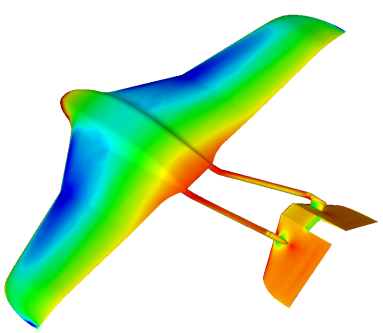
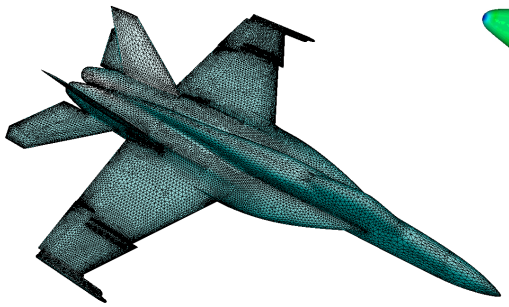
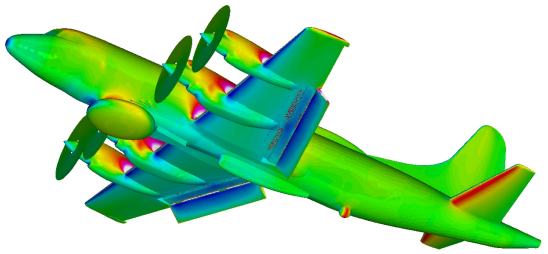


The Rise of Unstructured-Grid Methodology In Modern Aerodynamic Analysis and Design

Neal. T. Frink
NASA Langley Research Center
Hampton, Virginia, USA







Invited Lecture for 2013 AIAA Aerodynamics Award

June 24-27, 2013

San Diego, California

But first, let me introduce myself

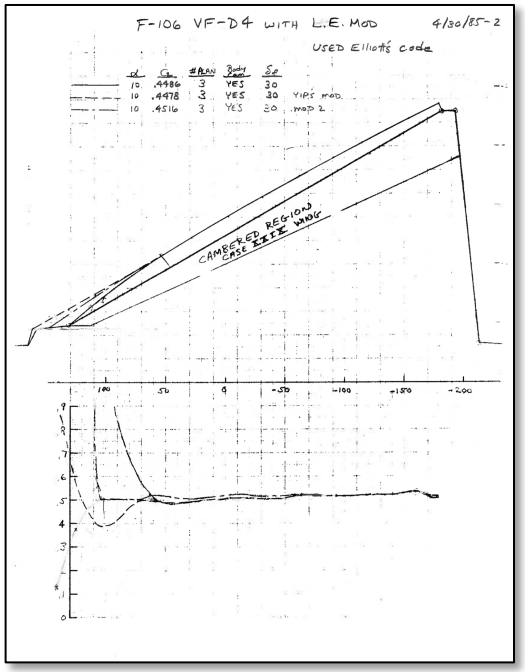


- Fascinated with flight at 3-years old
- Building model airplanes by 6-years old
- Mesmerized by NASA moon race in 60's
- Built hang glider for HS physics project
- Earned private pilot license during HS
- Entered NCSU aero engineering in 1972
- Co-oped at NASA LaRC from 1973-1977
- BS/MS from NCSU in 1977/1979
- Hired at NASA Langley Research Center in 1980
- Ph.D. from Virginia Tech in 1991
- Developing/applying USG CFD tools 1989 → today

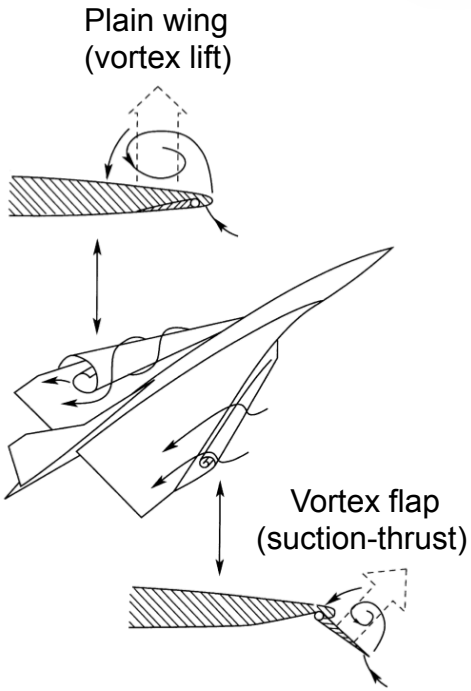
Neal.T.Frink@nasa.gov

An Exciting Project from 80's
From Concept to Flight Test

Design of F-106B vortex flap contour

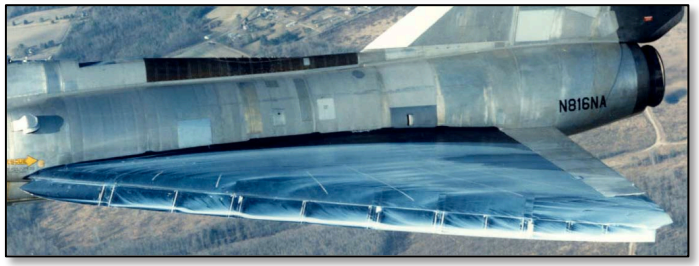


Frink, N. T.:
"A Concept for Designing Vortex Flap Geometries."
NASA TP-2233, Dec. 1983.



Flight test of NASA F-106B with vortex flap





(In-flight flow visualization)

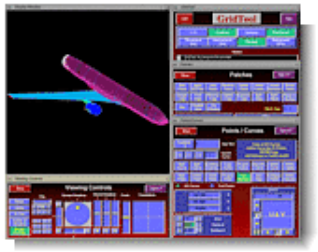
Brandon, Hallissy, Brown, and Lamar: "In-Flight Flow Visualization Results of the F-106B with a Vortex Flap" NATO RTO/AVT MP-69-P-43, May 2001.

Used simple analogy to design for complex flow physics

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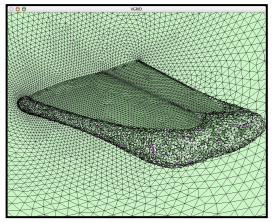
Enjoyable Project from 90/00's
Led Collaborative Development Team

TetrUSS - Tetrahedral Unstructured Software System

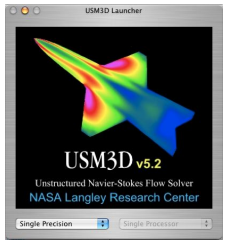


Geometry Setup
GridTool
(Samarah)

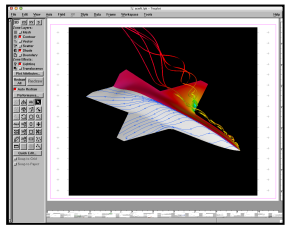
- USM3D written for Ph.D. dissertation
- Formed initial team of 4 researchers
- Strived to simplify the complex
- Won NASA SOYA in 1996 and 2004 and 2004 Apple Design Award.
- Led to many other fruitful collaborations



Grid Generation
VGRID
(Pirzadeh)



Flow Solver
USM3D
(Frink)



Visualization
ViGPLOT
(Parikh)



Tools & Utilities

Enjoyable Project from 90/00's

This is what made it all worthwhile.

The TetrUSS Team circa 2004



The TetrUSS team, left to right: Khaled S. Abdol-Hamid, Jamshid A. Samareh, Paresh C. Parikh, Craig A. Hunter, Shahyar dZ. Pirzadeh, Neal T. Frink, Mohagna J. Pandya.

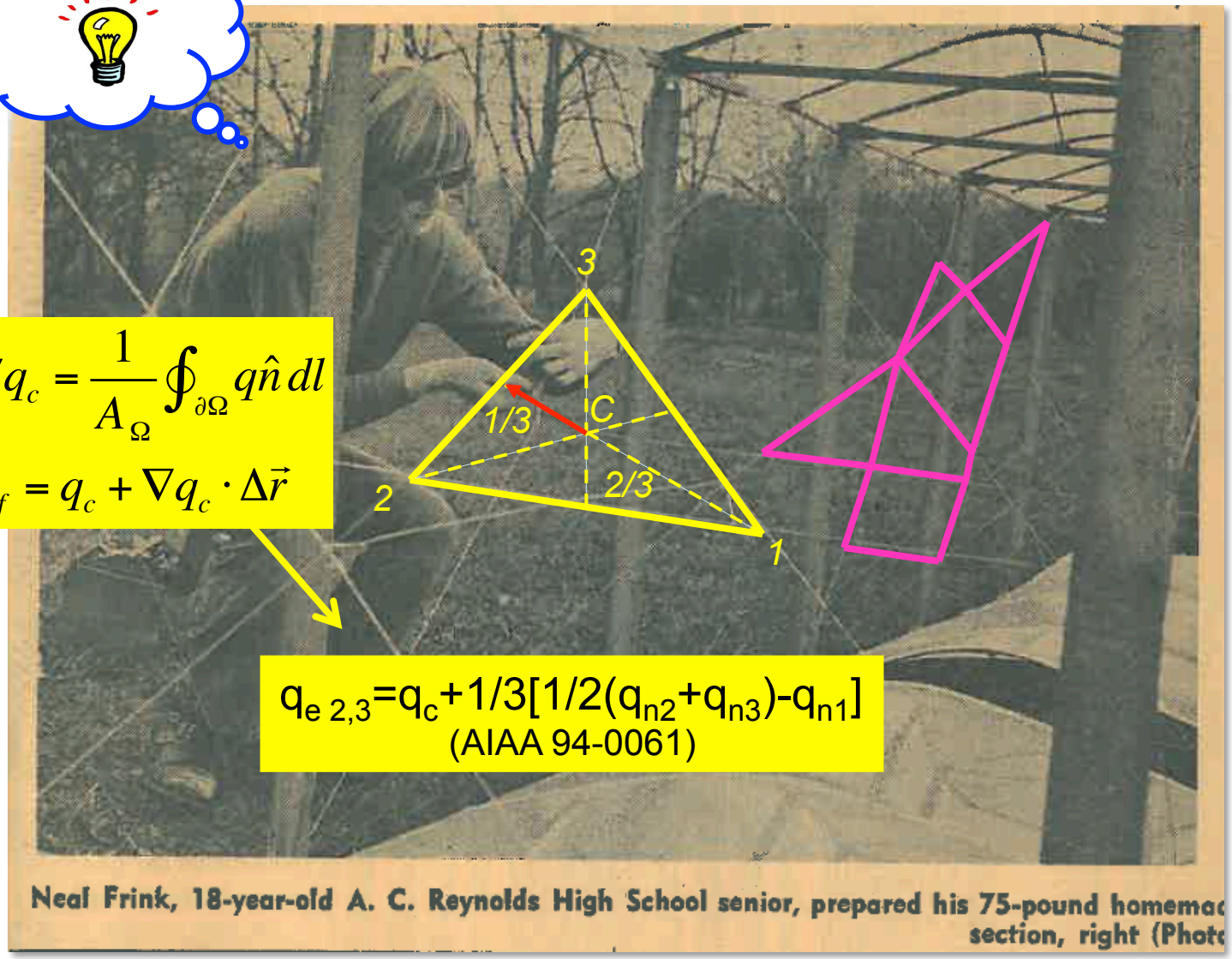
Research Before Unstructured CFD

Asheville NC, April 1, 1972



Youtube: Search for “Frink hang glider”

Already Pioneering Concepts for USG as early as April 1, 1972



$$\nabla q_c = \frac{1}{A_\Omega} \oint_{\partial\Omega} q\hat{n}\, dl$$

$$q_f = q_c + \nabla q_c \cdot \Delta\vec{r}$$

$q_{e\ 2,3}=q_c+1/3[1/2(q_{n2}+q_{n3})-q_{n1}]$
(AIAA 94-0061)

My Desire for You Today



- **Enjoy a multi-decade perspective of USG**
  - My involvement in development/application since 1989

- **In the end, I hope we will**
  - Better understand the key factors that produced revolutionary advances in CFD
  - Appreciate the level and breadth of innovation inspired by a relatively small number of pioneers
  - Be inspired to forge ahead on next revolution in CFD

Neal.T.Frink@nasa.gov

Unstructured-Grid Methodology

*Three Decades of Innovation**

1985 1990 1995 2000 2005 2010

Beginnings

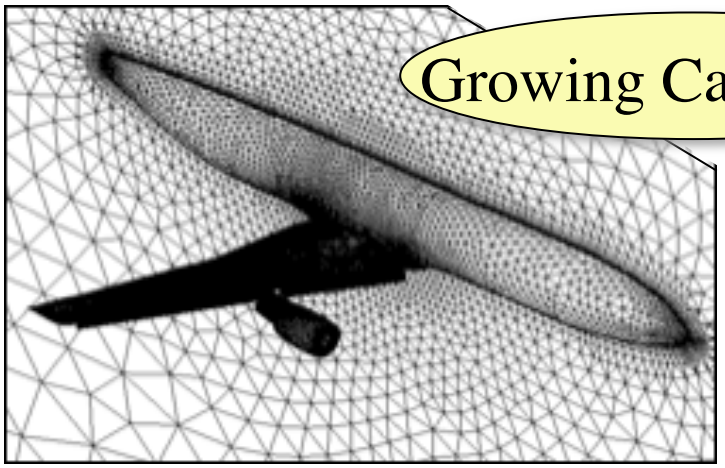
Enabling Technologies

Growing Capabilities

Entering the Mainstream

New Frontiers

Will touch on some of the more pivotal innovations that opened new doors in CFD

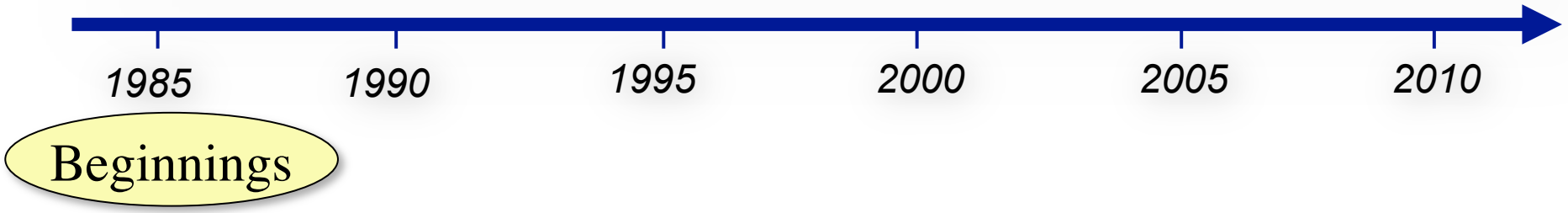


** Built on the shoulders of giants from '60s and '70s*

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Unstructured-Grid Methodology

Three Decades of Innovation



- **The forces of change**
  - Critical needs
  - Roadblocks in contemporary approaches

- **New approaches**
  - Fresh, raw innovation needed
  - Essential to “break out of the box”

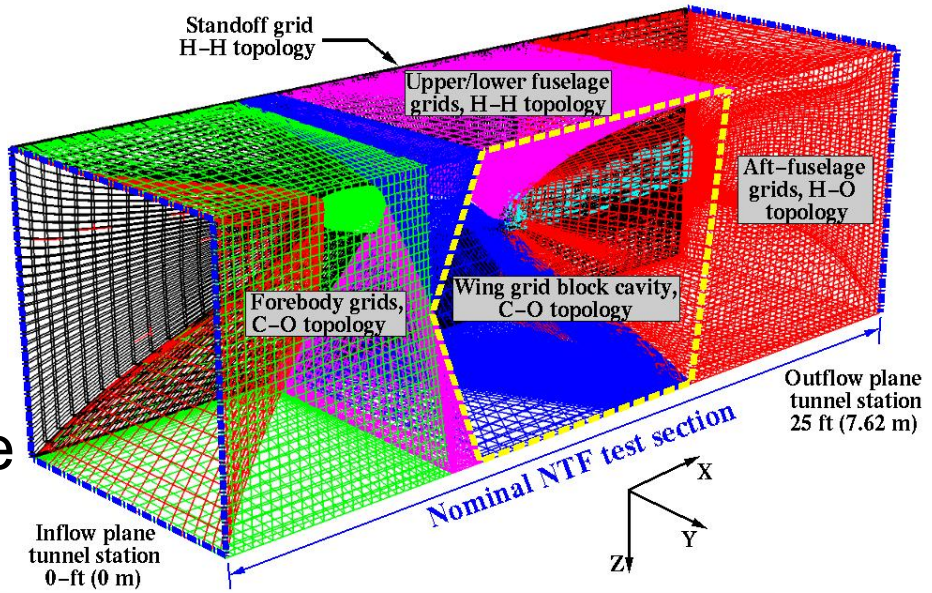
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Beginnings of USG

The Forces of Change - Roadblocks

1985 1990 1995 2000 2005 2010

- **"Hit the wall" in grid generation**
  - Structured hexahedral grids were pursued for CFD almost exclusively up thru mid '80s
  - Heavy investment in structured multiblock grid methods, nonuniform patching, better grid generation codes, etc.
  - Grid generation became the barrier problem



With best efforts there was no solution in sight

Beginnings of USG

The Forces of Change - Critical Needs



- **Growing pressure for CFD to reduce costs**
  - – Aerospace industry looking for payoff technologies to reduce design cycle time for new vehicles
  - – Structured-grid methods became very productive for clean, cruise configurations via grid templates
  - – For unconventional geometries, grid generation for complex geometries took months
  - – Growing need for new “out-of-the-box” approaches

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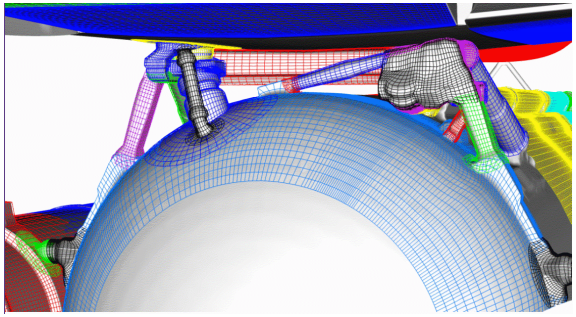
Beginnings of USG

The Forces of Change - New Approaches

1985 1990 1995 2000 2005 2010

- **Early pioneers explored alternate approaches**
  - **Benek, Buning, Steger** (mid/late ‘80s) developed structured overset grid methods (coarse-grain unstructured)
  - Very powerful, but grid generation still time consuming
  - Was the primary CFD support tool for the Space Shuttle





Overlapping grid system on space shuttle
(Slotnick, Kandula and Buning 1994)

Still as viable today as ever.

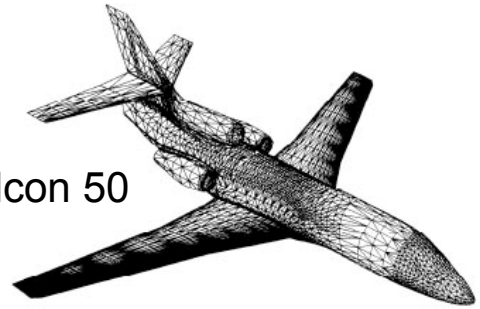
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Beginnings of USG

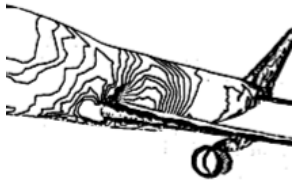
The Forces of Change - New Approaches

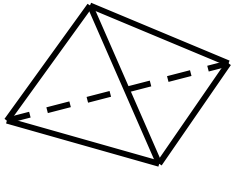
1985 1990 1995 2000 2005 2010

- **Early pioneers explored alternate approaches**
  - **Bristeau, et. al, (1985)** demonstrated finite element transonic flow over Falcon 50 on triangular mesh
  - **Jameson, Baker, Weatherill (1986)** - demonstrated of the generation of coarse tetrahedral grid and inviscid finite-volume flow solution on B-747 aircraft
  - landmark work that opened door for non-hexahedral elements in numerical simulation of flow equations



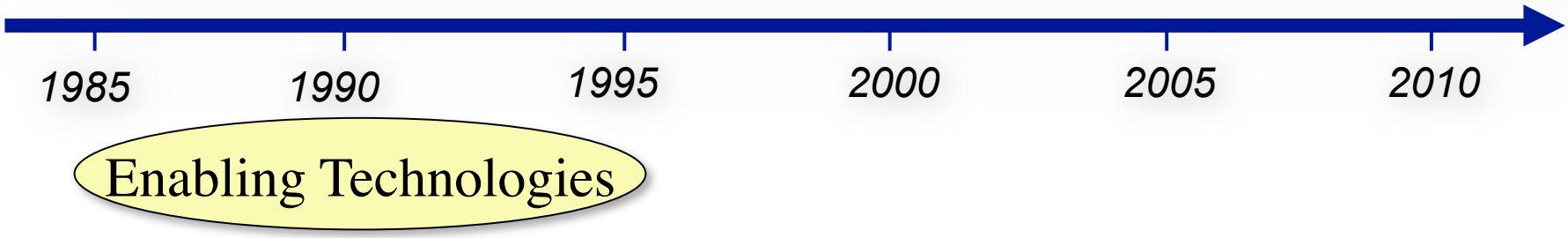






Unstructured-Grid Methodology

Three Decades of Innovation



- **Key obstacles**
  - How does one numerically solve the Navier-Stokes equations on tetrahedral cells?
  - How do you generate thin-layer tetrahedral grids?
  - Memory and runtime requirements seem prohibitively large for current computers
- **Pivotal advancements**
  - 2nd order reconstruction schemes
  - One-equation PDE turbulence model
  - Advancing Front / Advancing Layers grid generation

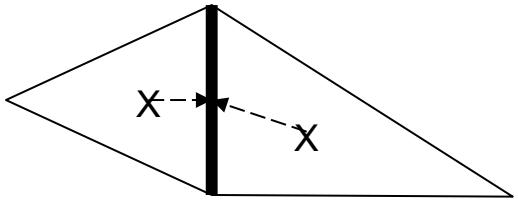
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Enabling Technologies

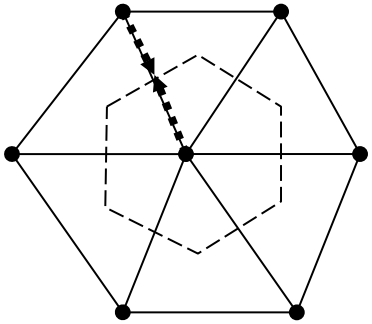
Key Innovations in Discretization



- **New approaches devised to solve problem of discretization in space and time**
  - 2nd order tetrahedral reconstruction schemes
    - Anderson, Baker, Barth, Batina, Frink, Lohner, Peraire, Marcum, Mavriplis, Mitchell, Morgan, Nakahashi, Weatherill
  - Multigrid
    - Mavriplis



Cell-based



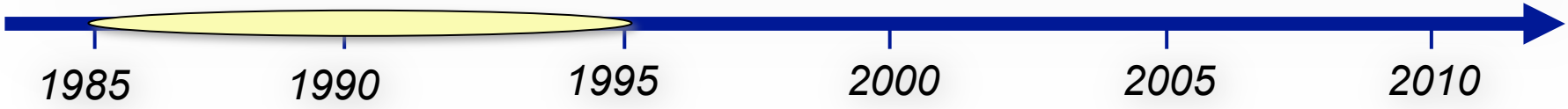
Vertex-based

How do you reconstruct flow solution on tetrahedral elements?

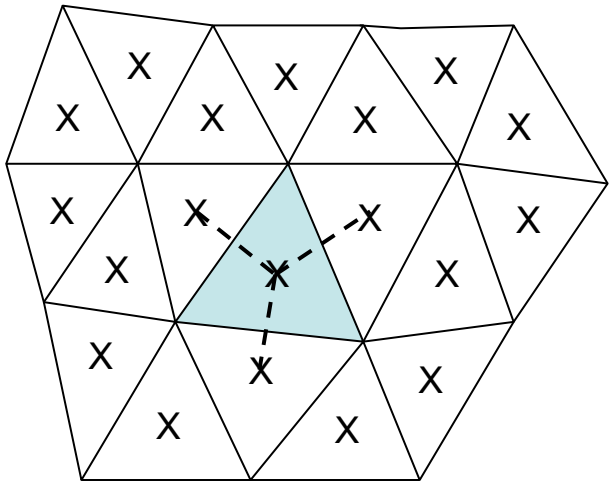
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Enabling Technologies

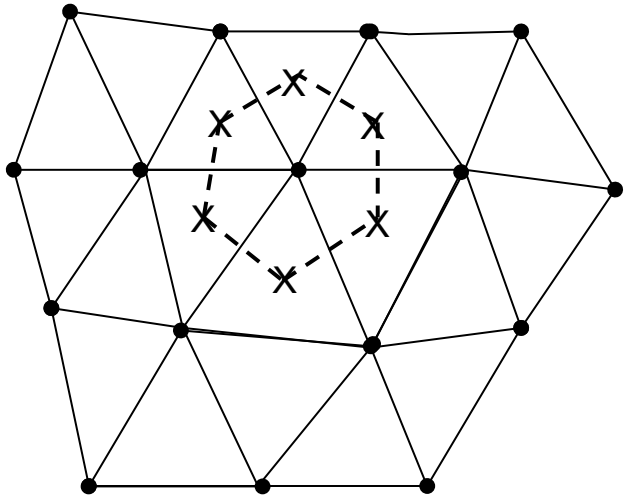
Key Innovations in Discretization



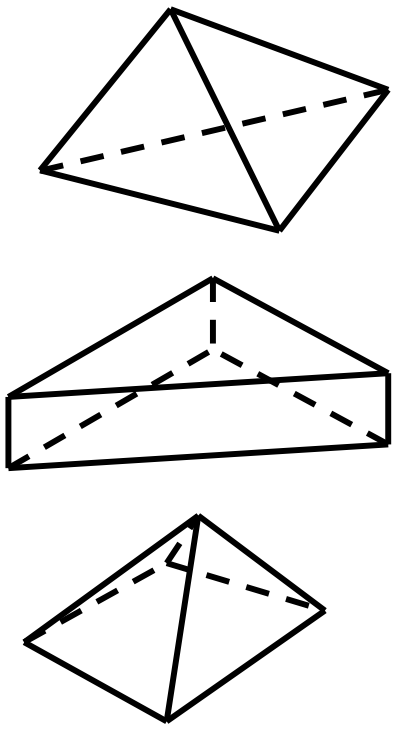
- **Fundamentals of unstructured-grid methodology**
  - Cell topologies (tetrahedra, prisms, pyramids, etc)
  - Data structure (face-based, edge-based)
  - Cell- vs. vertex-based reconstruction



Cell-centered topology



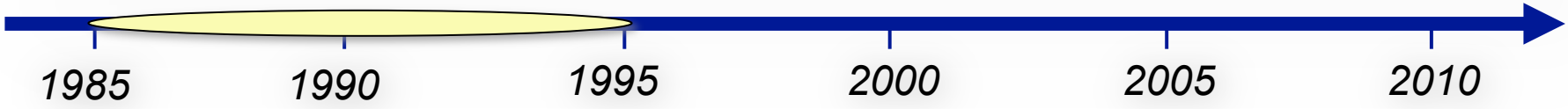
Vertex-centered topology



Approx. 5.5 cells per 1 vertex

Enabling Technologies

Key Innovations in Turbulence Modeling



- **Solving the problem of turbulence models**
  - Early attempts by Mavriplis to implement popular Baldwin-Lomax algebraic model to tetrahedral grids
    - » not amenable to "unstructured" cell topology
  - One-equation PDE turbulence models
    - » Spalart-Allmaras devised 1-eqn model
    - » Baldwin-Barth 1-eqn model
    - » paved way for advanced 2-eqn PDE models

The PDE turbulence model was an enabling technology for USG

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Enabling Technologies

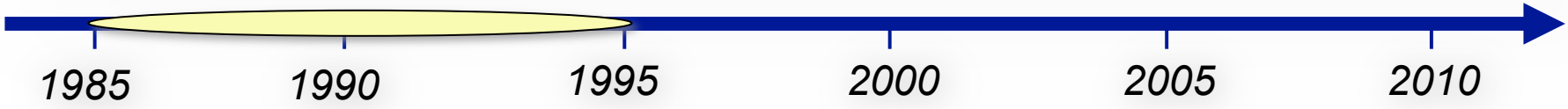
Key Innovations in Grid Generation



- **Solving the problem of grid generation**
  - Delauney triangulation (inviscid)
    - Baker, Weatherill
  - Advancing Front (inviscid)
    - Lohner, Parikh, Peraire, Morgan
  - Thin-layer grid generation (viscous)
    - Pirzadeh, Kallinderis, Nakahashi, Marcum, Lohner

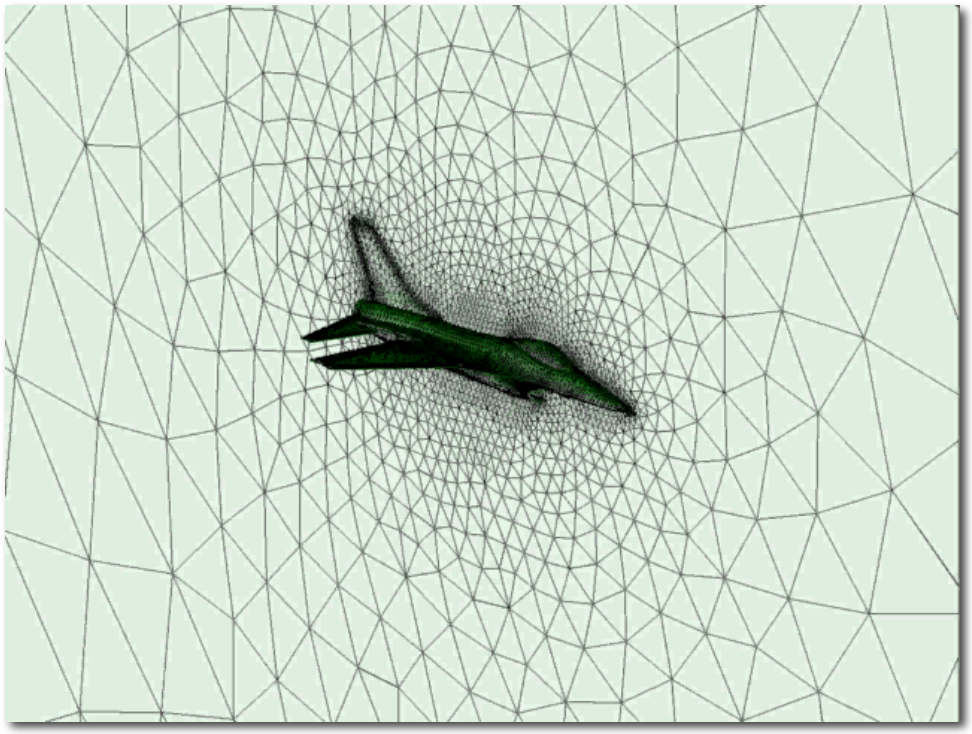
Enabling Technologies

Advancing Front Grid Generation



- Advancing Front Method by Lohner and Parikh (1988) embodied in the VGRID code

- Enables rapid generation of tetrahedral grids on very complex geometries



Video courtesy of J. Garriz, ViGYAN, Inc.

Enabled easy generation of tetrahedral grids on complex geometries

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Enabling Technologies

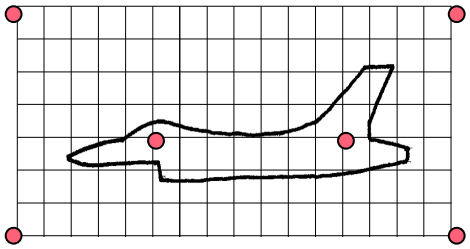
Key Innovations in Grid Generation

Innovations of S. Pirzadeh, NASA LaRC



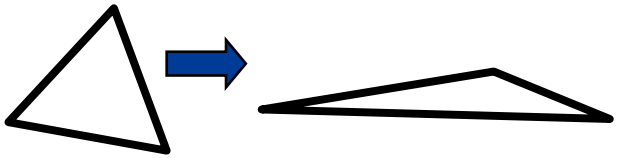
1985 1990 1995 2000 2005 2010

"Source" spacing control



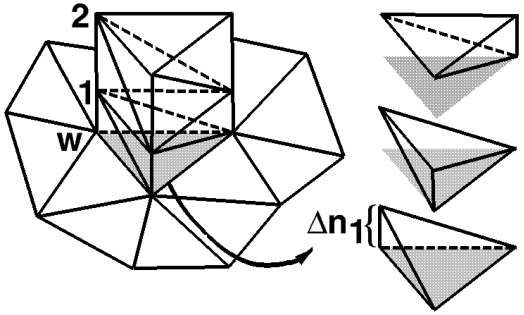
USG grid generation time reduced from weeks to days

Anisotropic Stretching



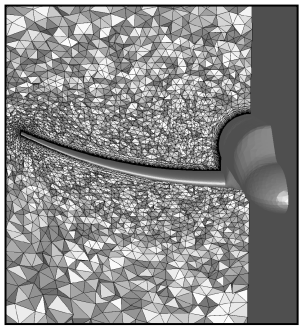
Problem size reduced by a factor of 3

Thin-Layer Tetrahedra



Enabled unstructured N-S solutions

Viscous Grid Movement



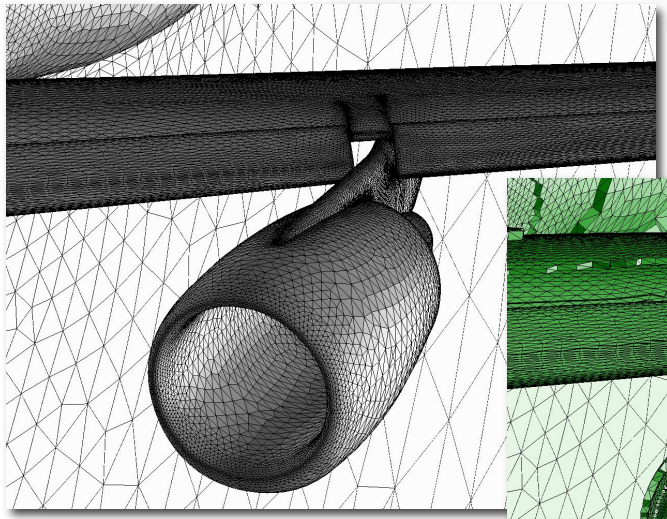
Enabled rapid N-S design

Enabling Technologies

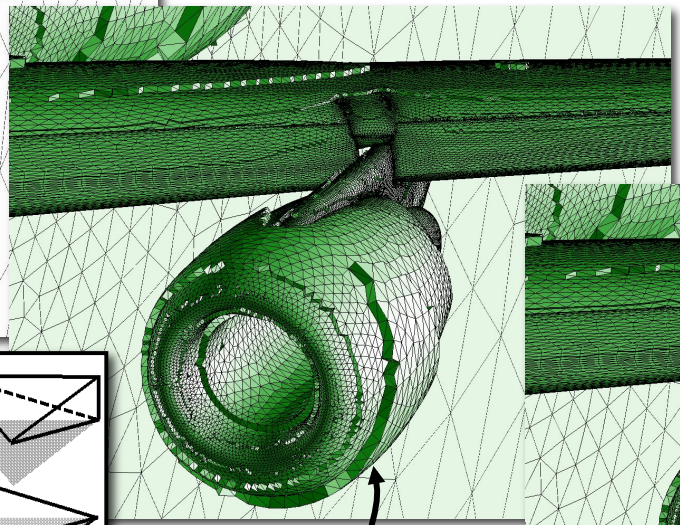
Advancing Layers Method Grid Generation

Courtesy of S. Pirzadeh, NASA LaRC

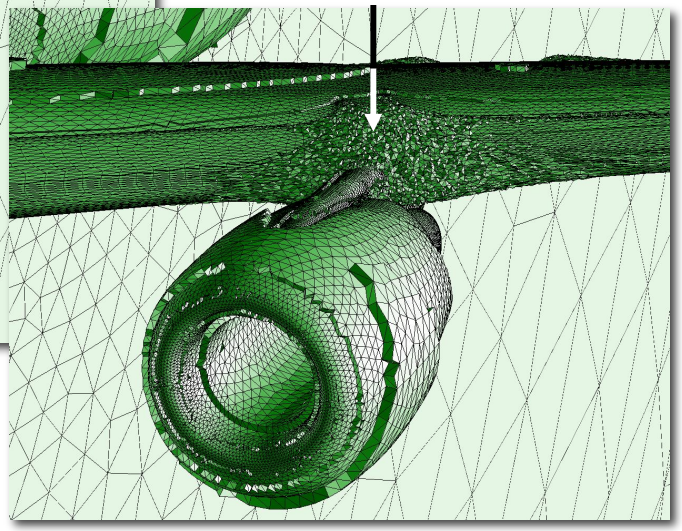
1985 1990 1995 2000 2005 2010

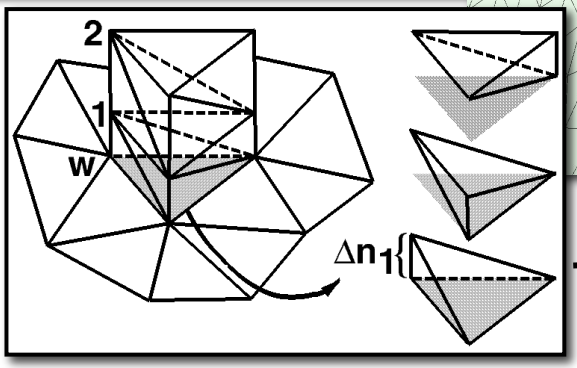


"ALM"
Advancing Layers



"AFM"
Advancing Front



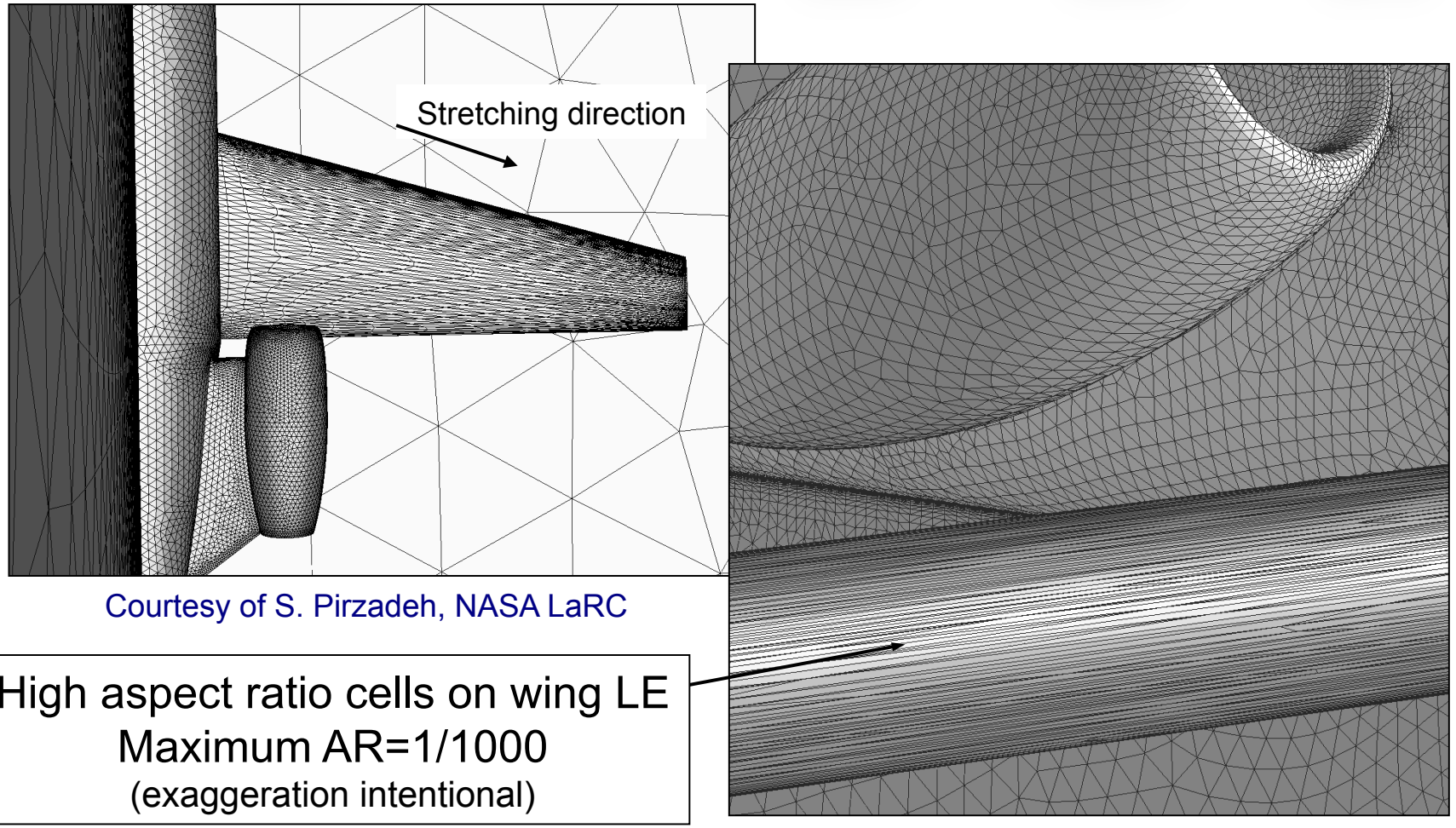


ALM - Breakthrough enabling full Navier-Stokes with USG

Enabling Technologies

Anisotropic Unstructured Grid Generation

1985 1990 1995 2000 2005 2010



Courtesy of S. Pirzadeh, NASA LaRC

High aspect ratio cells on wing LE
Maximum AR=1/1000
(exaggeration intentional)

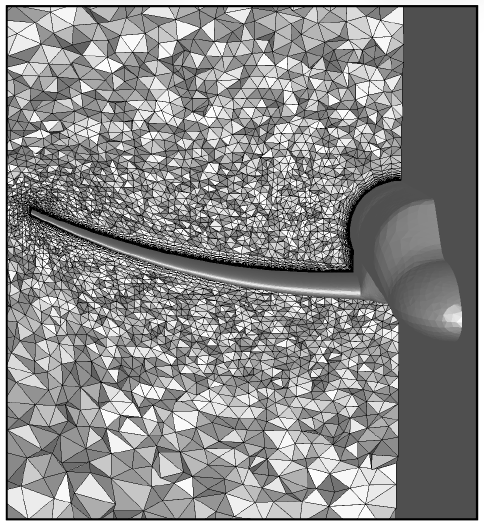
Enabling Technologies

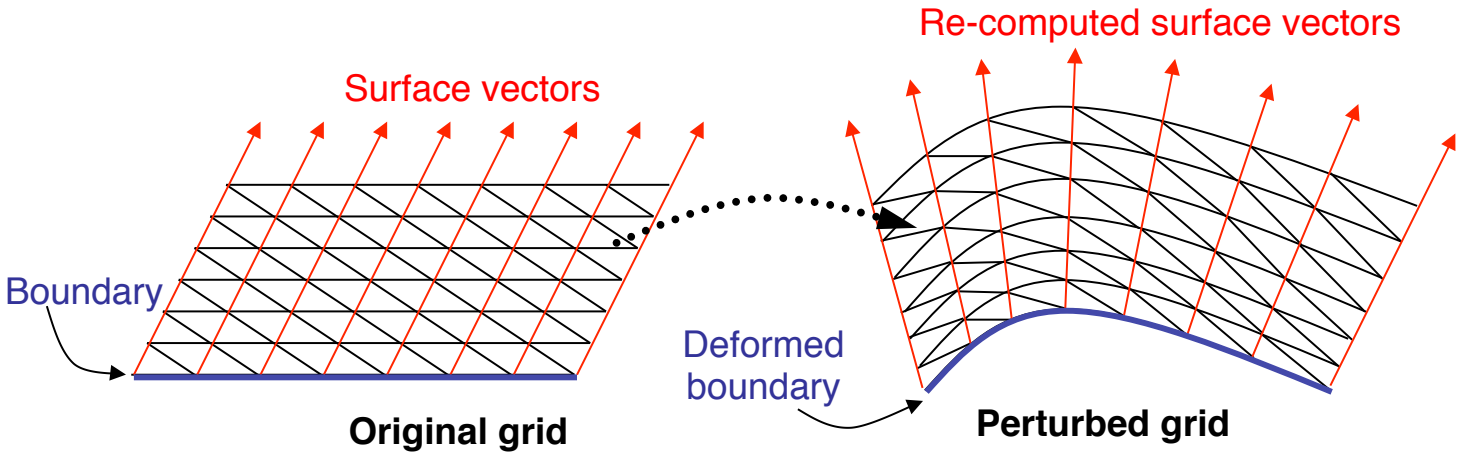
Moving Mesh Method

Courtesy of S. Pirzadeh, NASA LaRC



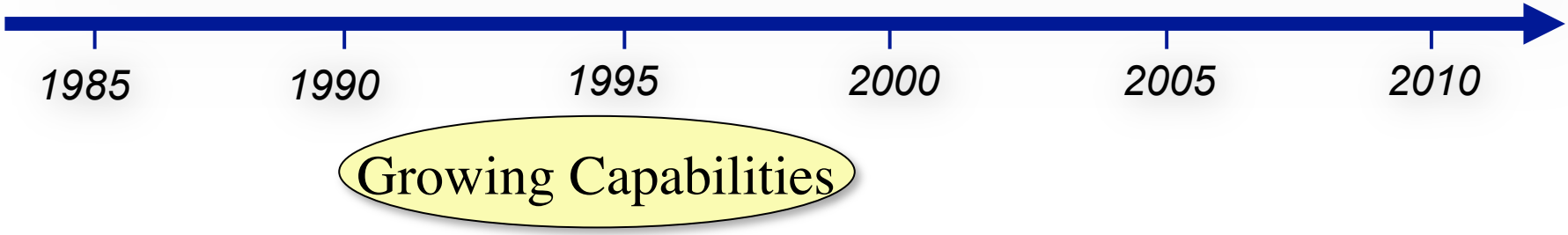
- Viscous grid movement based on
  - re-computation of surface vectors
  - re-distributed of existing nodes along vectors
- Inviscid grid movement based on
  - spring method
  - local remeshing (if necessary)
- Grid refinement incorporated in the code ***MoveMesh***





Unstructured-Grid Methodology

Three Decades of Innovation



- **Faster hardware**
  - Massively parallel processing
- **Increased functionality**
  - Better usability, reduced turn-around time
  - Rotor/propellers
  - Advanced turbulence models
  - Faster grid generation
  - Design

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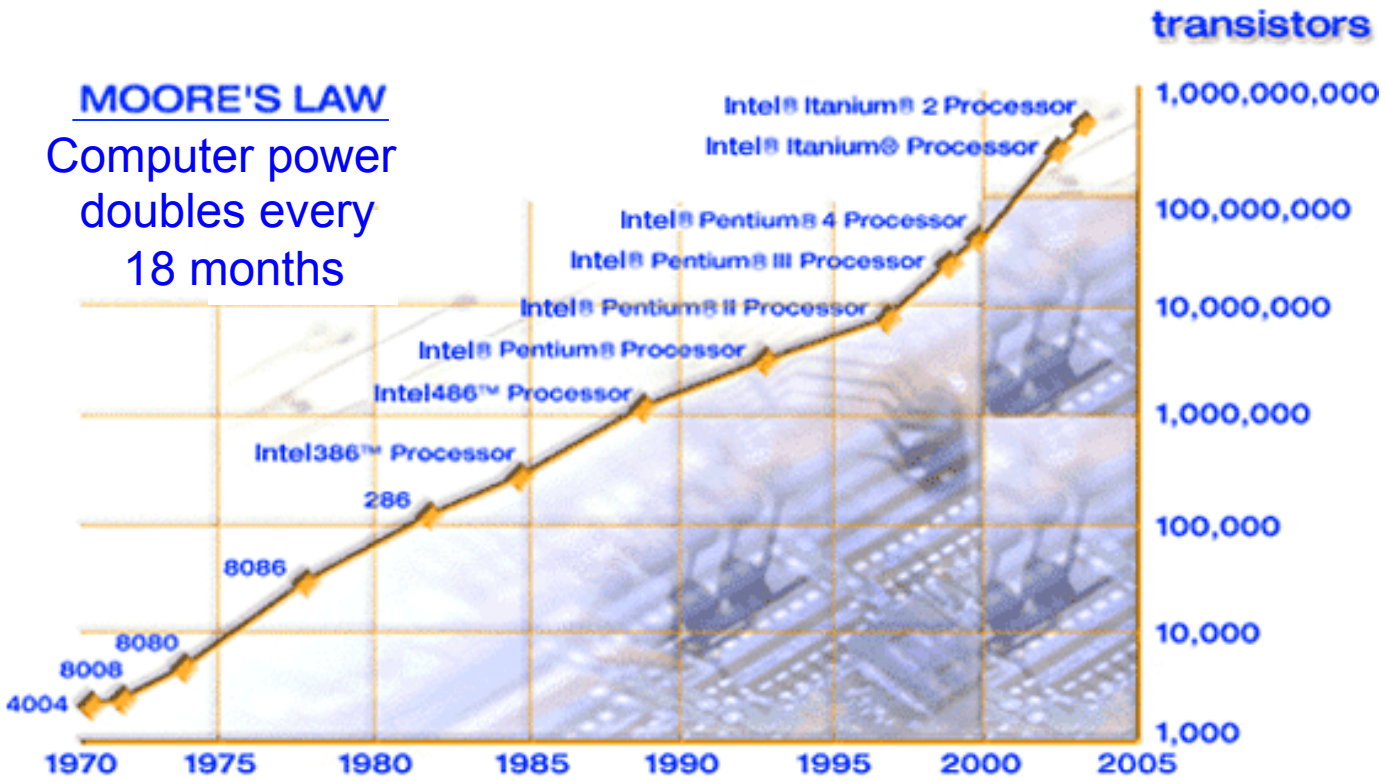
Growing Capabilities

Faster Hardware



MOORE'S LAW

Computer power doubles every 18 months



Profound impact on USG computational capabilities

Neal.T.Frink@nasa.gov

Growing Capabilities

Faster Hardware



- **Massively parallel computers**
  - Enabled scalability; orders of magnitude faster
  - Removed issue of large memory requirements
  - Orders of magnitude lower cost



Inexpensive PC Cluster



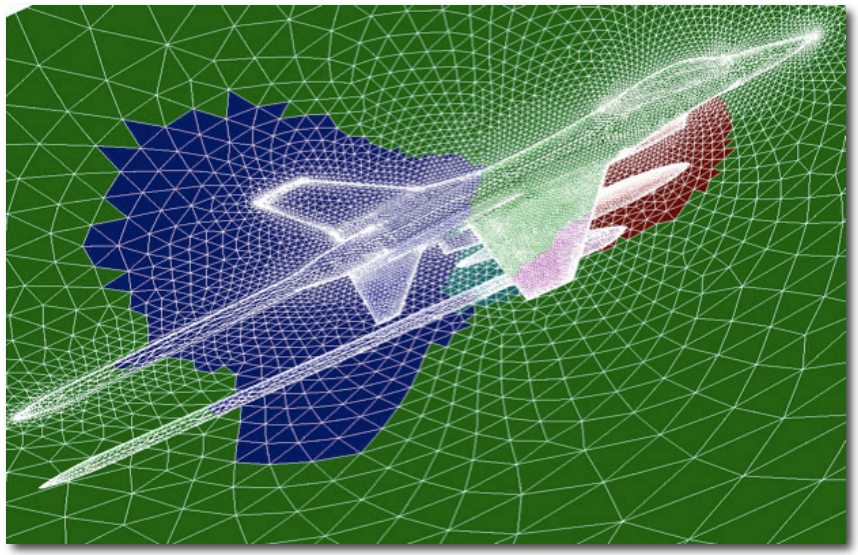
NASA Project Columbia (2005)
10,240-proc SGI Altix

Growing Capabilities

Parallel Processing



- **New grid partitioning strategies developed**
  - **Metis code** from University of Minnesota
  - Provided even load balancing of decomposed grids



Single-zone tetrahedral grid is decomposed into contiguous zones and scattered among processors

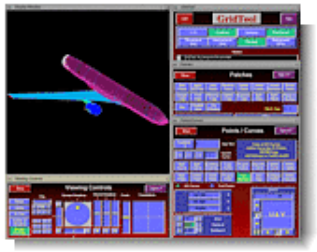
Colors indicate cells in different processors

Metis was an enabling development for parallelization in USG

Growing Capabilities

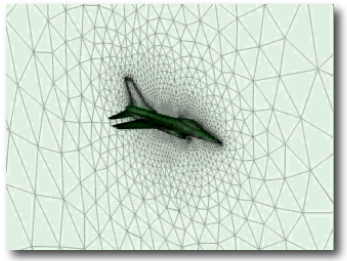
Better Usability

1985 1990 1995 2000 2005 2010



Geometry Setup
GridTool

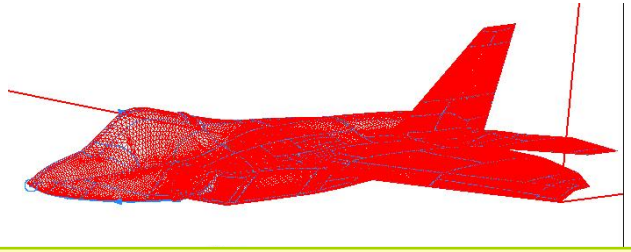
J. Samareh
NASA LaRC



Grid Generation
VGRID

S. Pirzadeh
NASA LaRC

F-22
Viscous Volume Mesh
~8x10^6 cells (VGRID)



~60 – 70 Total Labor Hours
(Can now be done in 2 hours)

Courtesy of R. Hooker
Lockheed Martin Aircraft Company

Grid generation time reduced from weeks/months to days

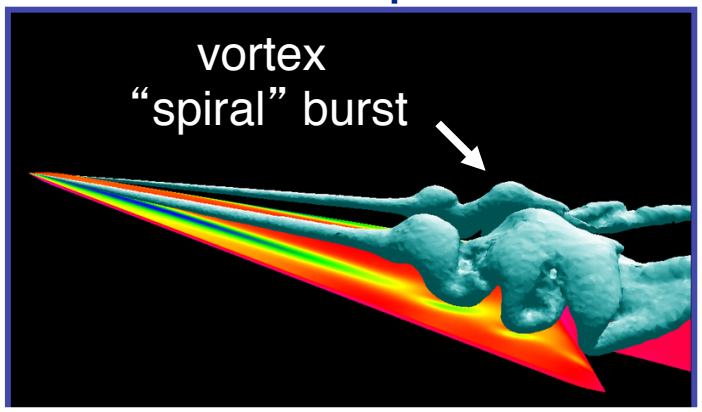
Growing Capabilities

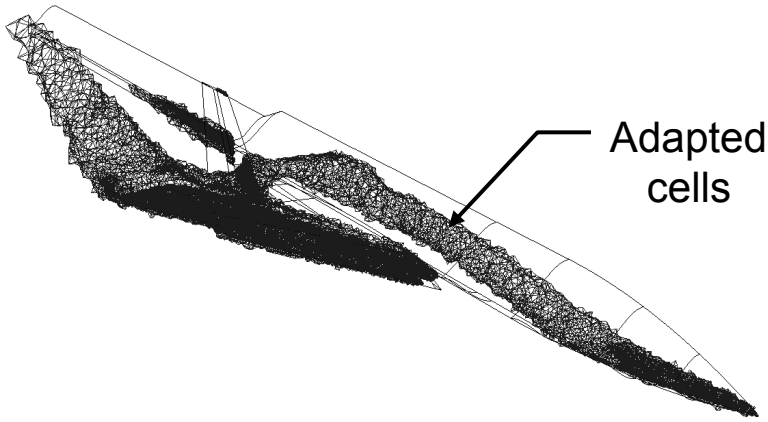
Advances in Grid Generation

Courtesy of S. Pirzadeh, NASA LaRC

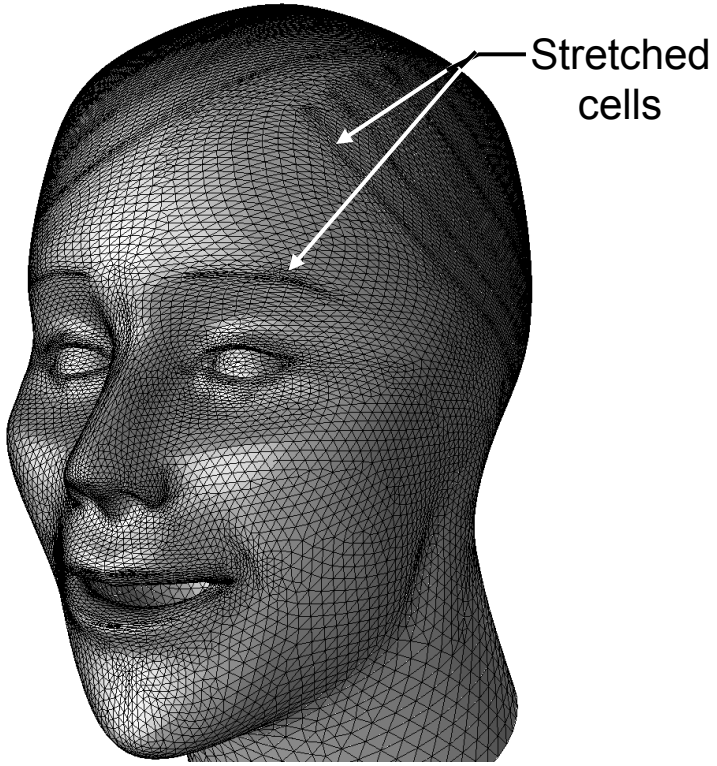


Solution Adaptive Grids





Anisotropic Stretching on CAD/NURB Surfaces



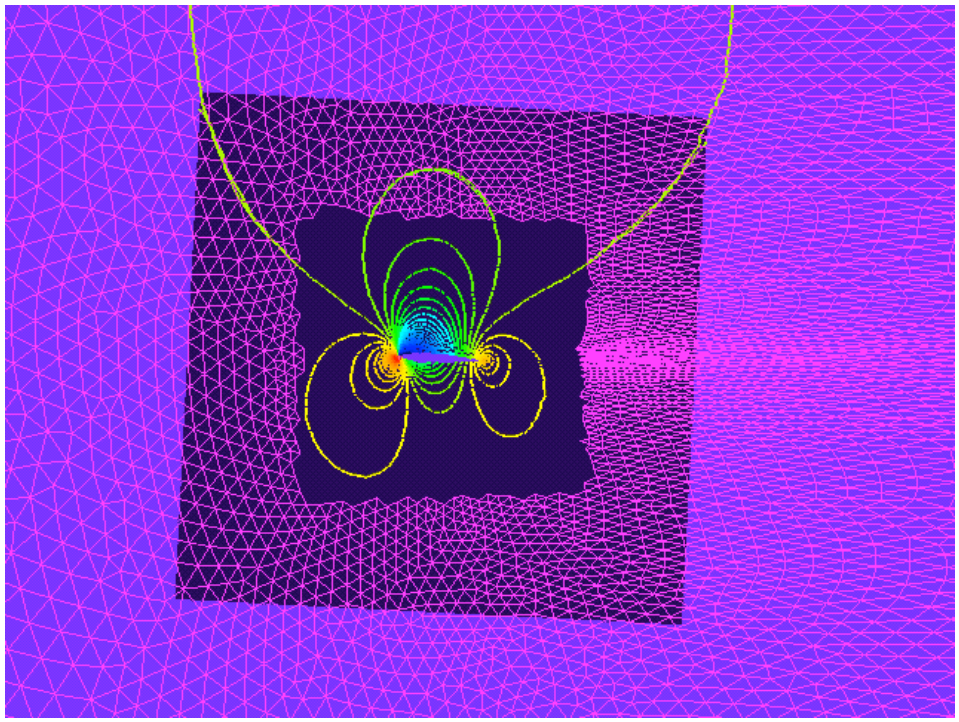
Growing Capabilities

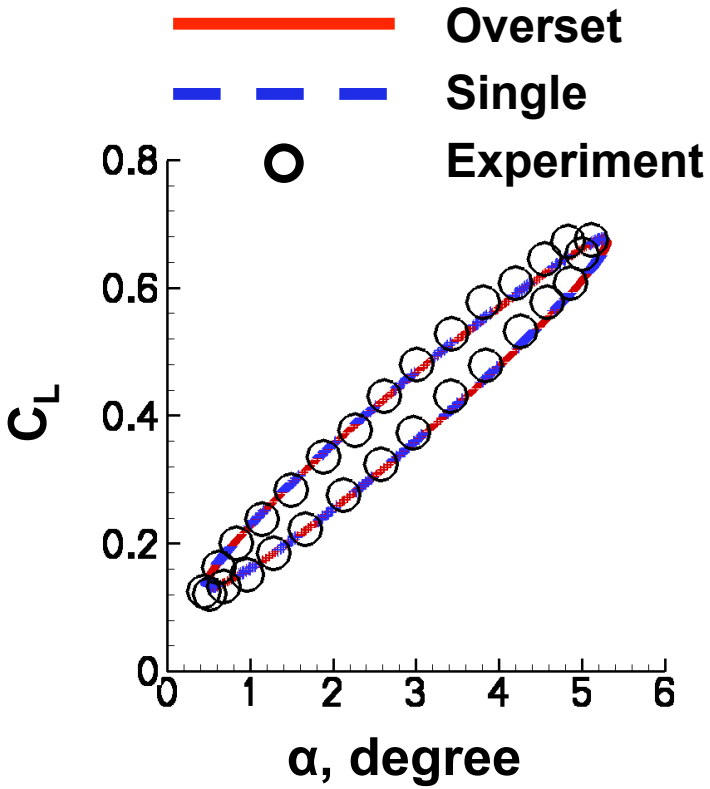
Unstructured Overset Grids

1985 1990 1995 2000 2005 2010

USM3D with DiRTlib/SUGGAR

NACA 0012: M=0.6, α=0 deg, κ=0.081, Re=4.8M





Noack's DiRTlib/SUGGAR enabled overset USG

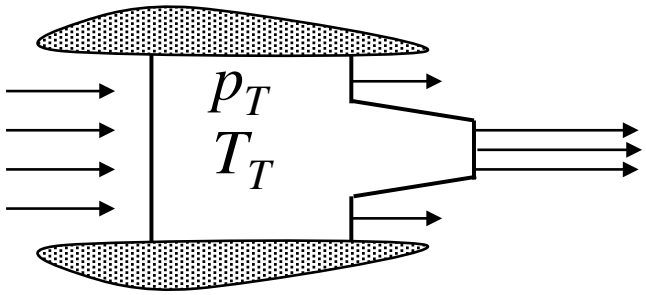
Growing Capabilities

Special Boundary Conditions

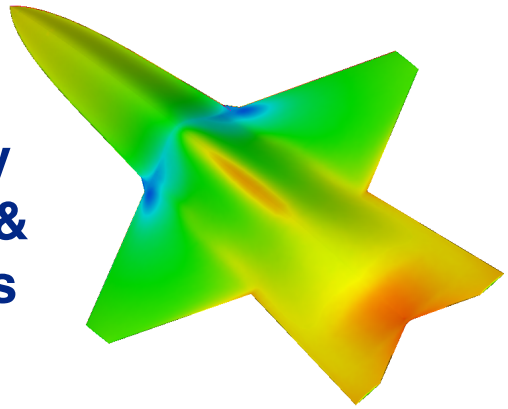


The addition of special BC's and functions began to transform USG methodology from "codes" into "tools"

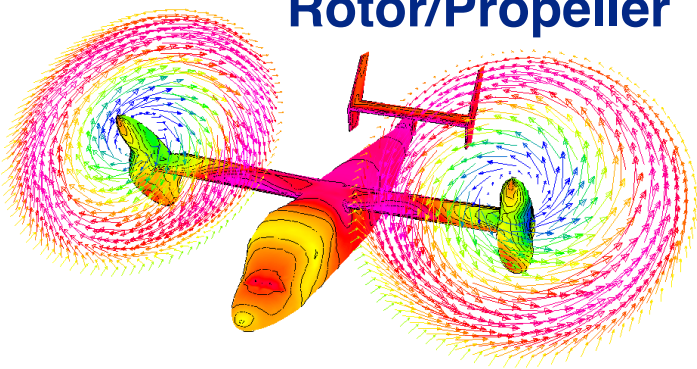
Jet Engine Simulation



Passive Porosity Design & Analysis



Rotor/Propeller



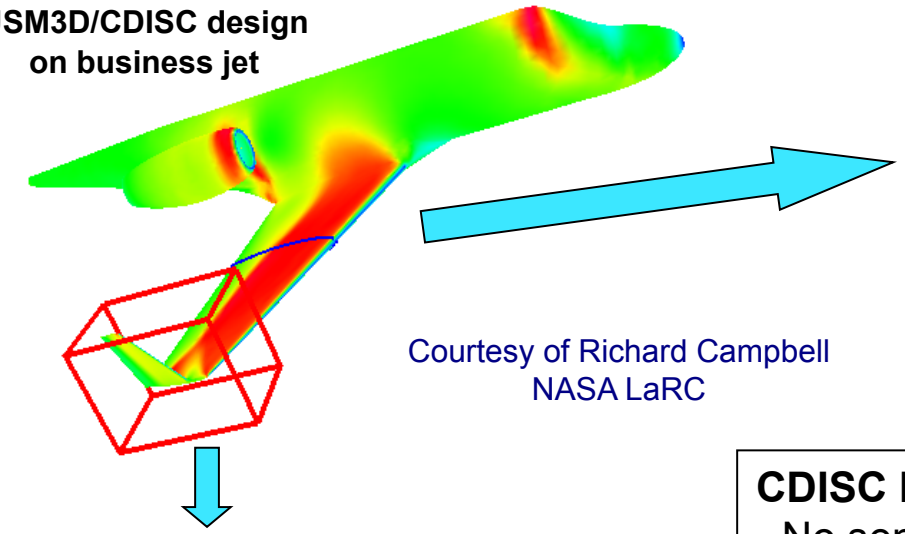
Growing Capabilities

Inverse Design

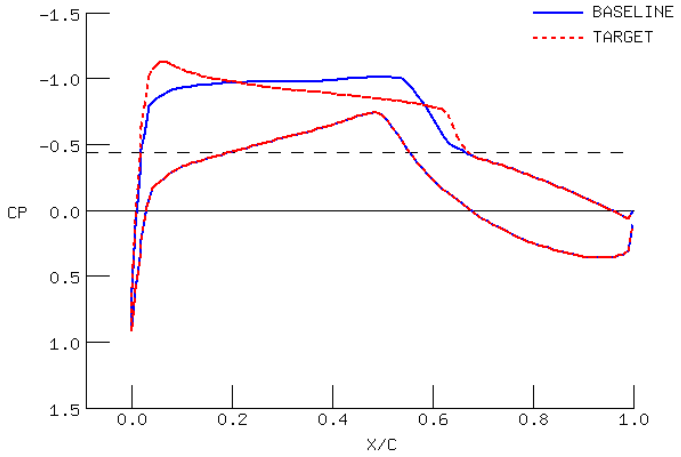
1985 1990 1995 2000 2005 2010

CDISC - Constrained Iterative Surface Curvature

USM3D/CDISC design on business jet



Courtesy of Richard Campbell
NASA LaRC

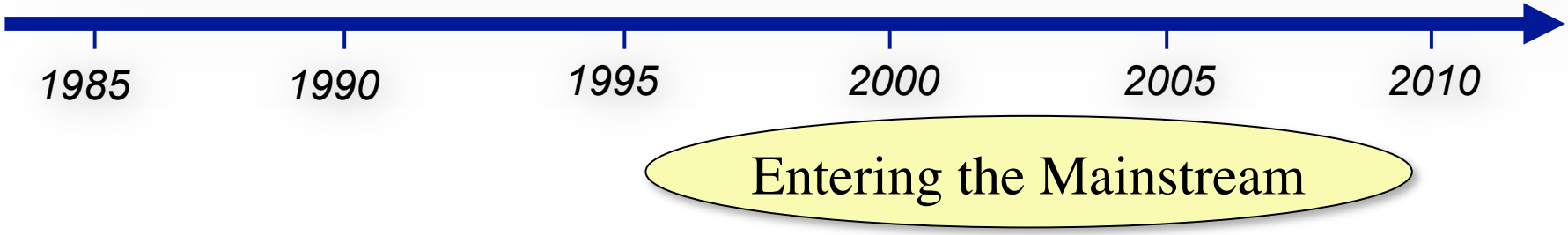


Zonal grid option
- Enables local redesign without using full grid
- Other potential applications: aero-elastics, store separation, local unsteady flow

CDISC knowledge-based design method
- No sensitivity derivative computation required (design ≈ analysis time)
- Target pressures automatically generated by flow constraints
- Multidisciplinary influence through geometry constraints

Unstructured-Grid Methodology

Three Decades of Innovation



- **Proliferation of codes**
  - U.S. Government/University
    - TetrUSS, FUN3D, CART3D, FELISA, AIRPLANE, AVUS . . .
  - European
    - Megaflow TAU code
  - Commercial vendors
    - Fluent, CFDRC, COBALT, CFD^{++}, ICEM, . . .

Entering the Mainstream

Impact Through Application



- **Accuracy relative to established methods**
  - AIAA Drag Prediction Workshops (2001, 2003, …)
  - AIAA CFD High Lift Prediction Workshop (2010, 2013)

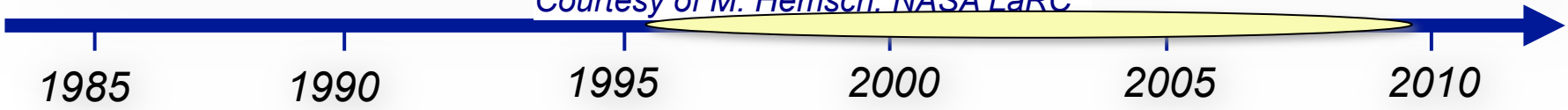
- **Large-scale applications (representative)**
  - X-43A/HyperX mishap investigation and RTF
  - P-3 Orion loads database
  - High-Lift
  - Abrupt Wing Stall program
  - Ares I aero database

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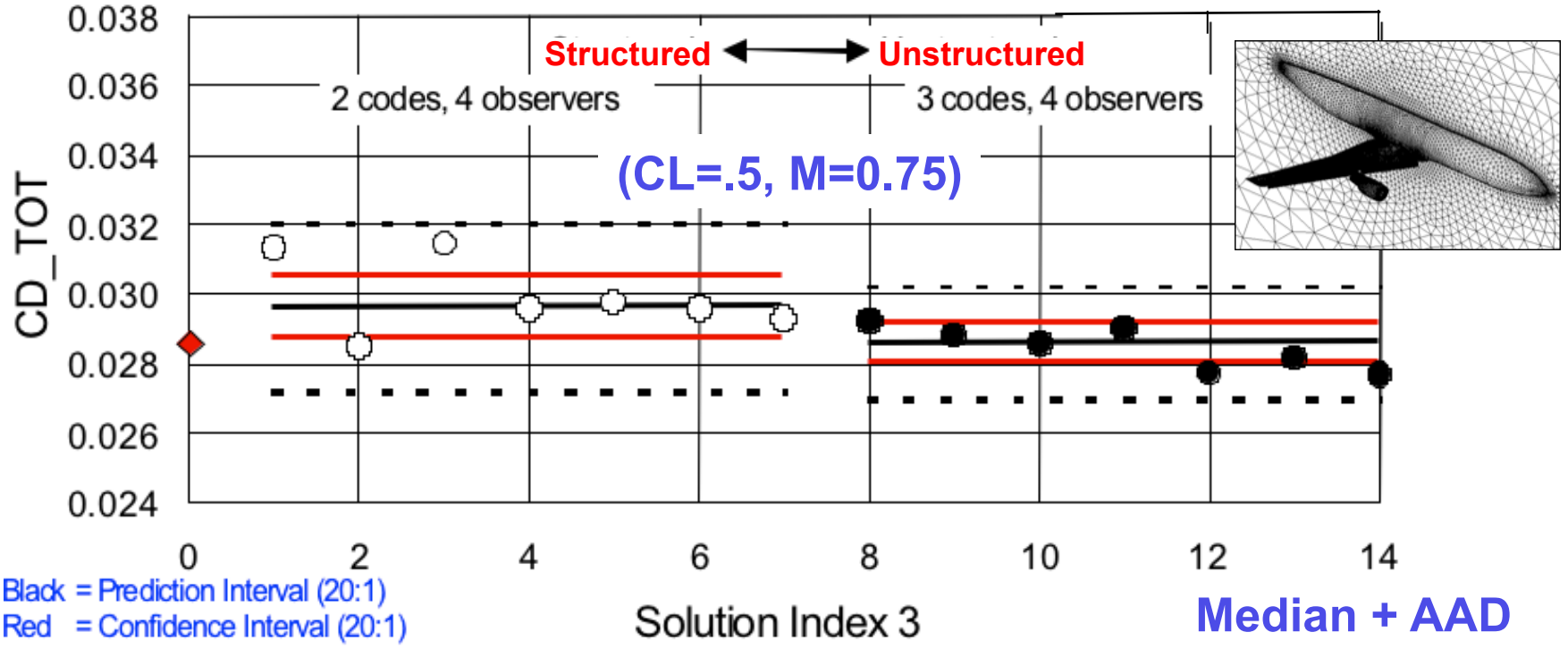
Entering the Mainstream

NASA Drag Prediction Workshops 1 & 2

Courtesy of M. Hemsch, NASA LaRC



CD TOT - Comparison of Grid Types for S-A model



USG is at least as good as classic structured-grid methods

Entering the Mainstream

X-43 Mishap Investigation and RTF

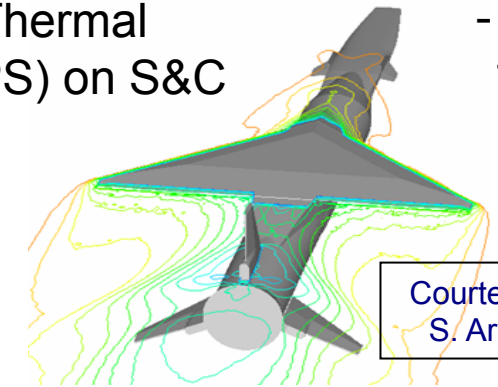


Mishap Investigation

- Over 60 USM3D N-S solutions on 8 separate grids in a 3 month period
- **TetrUSS used for:**
  - Filling in "gaps" in exp. data
  - Resolve discrepancies in exp. data
  - Evaluate effect of Thermal Protection Sys. (TPS) on S&C
  - Component loads
  - Aeroelastic studies

Return to Flight (RTF)

- Over 100 USM3D N-S solutions on 16 different grids of full stack configuration with TPS in 3 months
- Mach range from 1.4 to 7.0
- **Additional TetrUSS uses:**
  - Trajectory design
  - Loads and hinge moments for mechanical re-design of spindle & gears for the control surfaces



Courtesy of P.Parikh, F. Ghaffari, M. Carter, NASA LaRC
S. Armand, AMA and E. Parlette, ViGYAN, Inc (2001)

Entering the Mainstream

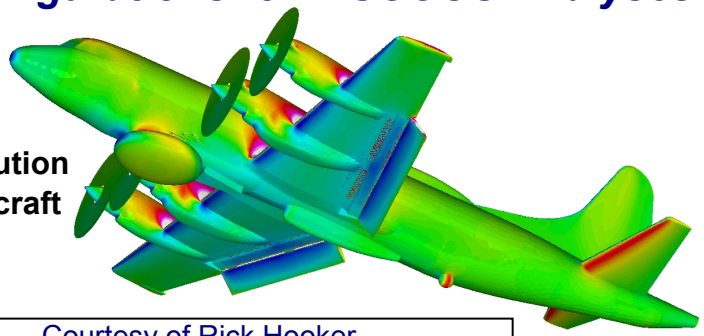
LMAC P-3C/EP-3E Loads Database

1985 1990 1995 2000 2005 2010

- Overview:
  - Develop structural upgrades to the P-3 for extended airframe service life
  - Support re-engine efforts (Multi-Mission Maritime Aircraft – MMA Program)
- Objectives:
  - Develop aerodynamic loads database used for structural analyses
  - Evaluate any adverse propulsion airframe integration effects due to integration of a new propulsion system

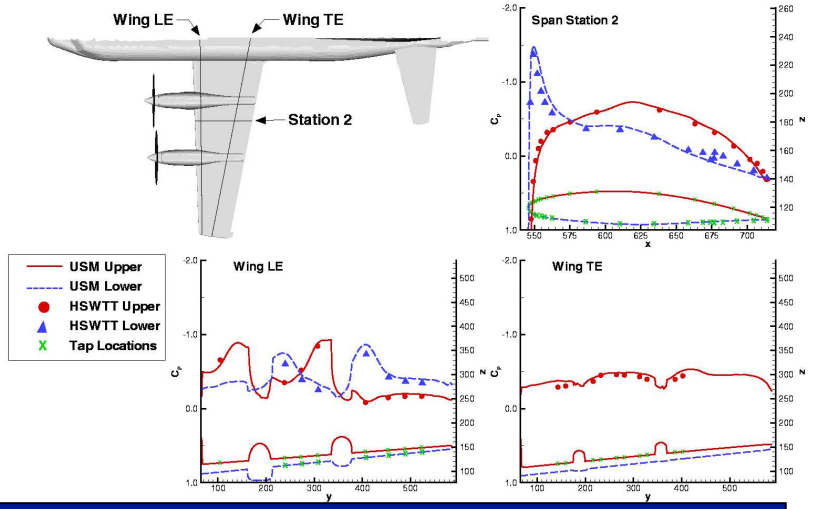
Capability to Model Complex Configurations for VISCOUS Analyses

USM3D solution on P-3C aircraft



Courtesy of Rick Hooker
Lockheed-Martin Aeronautics Company
AIAA 2001-1003

Correlation with Wind Tunnel Data
M = 0.250, AOA = -2.75º, h = 500'

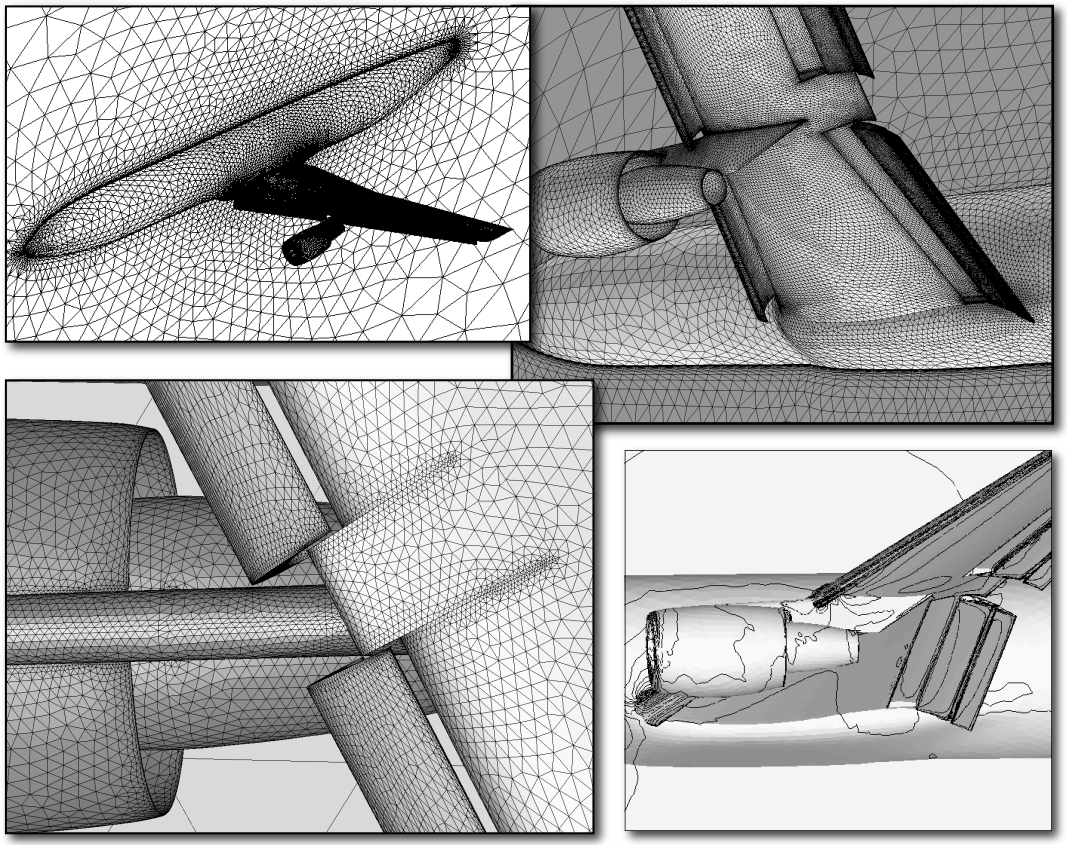


252 Euler/Navier-Stokes Solutions for P-3C, 128 Navier-Stokes Solutions for EP-3E

Entering the Mainstream

Energy Efficient Transport High-Lift Model

1985 1990 1995 2000 2005 2010



- Large-scale USG computation of high-lift configuration by Mavriplis and Pirzadeh (*JoA*, Vol. 36, No. 6, 1999)

- VGRID
  - 25 million nodes
- NSU3D
  - Multigrid
  - 1450 processors
  - 7.54 sec/cycle
  - 82 GFLOP/sec

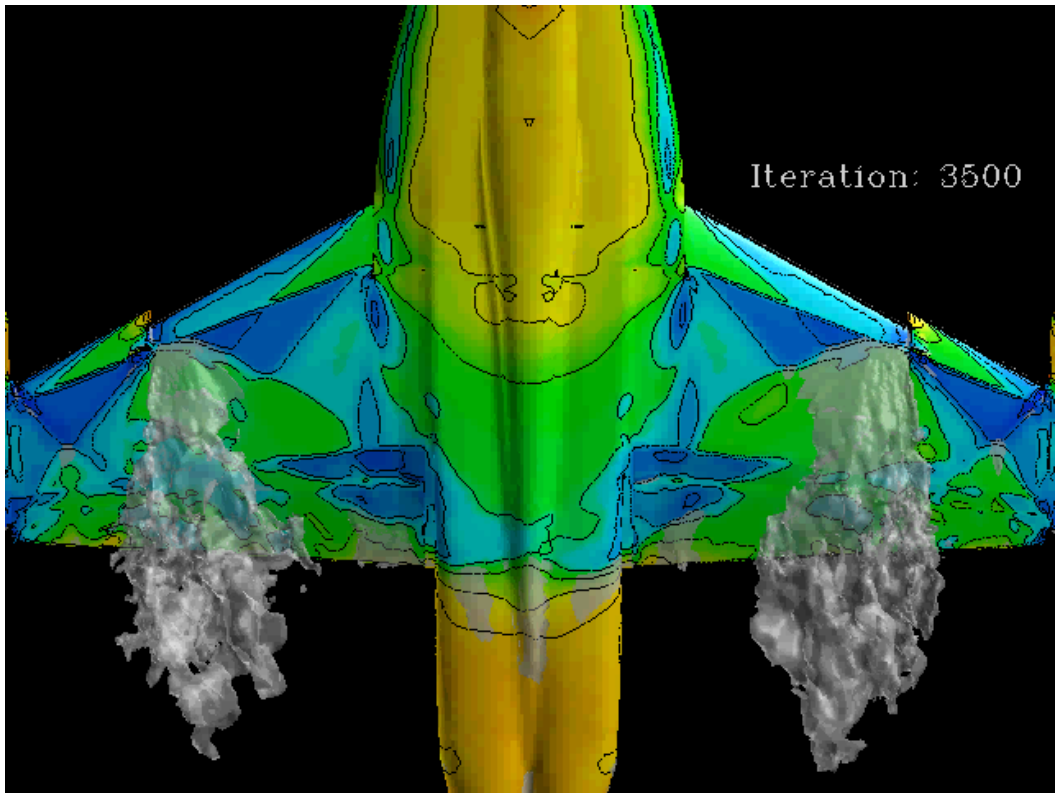
Demonstrated feasibility of production potential of USG

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Entering the Mainstream

Abrupt Wing Stall Program





- Abrupt wing stall simulation by Forsythe and Woodson (AIAA 2003-0594)

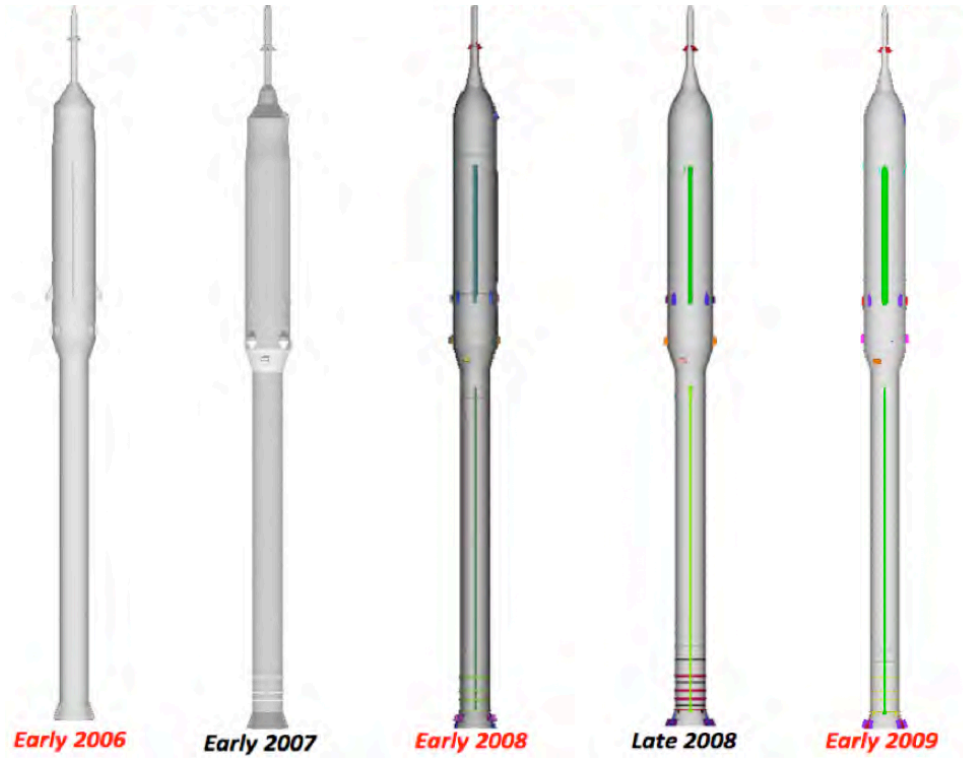
- Landmark unsteady computation of *preproduction* F-18E/F with Detached-Eddy Simulation (DES) using COBALT code

USG can address large-scale unsteady problems

Entering the Mainstream

Ares I Ascent Aero Database



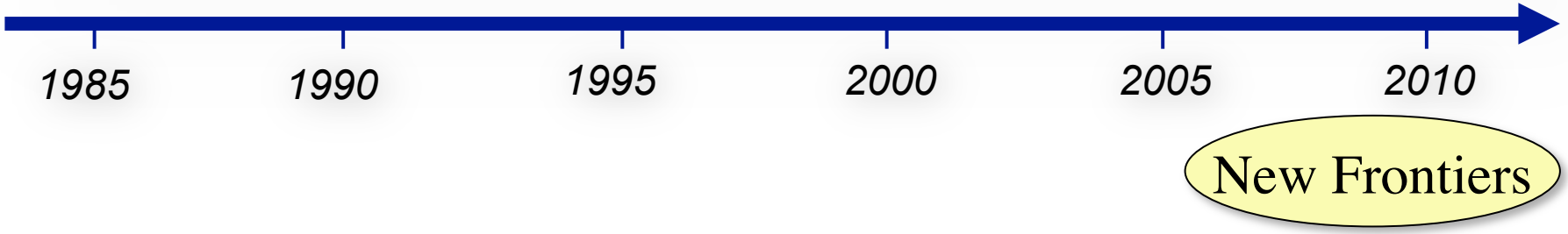


- USM3D provided over 7000 Ares solutions
- 10-15 solutions/day on grids from 50-100^{+}M tets
- Also provided protuberance design loads for Ares I-X flight vehicle
- Abdol-Hamid, Ghaffari, Parlette. *J. of Spacecraft and Rockets*, Vol 49, No 4, Jul/Aug 2012, pp. 596-608

Demonstrated USG productivity in large-scale development program

Unstructured-Grid Methodology

Three Decades of Innovation



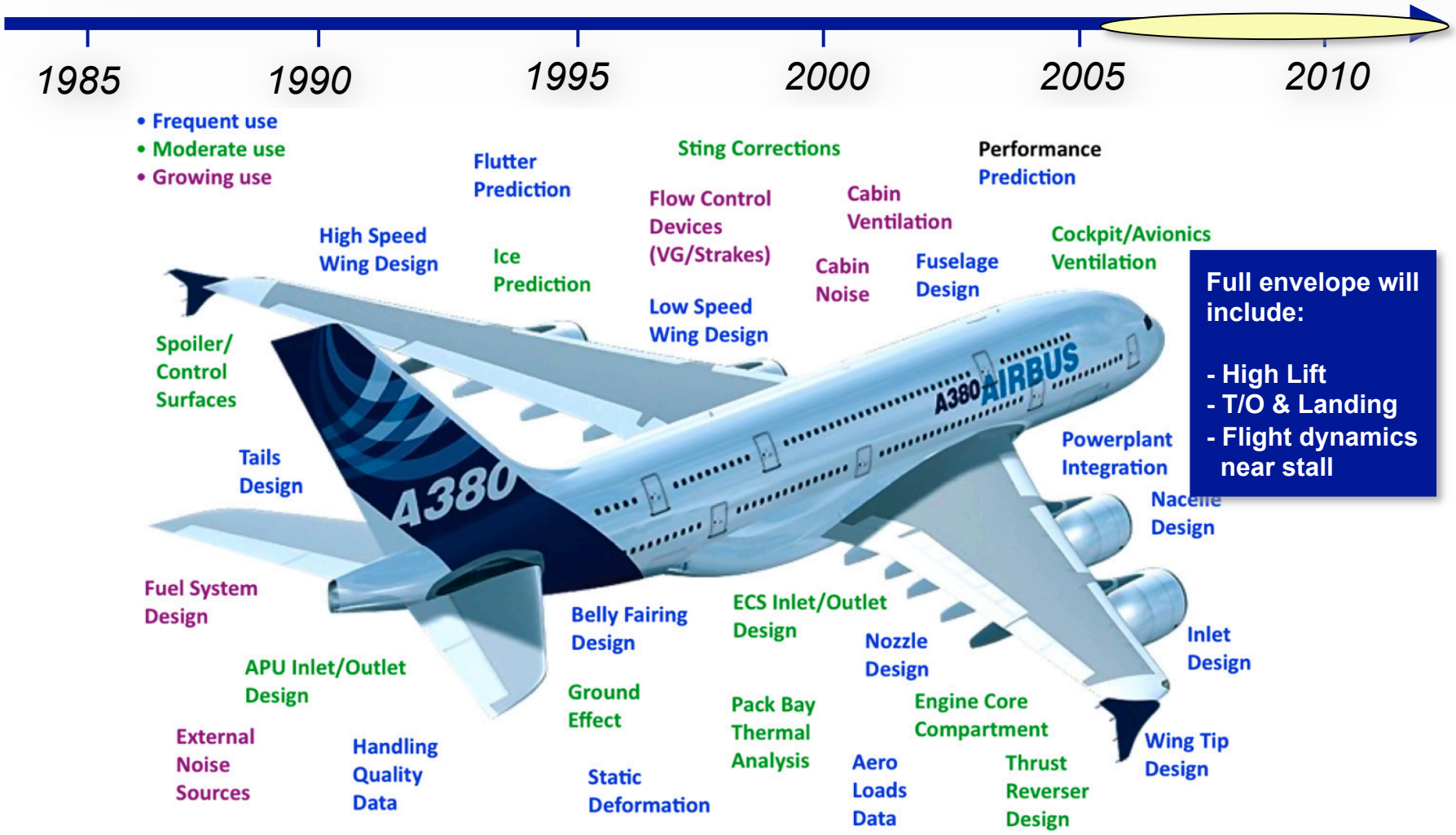
- **What are the critical needs in the future?**
  - "Certification by analysis" across full flight envelope
  - Supersonic transport over land
  - Revolutionary reductions in fuel burn
  - Noise reduction around airports
  - . . .
  - See "CFD Vision 2030" study currently underway

What will be the next "enabling" CFD technologies?

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New Frontiers

The Challenge of Certification by Analysis



Jameson A, Ou K. 50 years of transonic aircraft design. Prog Aerospace Sci (2011), doi:10.1016/ j.paerosci.2011.01.001

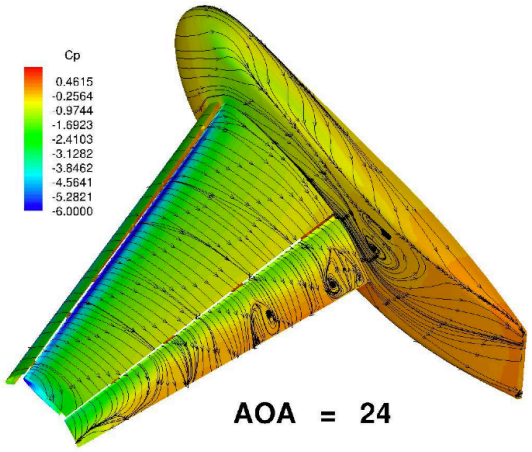
Neal.T.Frink@nasa.gov

New Frontiers

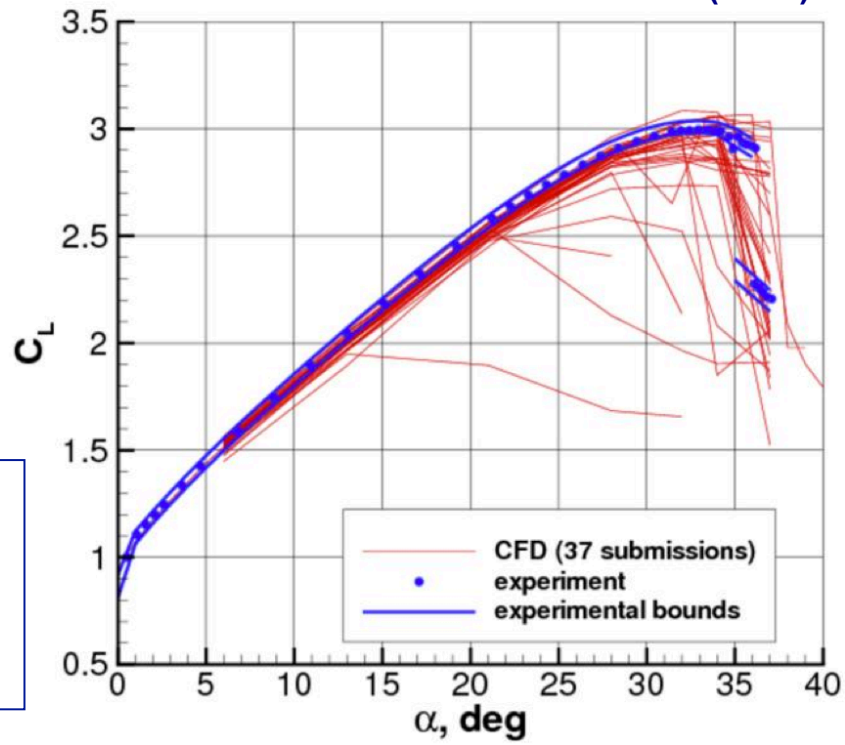
Results from 1st AIAA High-Lift Workshop

Courtesy of C. Rumsey, NASA LaRC

1985 1990 1995 2000 2005 2010



Lift results from 12 flow solvers (2011)



Inadequate modeling of separated flows is one of the most critical short comings in computational aerodynamics, and one of the most difficult problems to resolve

C. Rumsey, et. al. *Journal of Aircraft*, Vol. 48, No. 6 (2011), pp. 2068-2079

We have "hit the wall" with the modeling of separated flows

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New Frontiers

New innovations ahead



- **What are next "enabling technologies"?**
  - More accurate models for separated flow and smooth body separation
  - Automated, hands-off parallel grid generation
  - Integration of grid generation/surface with flow solver
  - Multi-disciplinary analysis/design
  - Self-adaptive analysis with known error bounds
  - Higher-order methods
  - Hybrid near/far field grid topologies
  - Software V&V, performance on next-gen computers

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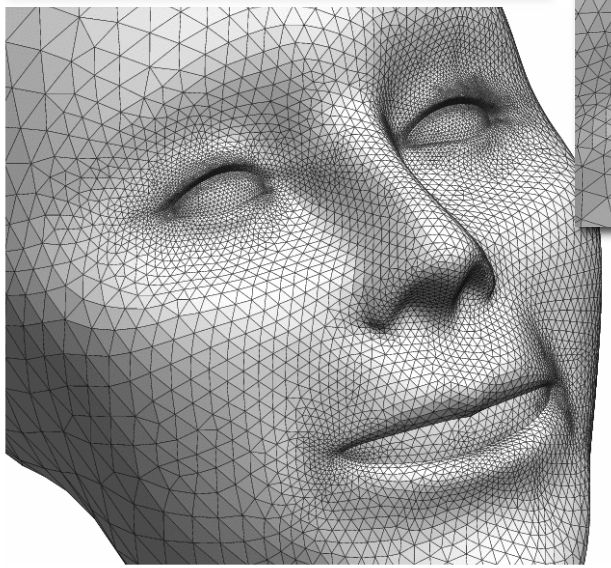
New Frontiers

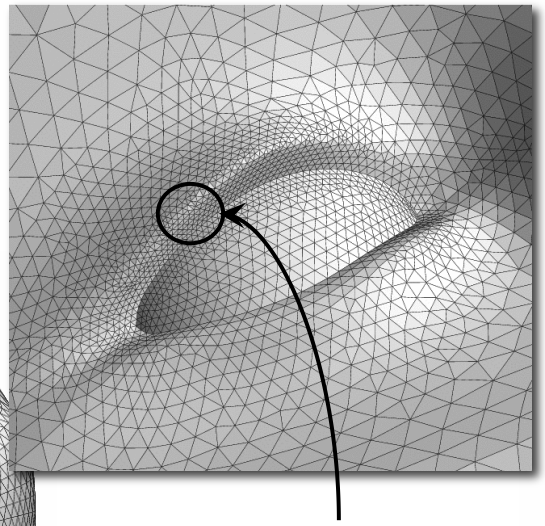
More Automated Grid Generation

Courtesy of Lee Kania, Blue Ridge Numerics

1985 1990 1995 2000 2005 2010

VGRID with **Octree spacing function** using surface curvature





minimum (and maximum) length scales are user-prescribed



unconverged element

converged element

Future grid generation must be automated hands off

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New Frontiers

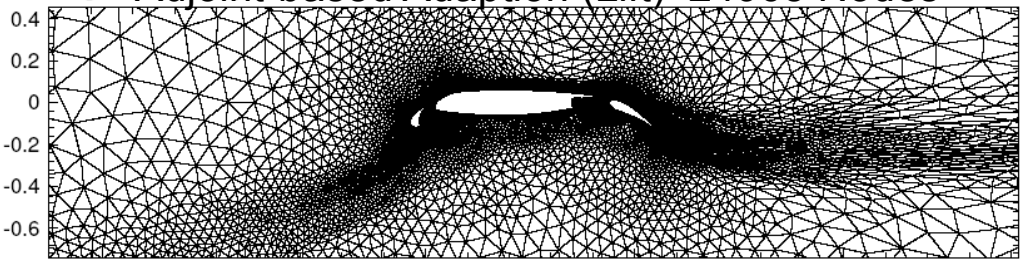
Self-Adaptive analysis with known error bounds

1985 1990 1995 2000 2005 2010

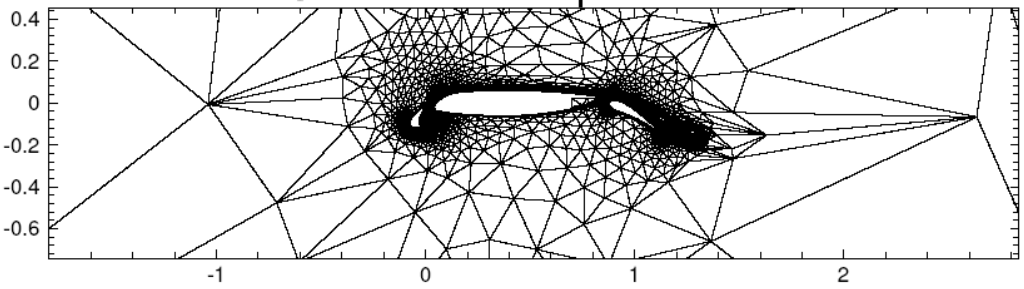
- **Adjoint** recognizes importance of "smooth" flow regions
- **Adjoint** technique is clearly superior to traditional ad hoc approach

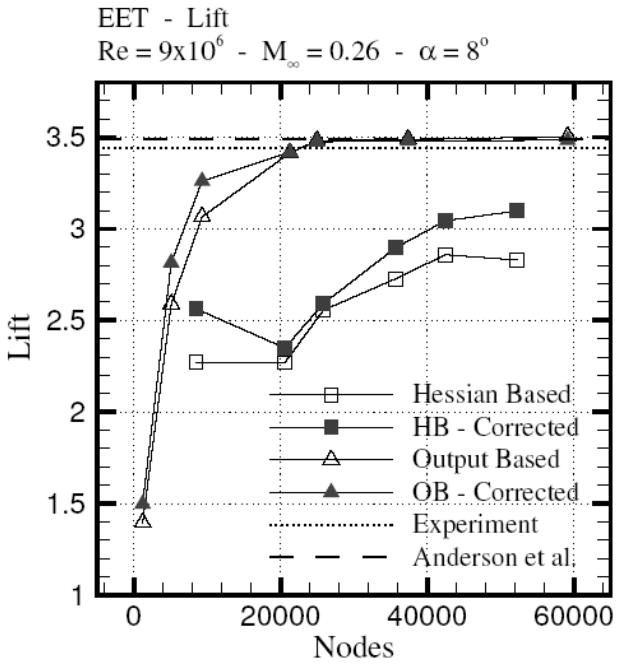
2D High-Lift Example

Adjoint-based Adaption (Lift) 24965 Nodes



Pure Hessian-based Adaption 52235 Nodes





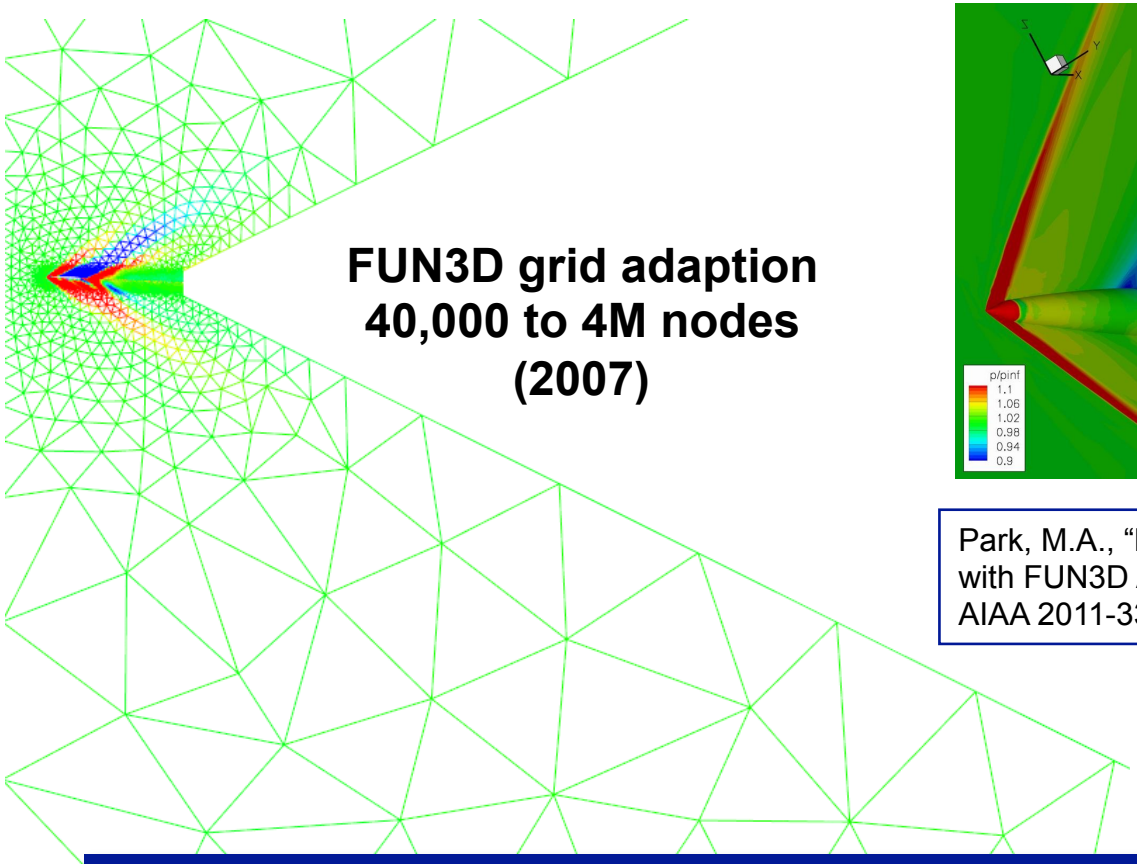
Courtesy Venditti & Darmofal at MIT (using FUN2D)

New Frontiers

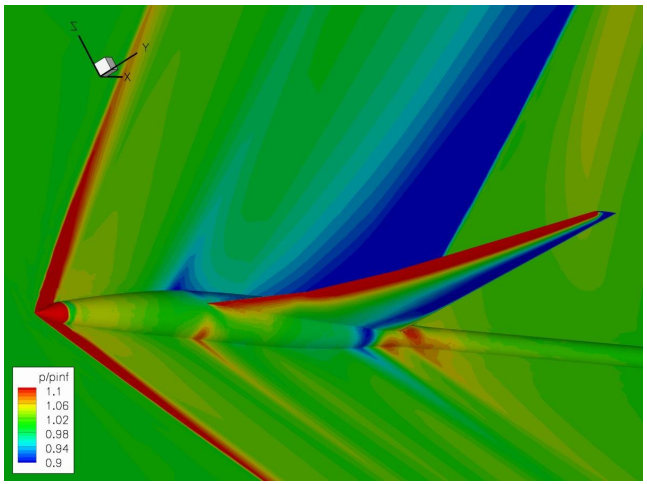
Output-based Grid Adaption

Courtesy of M.Park (NASA LaRC) and D.Darmofal (MIT)

1985 1990 1995 2000 2005 2010



FUN3D grid adaption
40,000 to 4M nodes
(2007)



Park, M.A., "Low Boom Configuration Analysis with FUN3D Adjoint Simulation Framework", AIAA 2011-3337, June 2011

Supersonic overland flight prohibited due to sonic boom

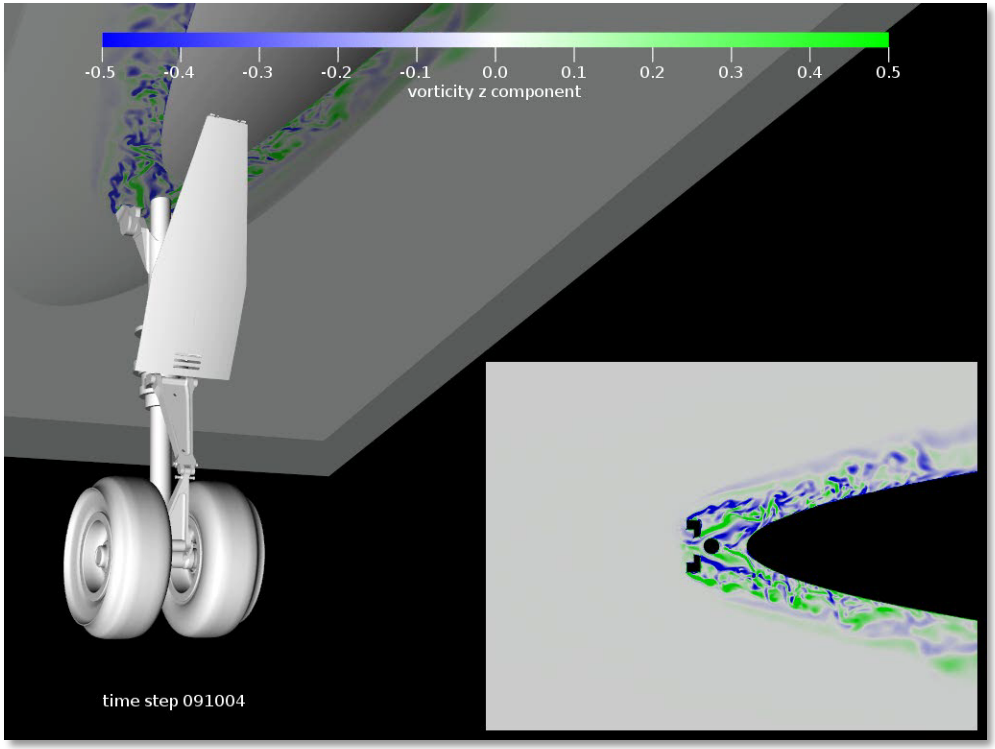
New Frontiers

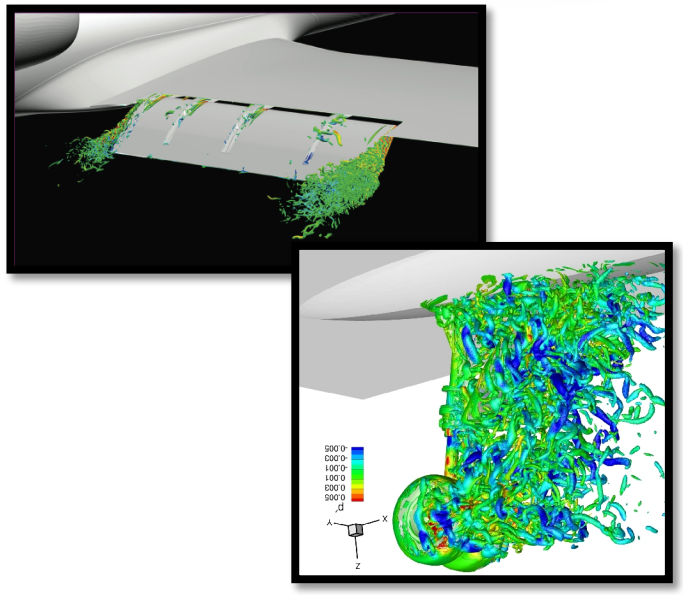
High Fidelity Simulations for Noise Research

Courtesy of V.Vatsa, M.Khorrami, R.Mineck, NASA LaRC

1985 1990 1995 2000 2005 2010

DES Simulations with FUN3D





Some landing gear simulations can require months on 1024 processors

Courtesy of NASA/Gulfstream Partnership on Airframe Noise Research

Critical need to reduce aircraft landing noise around airports

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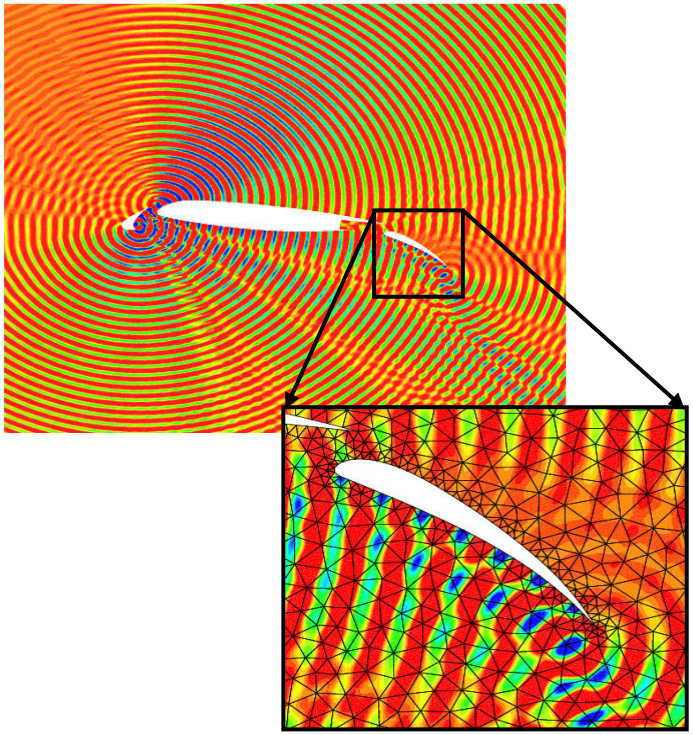
New Frontiers

Higher-Order Methods

Courtesy of H. Atkins, NASA LaRC

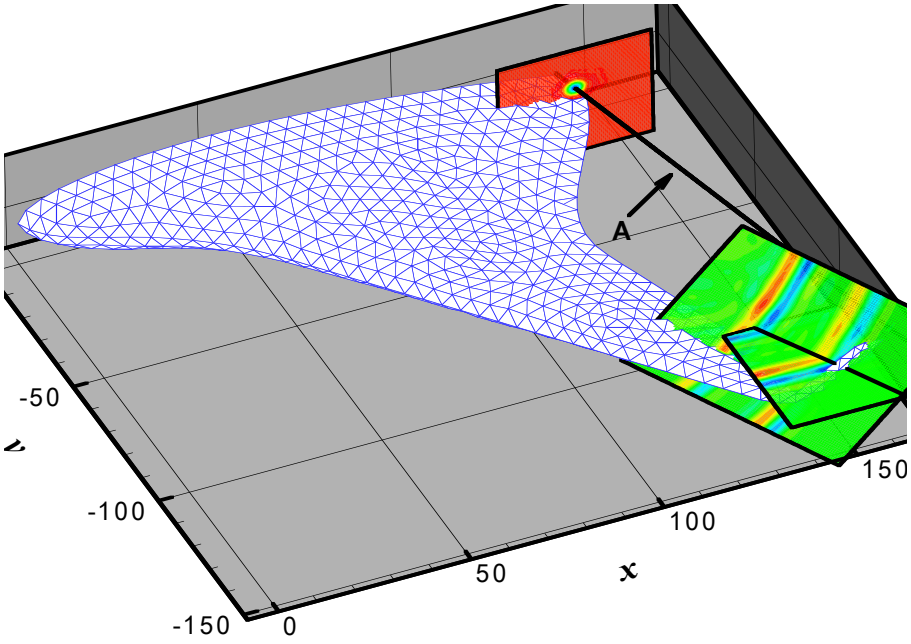
1985 1990 1995 2000 2005 2010

Acoustic scatter by 6th order method



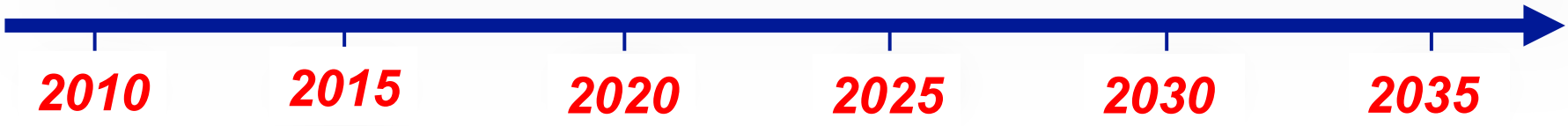
Discontinuous Galerkin

Acoustic scatter off BWB by 5th order method



Noise - one of the most critical problems in aeronautics

Parting Thoughts



- **Three fruitful decades of innovation**
  - Revolutionary advances in CFD capability
  - Many innovative individuals paved the way
  - It takes longer than you think to enter mainstream

- **What about the coming decades?**
  - What critical needs are driving the forces of change?
  - What are the roadblocks in current approaches?
  - What fresh innovation is needed?

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Parting Thoughts

2010 2015 2020 2025 2030 2035

- **Three fruitf** **n**
  - Revolution ty
  - Many inno vay
  - It takes lo ainstream
- **What about**
  - What critic s of change?
  - What are t baches?
  - What fresh



"That's right—it's an iceberg, and it's headed straight for the computer room!"

Thank you for coming.

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