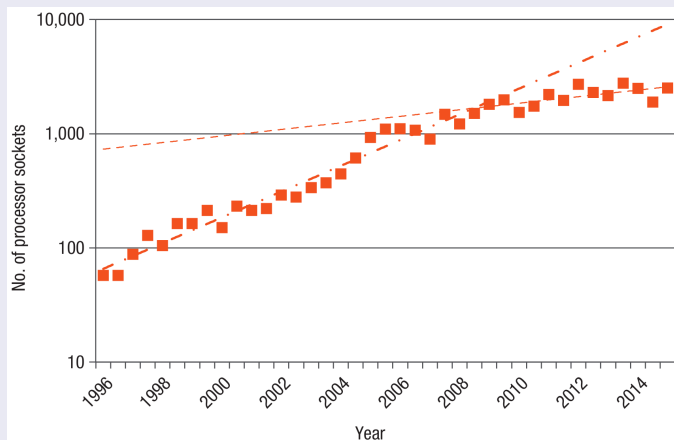
Reduction in single core performance gains³



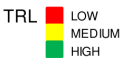
³Strohmaier et al., The TOP500 List and Progress in High-Performance Computing, Computer, 2015

Forecast: HPC

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



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



Technology Milestone ★ Technology Demonstration ✦ Decision Gate

2015

2020

2025

2030

HPC

CFD on Massively Parallel Systems

PETASCALE

Demonstrate implementation of CFD algorithms for extreme parallelism in NASA CFD codes (e.g., FUN3D)

Demonstrate efficiently scaled CFD simulation capability on an exascale system

30 exaFLOPS, unsteady, maneuvering flight, full engine simulation (with combustion)

CFD on Revolutionary Systems (Quantum, Bio, etc.)

Physical Modeling

RANS

Improved RST models in CFD codes

Highly accurate RST models for flow separation

Hybrid RANS/LES

Integrated transition prediction

Unsteady, complex geometry, separated flow at flight Reynolds number (e.g., high lift)

LES

Chemical kinetics calculation speedup

WMLLES/WRLES for complex 3D flows at appropriate Re

Combustion

Chemical kinetics in LES

Unsteady, 3D geometry, separated flow (e.g., rotating turbomachinery with reactions)

Algorithms

Convergence/Robustness

Automated robust solvers

Grid convergence for a complete configuration

Multi-regime turbulence-chemistry interaction model

Production scalable entropy-stable solvers

Uncertainty Quantification (UQ)

Characterization of UQ in aerospace

Reliable error estimates in CFD codes

Scalable optimal solvers

Large scale stochastic capabilities in CFD

Geometry and Grid Generation

Fixed Grid

Tighter CAD coupling

Large scale parallel mesh generation

Uncertainty propagation capabilities in CFD

Automated in-situ mesh with adaptive control

Adaptive Grid

Production AMR in CFD codes

Knowledge Extraction

Integrated Databases

Simplified data representation

Creation of real-time multi-fidelity database: 1000 unsteady CFD simulations plus test data with complete UQ of all data sources

Visualization

On demand analysis/visualization of a 100B point unsteady CFD simulation

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MDAO

Define standard for coupling to other disciplines

High fidelity coupling techniques/frameworks

Incorporation of UQ for MDAO

Robust CFD for complex MDAs

MDAO simulation of an entire aircraft (e.g., aero-acoustics)

UQ-Enabled MDAO

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

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

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

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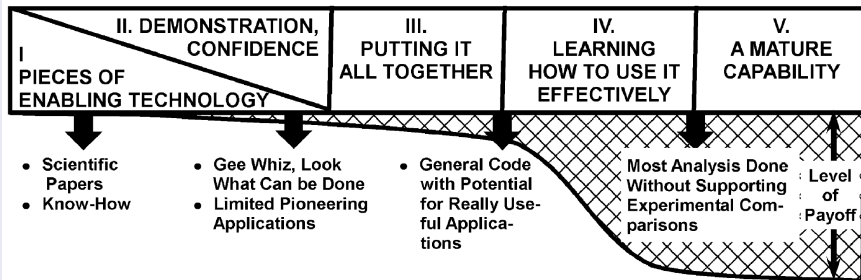
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In industry, CFD has no value of its own. The only way CFD can deliver value is for it to affect the product. To affect the product, it must become an integral part of the engineering process for the design, manufacture, and support of the product.⁶

⁶Johnson, 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}

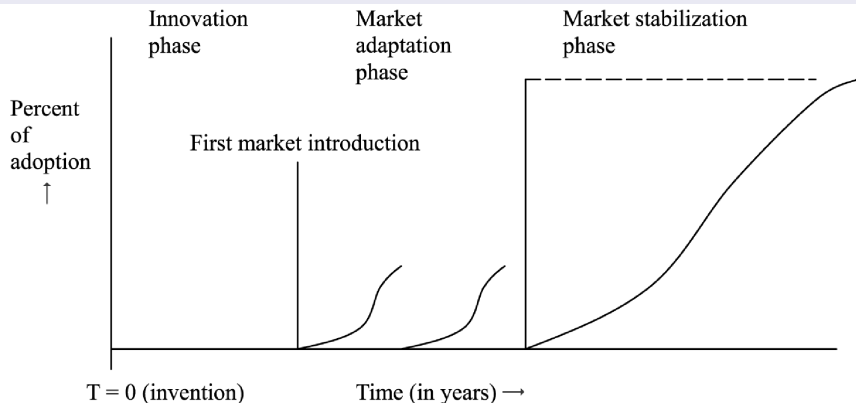


⁷Johnson, Tinoco, and Yu, Thirty Years of Development and Application of CFD at Boeing Commercial Airplanes, Seattle, Computers and Fluids, 2005

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

Grid Adaptation Technology Diffusion Strategy

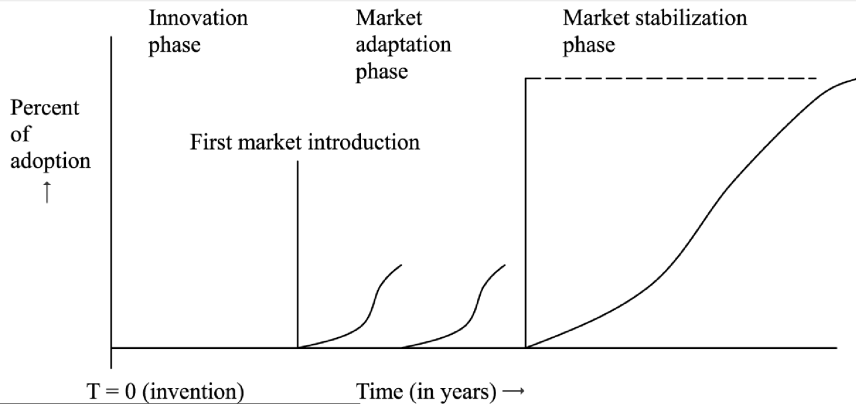
Phases in the technology diffusion process⁹



⁹Ortt 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



¹⁰Ortt and Schoormans, The Pattern of Development and Diffusion of Breakthrough Communication Technologies, European Journal of Innovation Management, 2004

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.]

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

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

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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 the paper

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