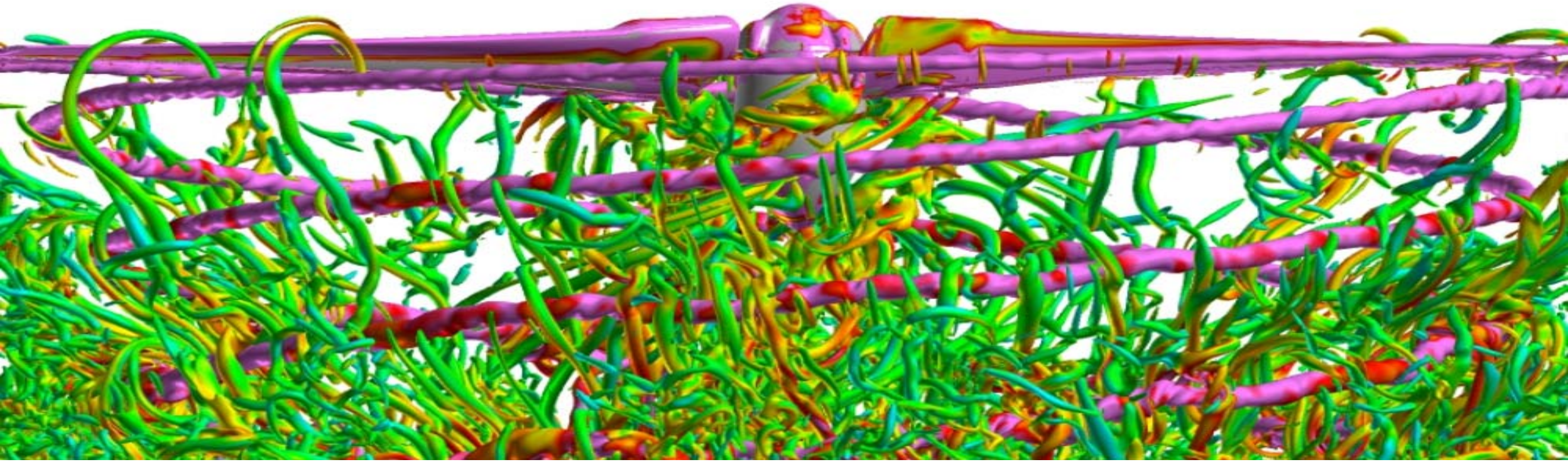
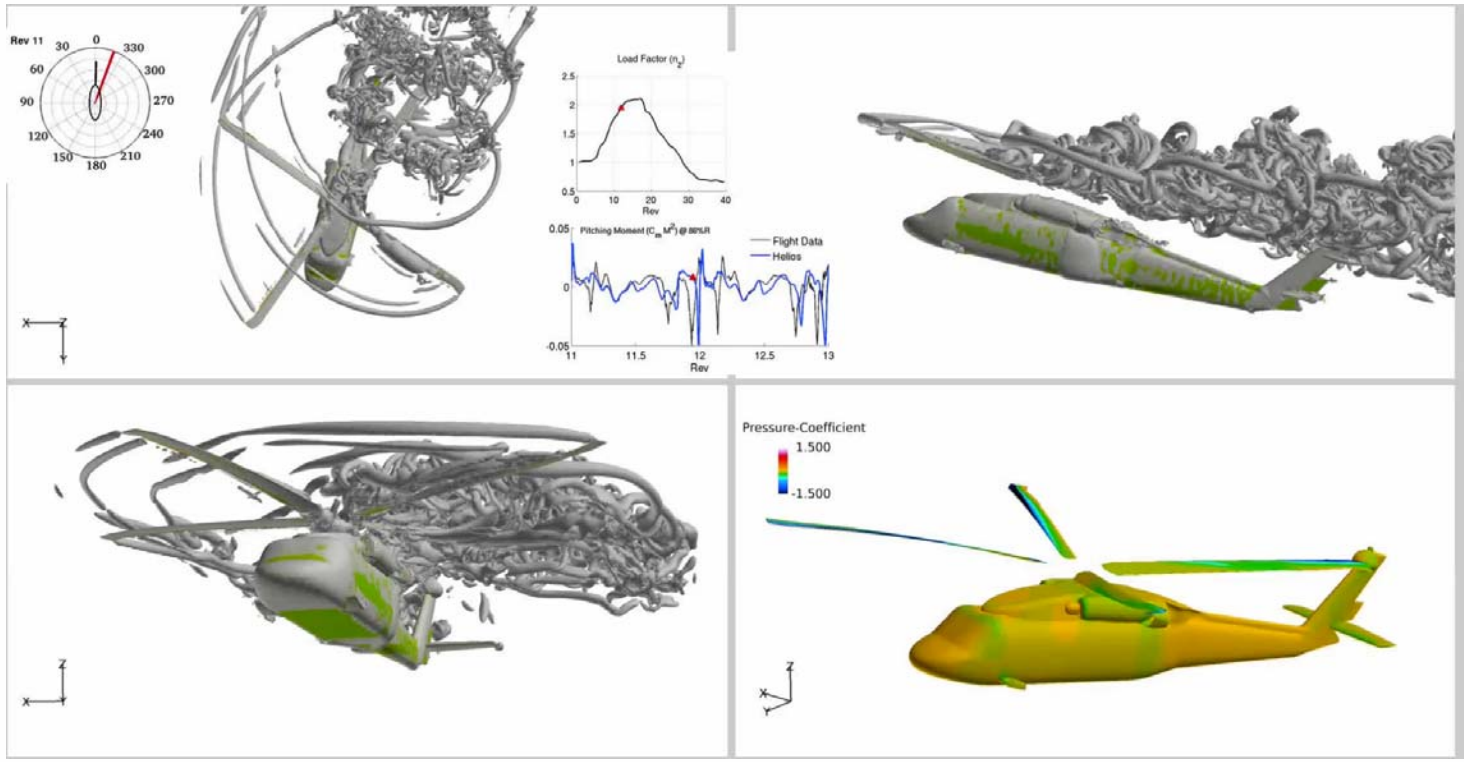
Data Science Meets CFD: FieldView Analytics in Engineering

Steve M. Legensky
GM & CTO

Intelligent Light



- Company Update
- Big Data and CFD
- FV Analytics



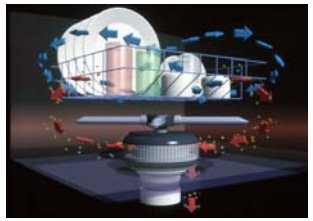
Intelligent Light Overview

A Rich Heritage in Data Visualization & Analytics

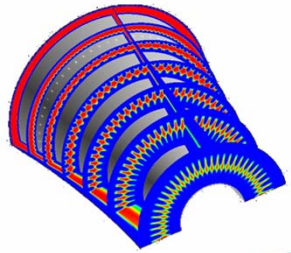
1984 — Hughes Aircraft Flight Simulator

Commercial Animation/ Photo-realistic Rendering

1986 — Turnkey Animation & Parallel Rendering **3DV**

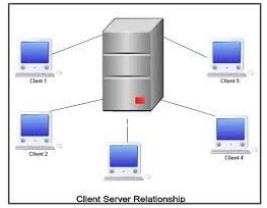


1990 — United Technologies Joint Development CFD Post-Processing **FieldView**



1995 — Large CFD Dataflows via NASA SBIR

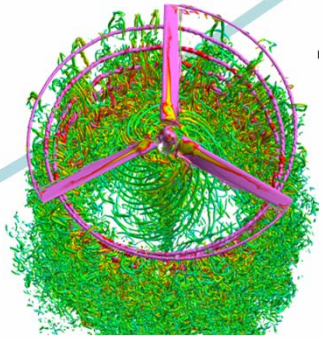
2000 — **Client Server**



Extract Workflows

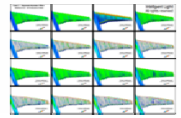
XDB view

2013 — **Parallel FieldView**



VisIt

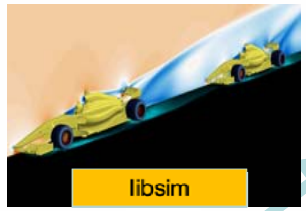
2017 — **Insitu Post Processing**



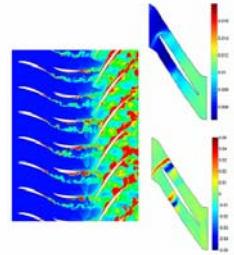
Local

XDB

HPC



Reduced Order Models for CFD



Next Generation Data Visualization & Analytics

1984 1986 1990 1995 2000 2013 2017

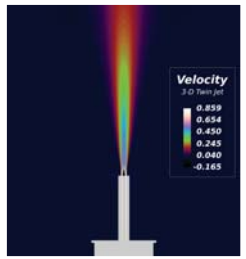
Software Products

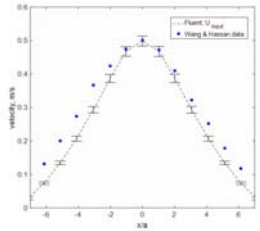
Fieldview Suite
Visualization / Data Analysis
Data Management / Optimization

- FieldView
- FieldView Express
- HPC FieldView
- XDB – Extract db
- VisIt – Open Source

Applied Research

Funded R&D
Advanced Post-Processing,
Methods & Customization





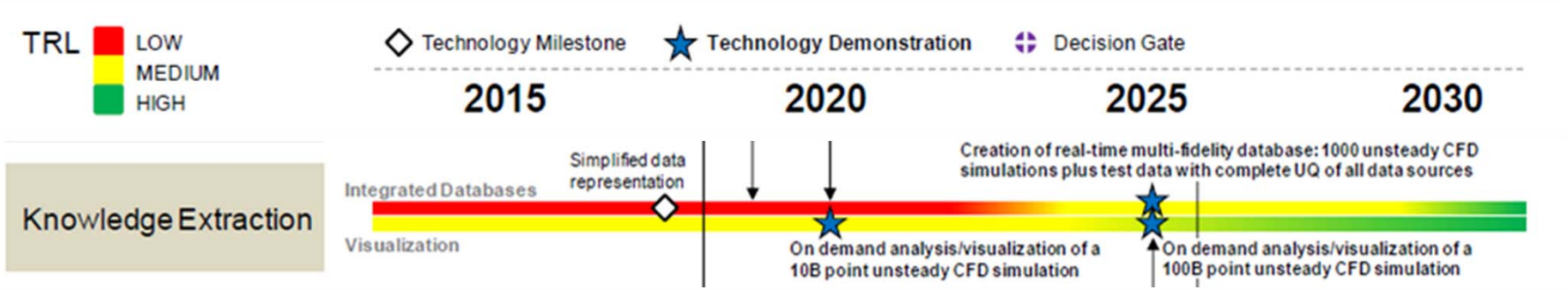
Uncertainty Quantification

Consulting Services

Technology Transfer & Training
FV Customization & Scripting
Workflow Automation
In situ integration in solvers

CFD 2030 Vision Road Map

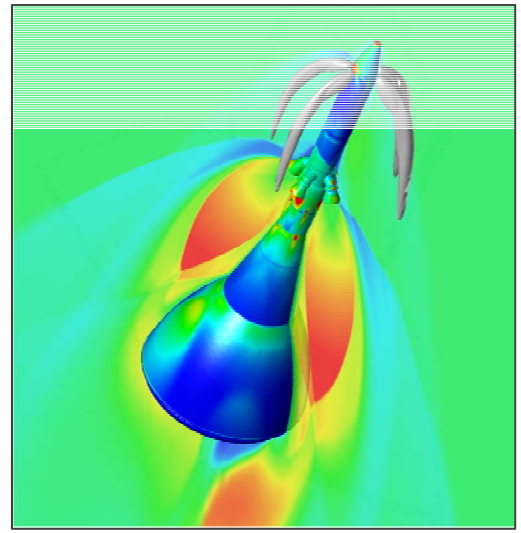
Slotnick, J., et.al. CFD vision 2030 study: a path to revolutionary computational aerosciences," (2013).



- **Post-Processing Needs:**
  - 2020: On-demand analysis/visualization of a 10B point unsteady
  - 2025: On-demand analysis/visualization of a 100B point unsteady
  - **2030: HO Common Practice**
- Need: Data demands, **In situ analysis requirements**, coupled data storage, **interactive visualization**.

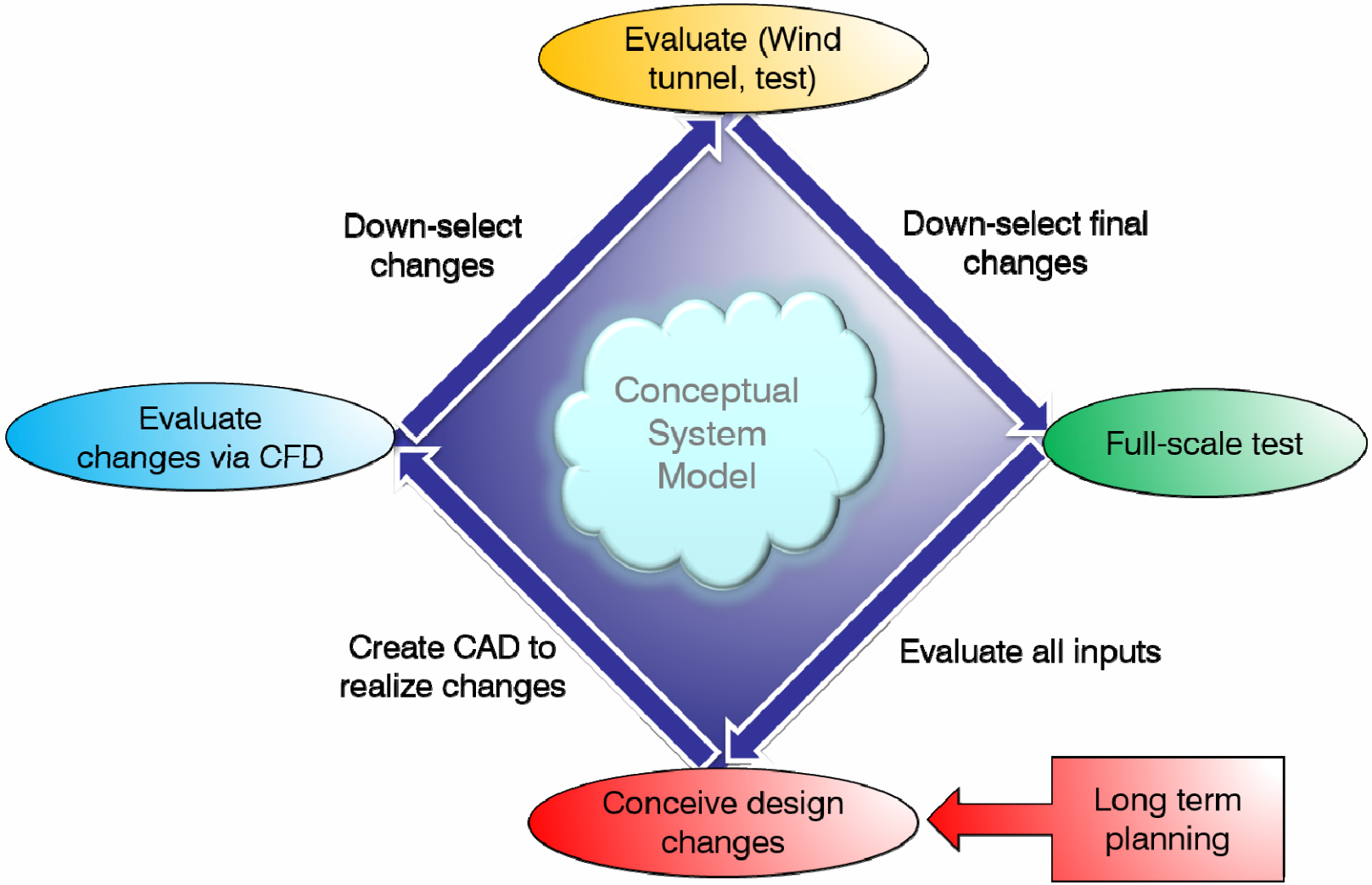
CFD in the Engineering Process

- Understand the physics of a device
- Test out theories about design changes
- Verify performance after a change
- Certify performance by simulation



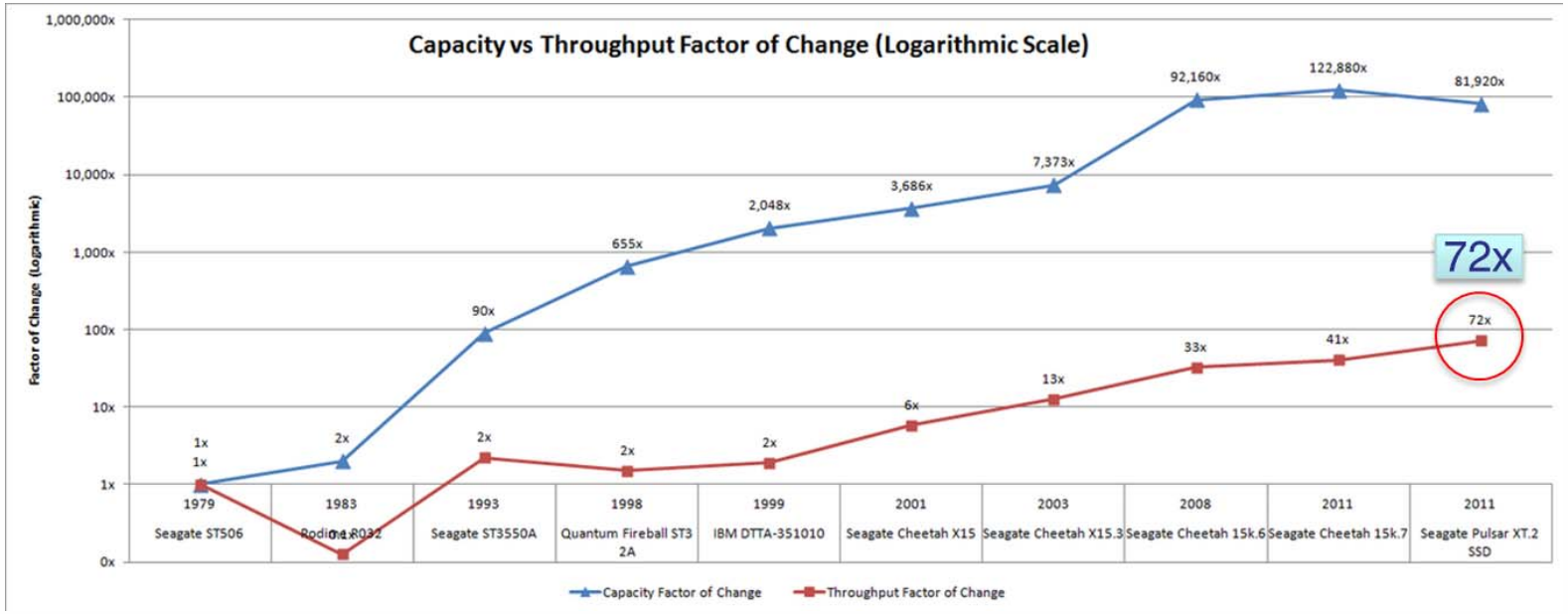
CAD / Parameters → Mesh & job setup → Compute (HPC) → Analyze result to gain understanding

CFD, Experiment and Test



Issues

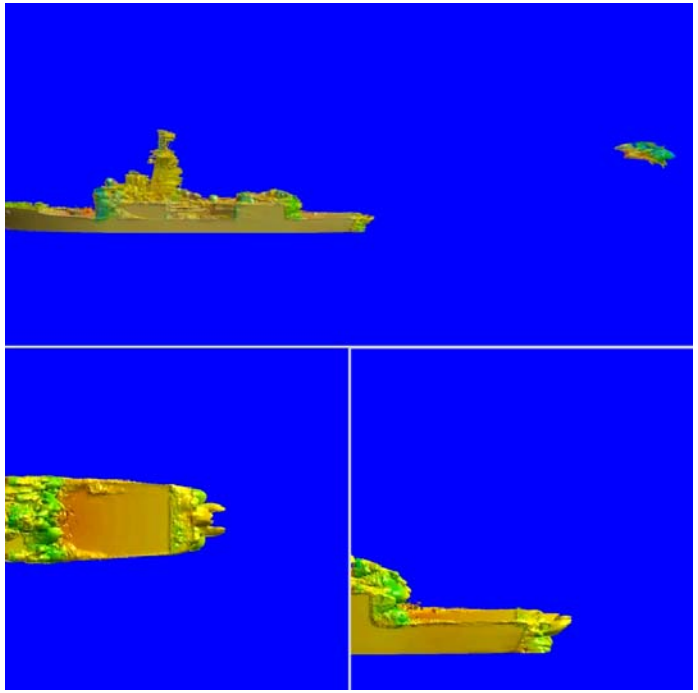
- Results file size is related to precision of discretization
- HPC resources can be physically or logically distant
- Optimization, uncertainty quantification, unsteady simulation require many runs
- Human ability to digest data

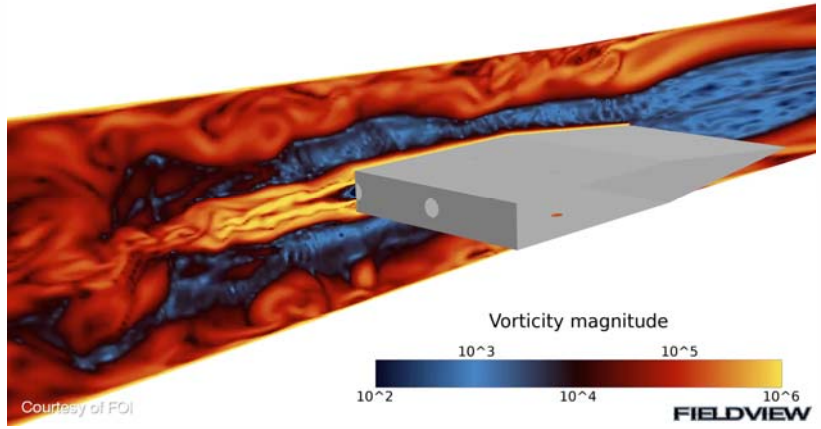


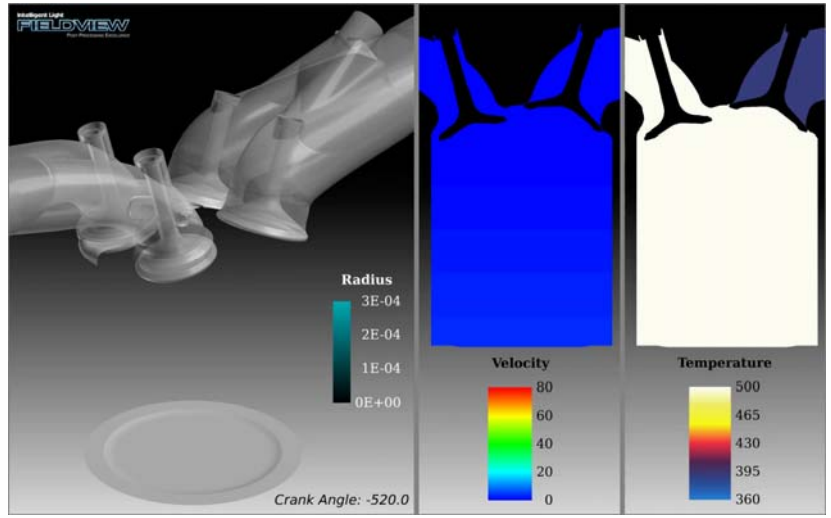
Compute is > 10,000 times faster, disk < 100x

Big Data Examples

- Formula One Teams
- Aerospace and Defense
- Internal Combustion
- Wind and Nuclear Energy







80 Gb per timestep
X
1000 steps
X
4 designs

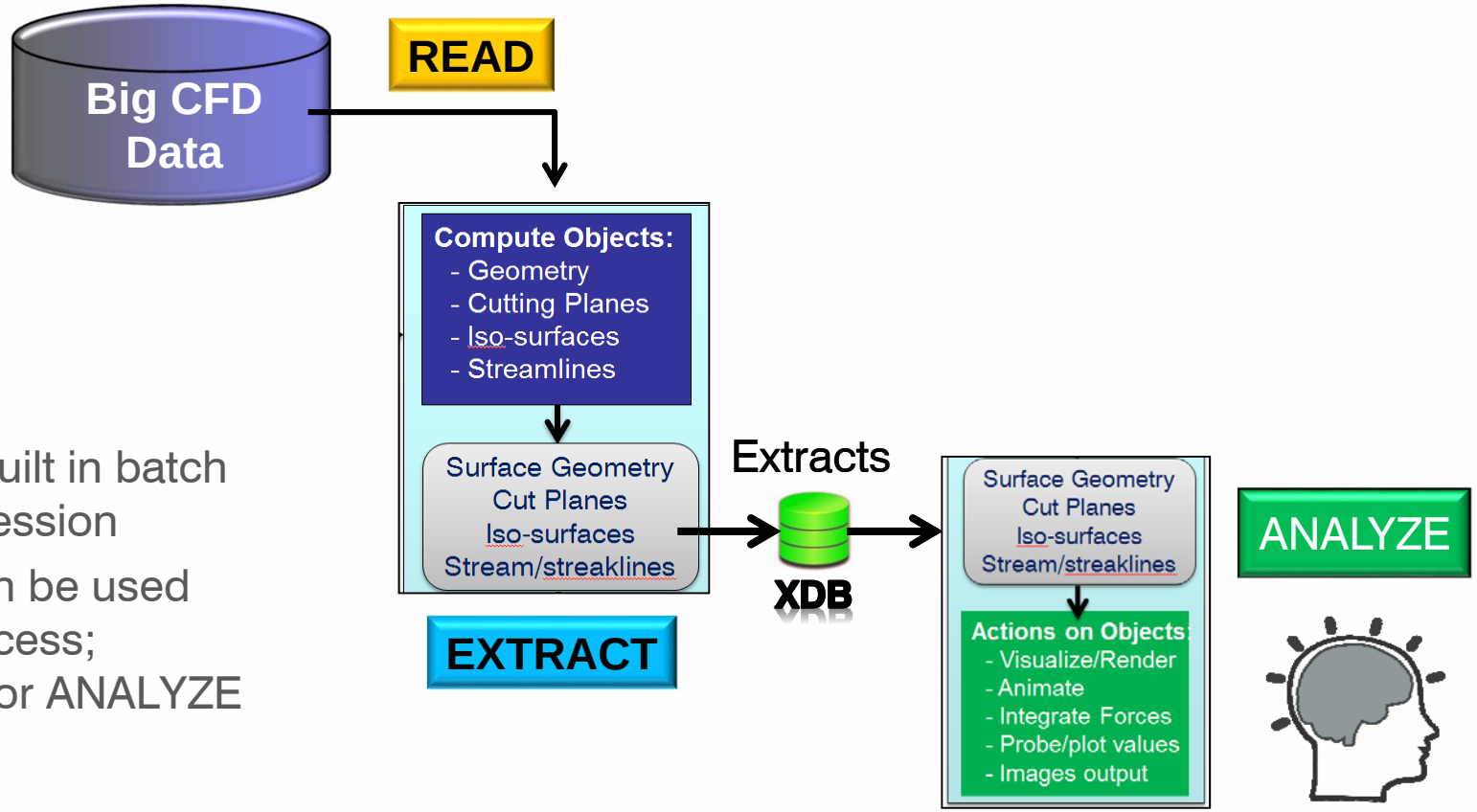
= ***320 Tb!***

Visit www.ilight.com to see these animations

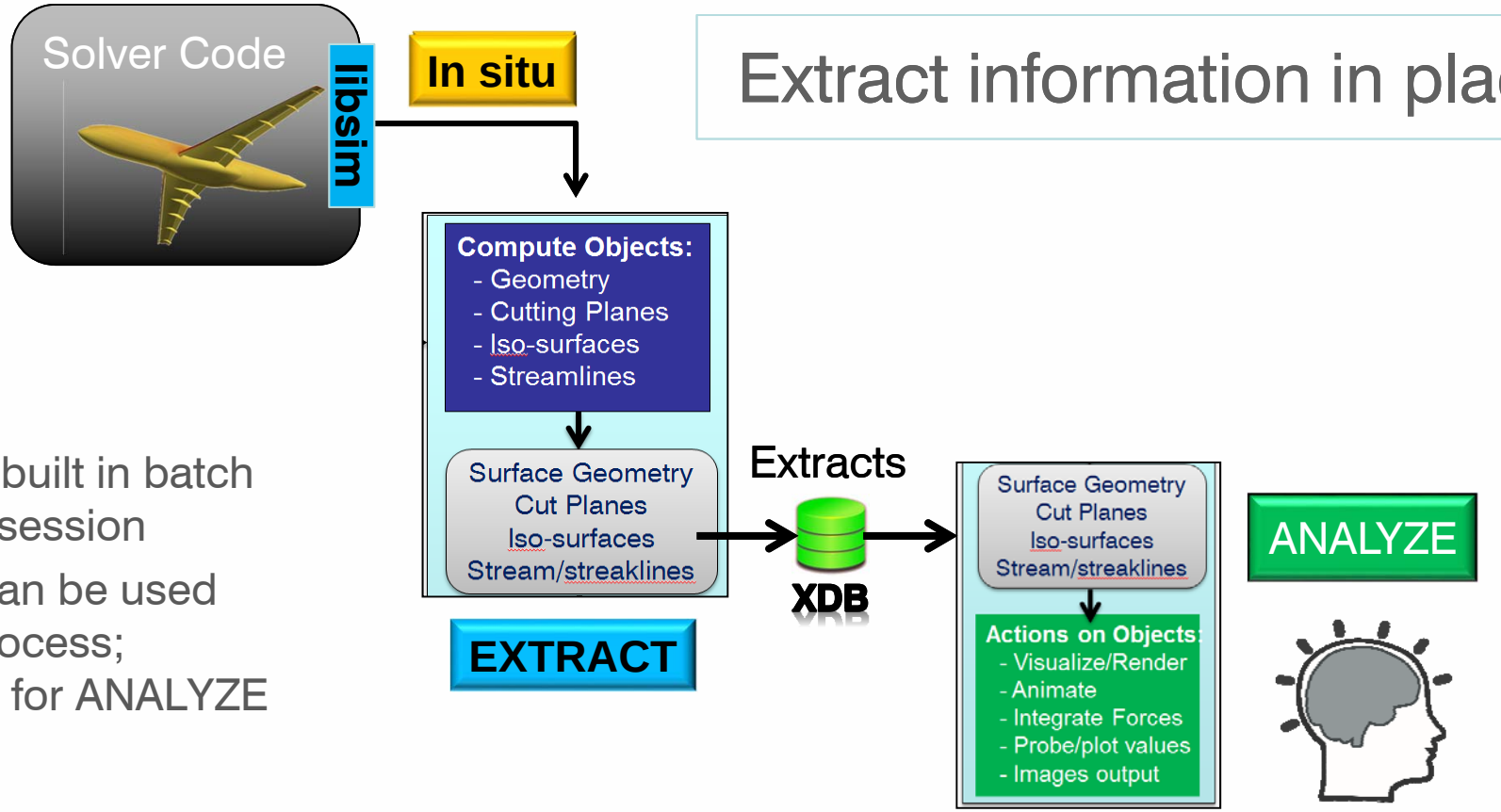
WHAT CAN WE DO?

Utilize Extracts, Physics-based Subsets

- Extracts can be built in batch or in interactive session
- HPC resource can be used for EXTRACT process; desktop or HPC for ANALYZE



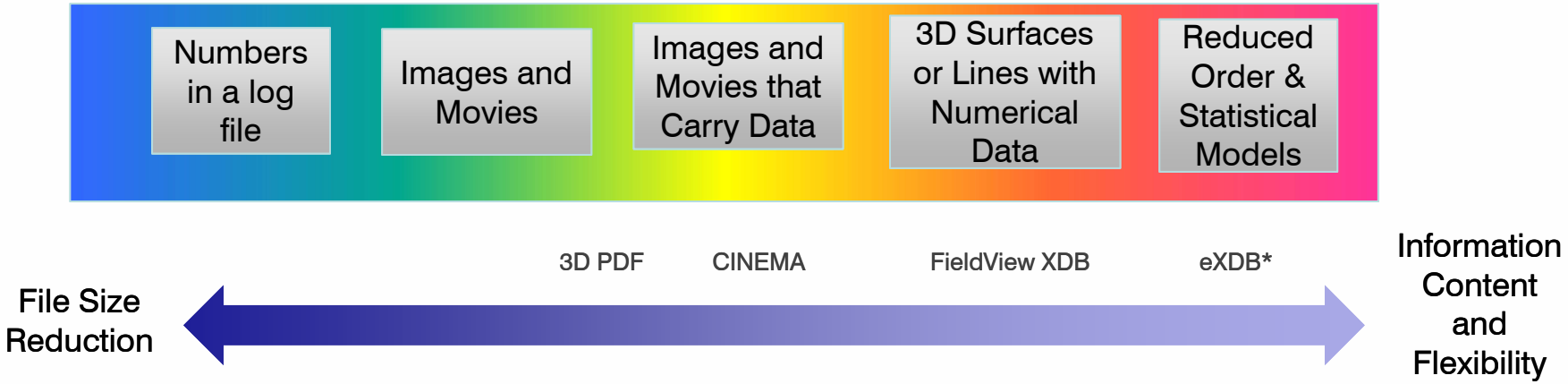
Utilize Extracts, Physics-based Subsets



- Extracts can be built in batch or in interactive session
- HPC resource can be used for EXTRACT process; desktop or HPC for ANALYZE

Extracts are a powerful and flexible tool

- Goal: derive work products that can substitute for the full volume data
- A subset of the computed results that is extracted for a specific purpose
  - Produced in batch, in situ & post-hoc
- Can be 100's to 1000's of times smaller than volume data
  - Exist on a spectrum of content & fidelity
  - Can be used as surrogates in workflows
  - Lightweight, free viewers



ADIOS Scalable I/O Cuts a Truckload of Time Off Simulation

Scientific Achievement

- The highly popular Commercial Fluid Dynamics (CFD) package FLUENT® has incorporated ADIOS into their latest version, 18.2
- In situ surface extracts saved to FieldView XDB format, based on ADIOS, allows higher fidelity output, resulting in more knowledge to come from commercial CFD work

Significance and Impact

- FLUENT® is one of the most popular and widely used commercial CFD solvers
- Enables engineers to perform cost effective design studies of internal combustion engines, chemical mixing processes, and motor vehicle aerodynamics

Research Details

- XDB, created by Intelligent Light, is a state of the art data extract system that accelerates productivity of CFD workflows by reducing 10-100 fold the amount of data written to disk
- A new XDB library leverages ADIOS by replacing the native XDB file format with ADIOS' BP format to accelerate the I/O on HPC systems for important FieldView customers

Image of Pressure Distribution over a Semi-Truck Cab:
(Image Credit: Simulation results courtesy of Navistar, Image Rendered in FieldView)

"... the ultra-fast CFD workflow seen in Formula One has gained further efficiency from the integration of recent FieldView XDB technology..."
Torbjorn Larssen (CREO Dynamics)

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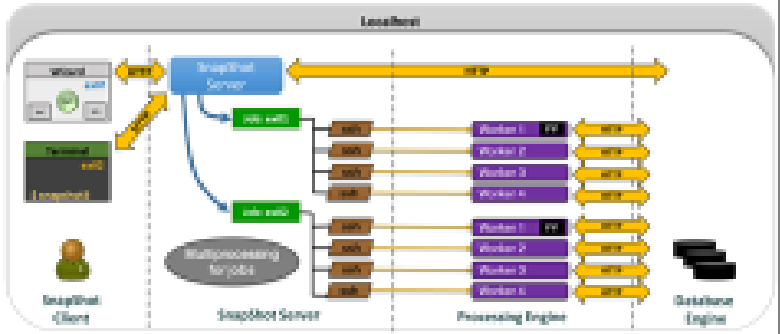
PI: Brad J. Whitlock

Intelligent Light

- Leveraging DOE's ADIOS scalable I/O library
- Each node writes in parallel, no need to gather before I/O
- RDMA and domain management are handled
- ANSYS included our XDBLIB 2.0 in FLUENT

SnapShot – Scalable and Automated V&V

Intelligent Light



Novel Ideas

- Complete Verification and Validation Framework
  - Automated data management
  - Easy to use wizards for code verification against experimental data and across solver
  - Automated/repeatable report generation
- Automated meta, validation and solver data storage via database systems
- Support many different data types and units
  - Matlab, Excel, adhoc ASCII
  - FVUNS (CFX, Fluent, CFD++) and PLOT3D

Impact and Champions

IMPACT

- Used in Nuclear Reactor, multi-phase and many species, Naval Nuclear Laboratory solver development V&V
- Bettis Laboratory
  - Using to support extensive code verification and validation efforts
- KAPL

Product Owner: Earl P.N. Duque, Intelligent Light

Milestones/Dates/Status

- Today Delivered Four (4) versions – file based
- Version 5 Milestones – Large Data and Databased
  - Milestone 1 – September 2018
  - Milestone 2 – January 2019
  - Milestone 3 – February 2019
  - FINAL Version 5 – March 2019
- Version 6 – Grid Convergence Support (TBD)

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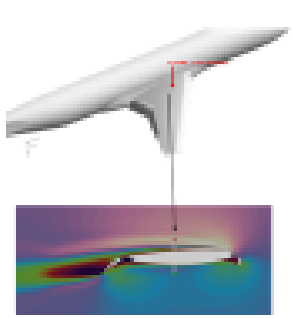
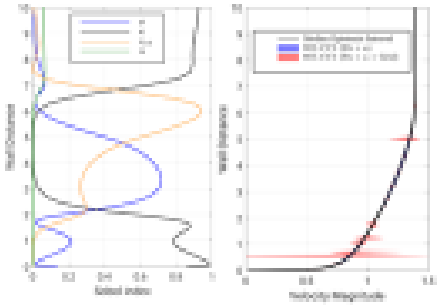
August 27, 2018

Spectre: a UQ tool engineering CFD simulations

Intelligent Light





Novel Ideas

- Complete UQ Framework
  - Automated data management
  - Easy to use web delivered GUI that integrates Numerical, Model Form and complete Model Input uncertainties.
- New UQ visualization techniques that couple statistical information with CFD field data visualizations
- New Model Form Uncertainty for aerodynamics-relevant problem

Impact and Champions

IMPACT:

- Spectre removes roadblocks to UQ in CFD applications
  - Encapsulates how to set up an analysis
  - Automatically manages hundreds or thousands of simulations on either in-house or in-the-cloud
- Presented to representatives from the DOD, NASA and major US aerospace companies to support military aircraft design, new launch vehicle design and Aircraft Certification by Simulation
- Started collaboration with Boeing as early adopters of Spectre Technology

Principal Investigator: Earl P.N. Duque, Intelligent Light

Milestones/Dates/Status

MS	Description	Plan	Act
1	Finalize GUI design	5/17	
2	Implement Complete Model Input Uncertainty	7/17	
3	Implement Model Form Uncertainty for AVM	10/17	
4	Implement Numerical Uncertainty and Dakota enhancements	1/18	
5	Complete UQ study on high lift wing	4/18	
6	Implement Field Data viewer	10/18	
7	Implement New MFU method	1/19	
8	Final Report	3/19	

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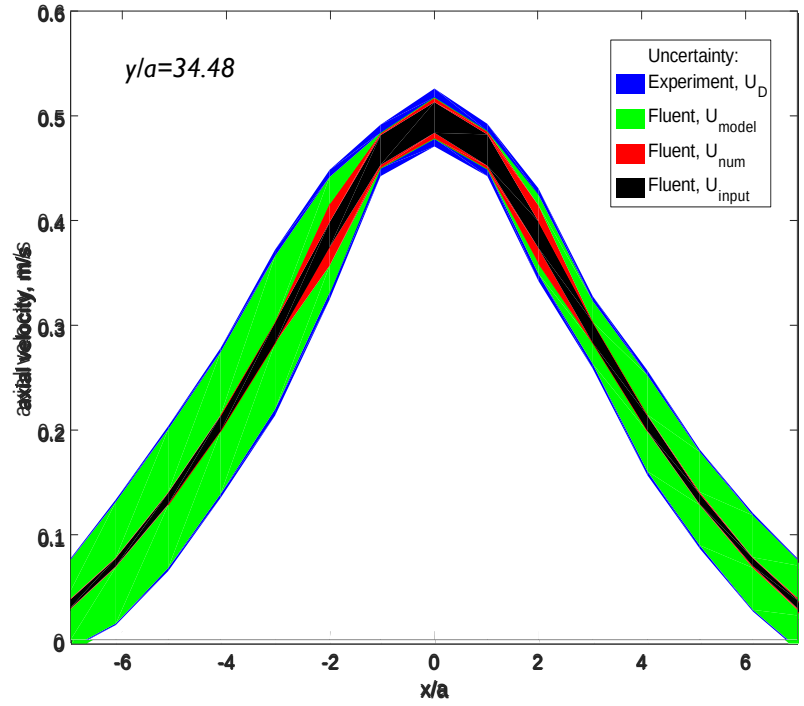
TOTAL UNCERTAINTY IN MODEL RESULTS

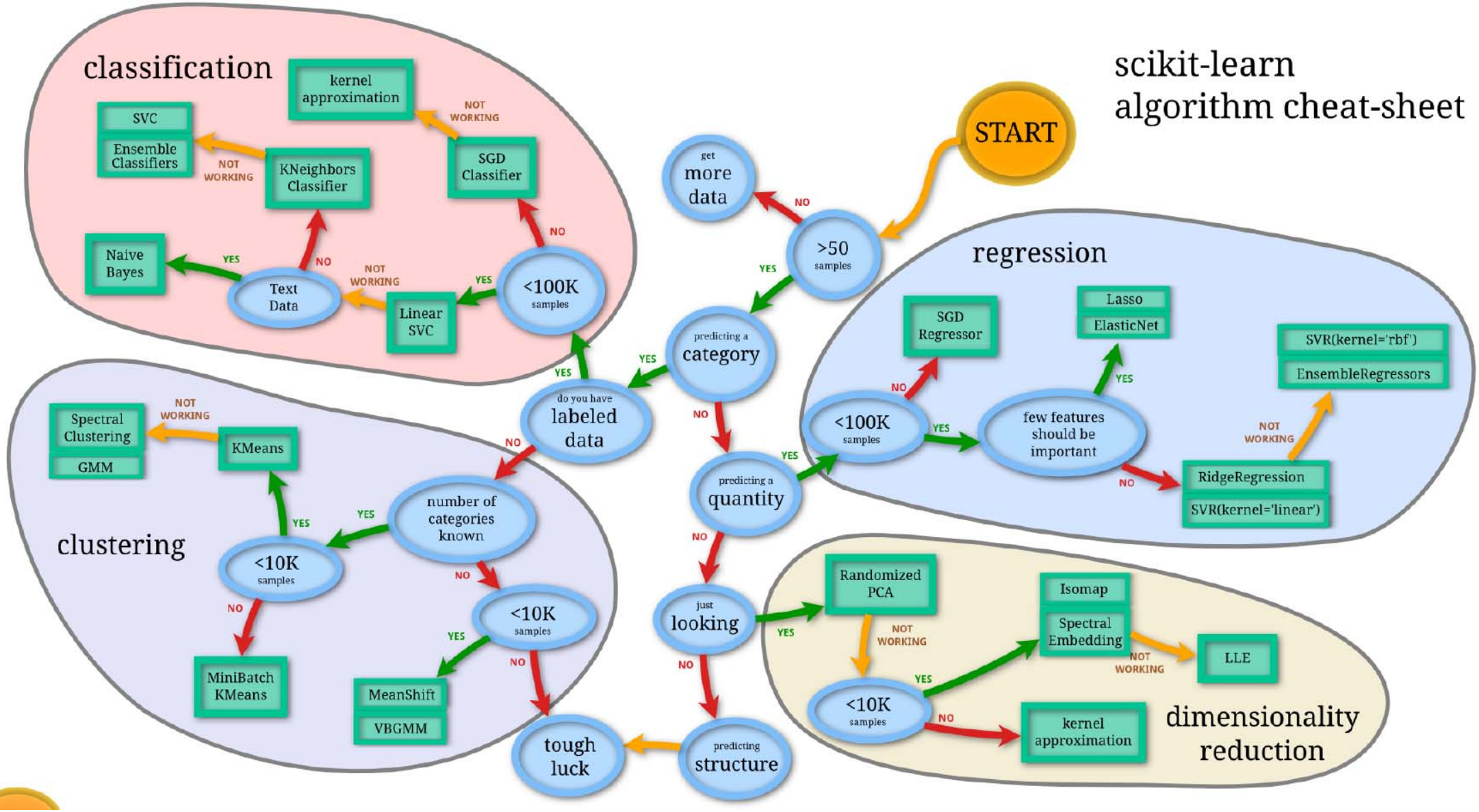
- Start with Input Uncertainty, U_{input}
  - Append Numerical Uncertainty, U_{NUM}
  - Append Model Form Uncertainty, U_{model}
  - Append Experimental Uncertainty, U_D

$$U_{total,95\%} = U_{input} \pm U_{NUM} \pm U_{model} \pm U_D$$

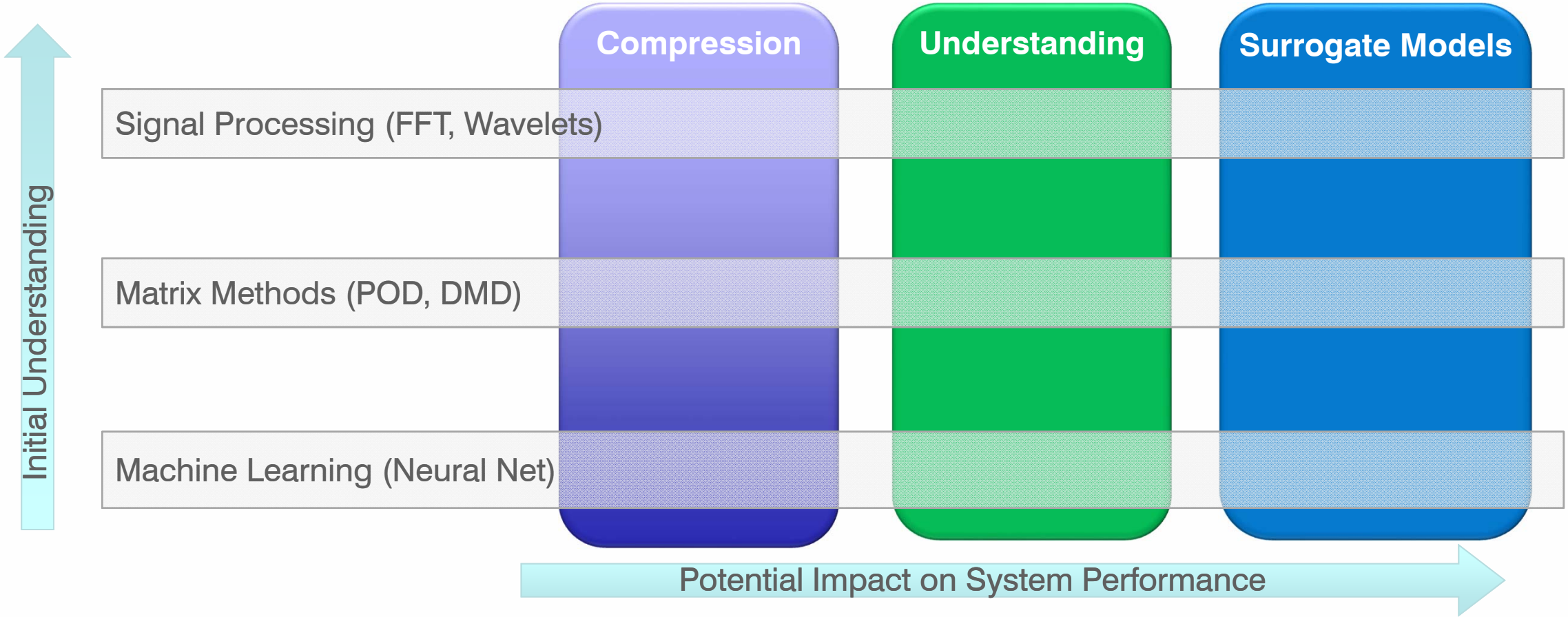


DATA SCIENCE…

scikit-learn algorithm cheat-sheet

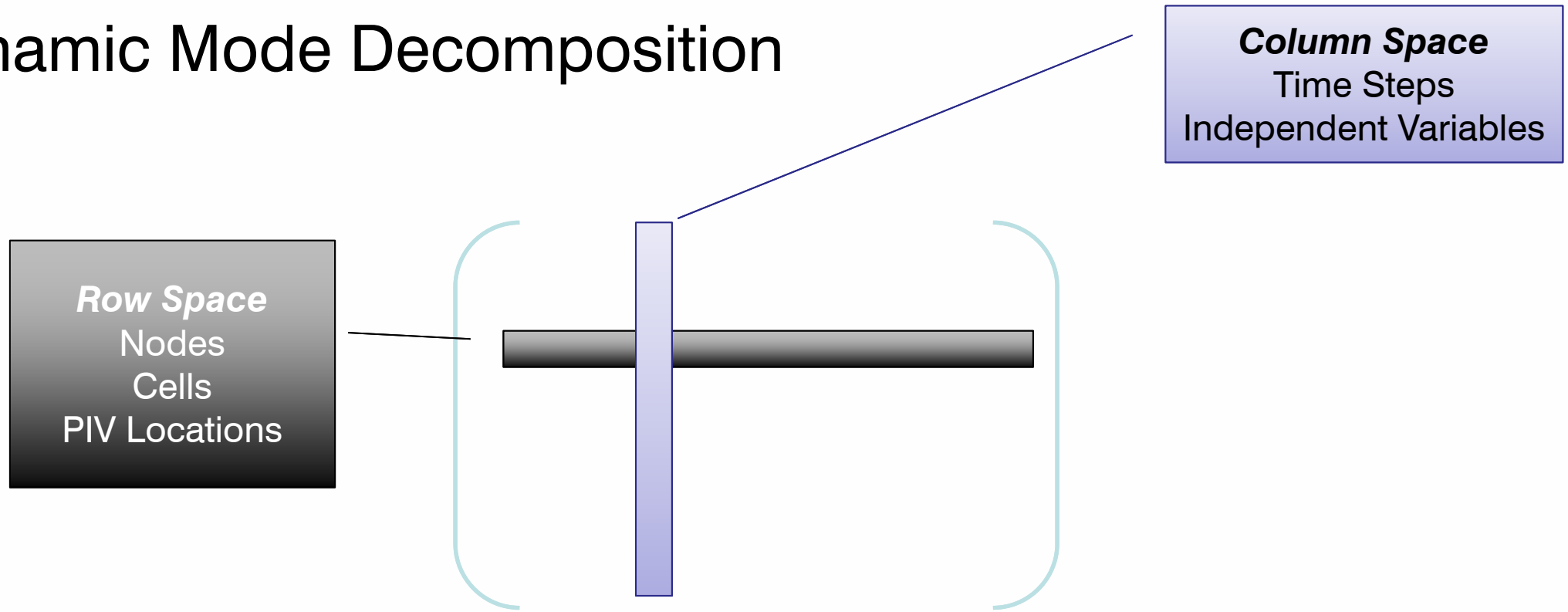


Our View of E/CFD Data Analytics

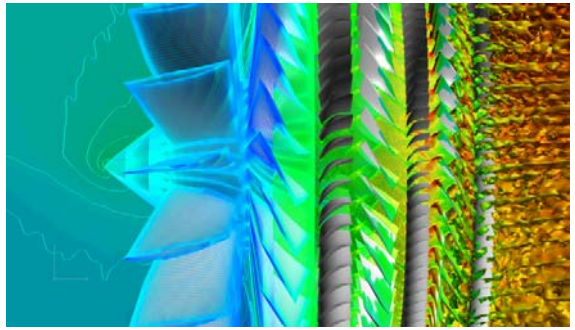


Getting Data into Analysis

- Single Value Decomposition
- Dynamic Mode Decomposition



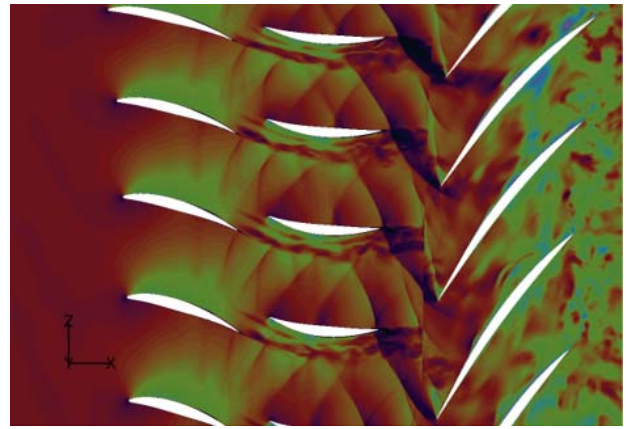
Research Funded by AFRL Propulsion Dir.



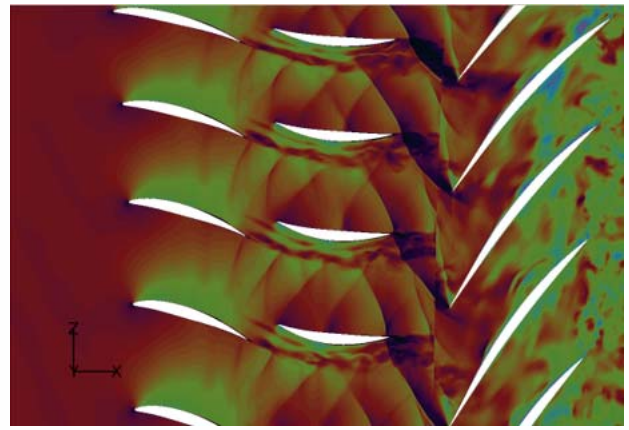
- Utilize Reduced Order Methods to analyze flow physics of 3D unsteady compressor
  - Basic research performed @ BYU
  - Prof. Steve Gorrell and Matt Jones
- Enabled POD and DMD capabilities in our FieldView products via python plugins
- Reconstruction occurs on the fly
- 100-1000X compression

AFRL FA8650-14-C-2439 2013-2014

Original results

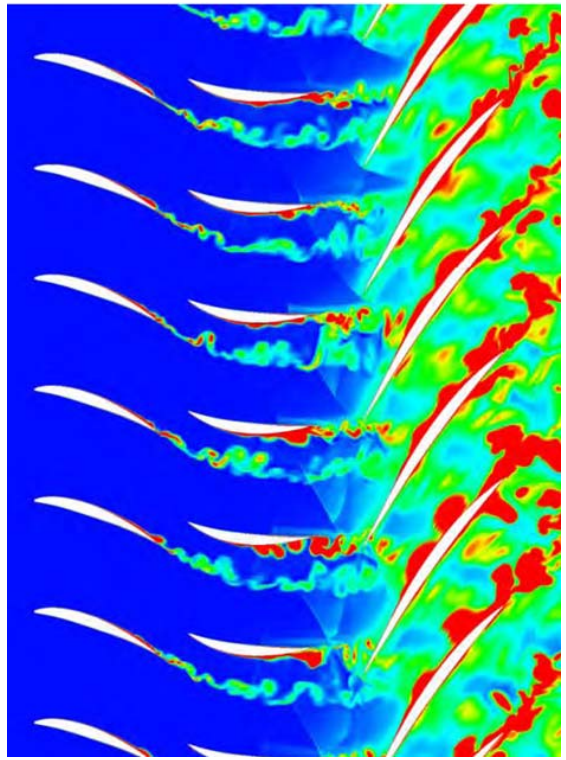


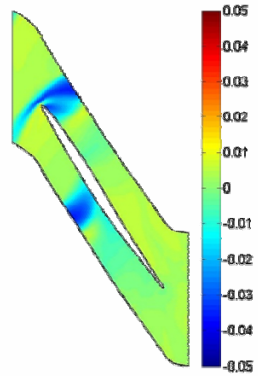
Reconstruct 99% energy, 1/100 size



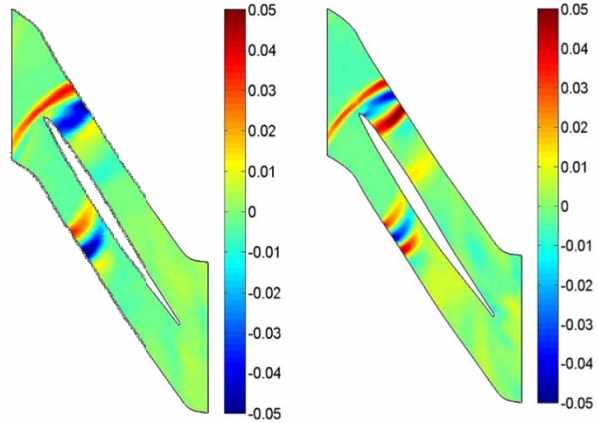
Feature Detection from POD Modes

Static Pressure





Mode 1:
Blue color corresponds to range of shock motion during rotation

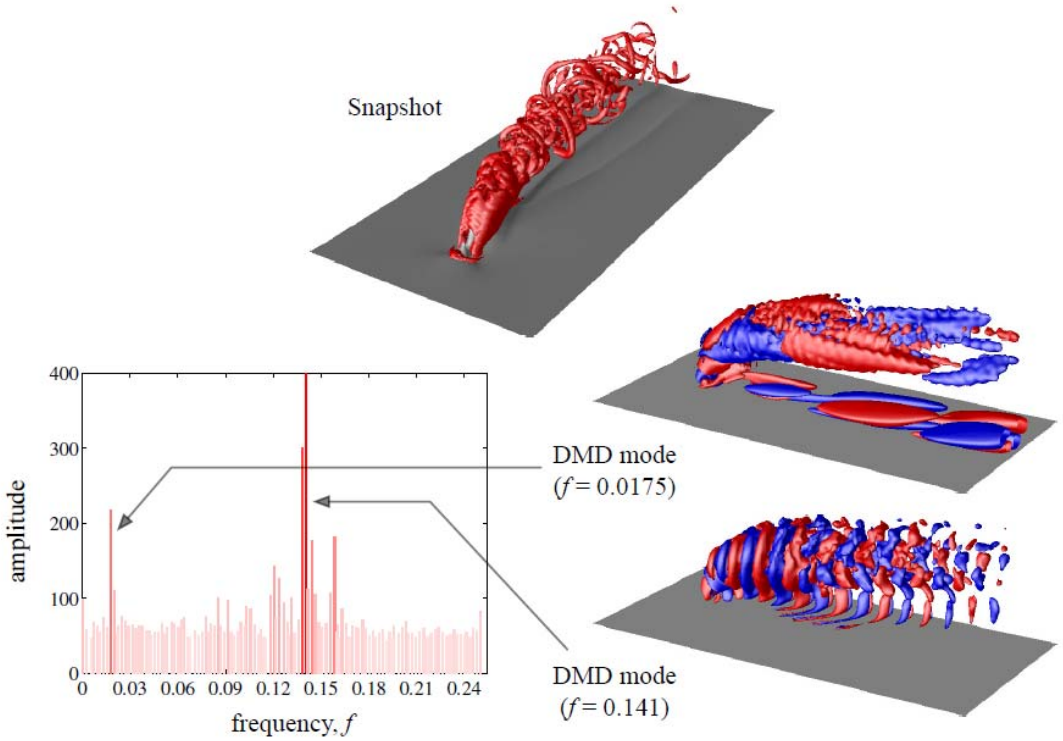


Modes 2 & 3:
Linear combination of higher order modes reveal exact shock location for a given angular position

Earl P.N. Duque, Daniel E. Hiepler, Steven E. Gorrell, Matthew R. Jones and Trevor J. Blanc , “Visualization and Post-Processing of Large Scale Engineering Applications using In-Situ Data Extracts and Proper Orthogonal Decomposition”, AIAA SciTech 2015, January 2015

What Comes Back Depends on Method

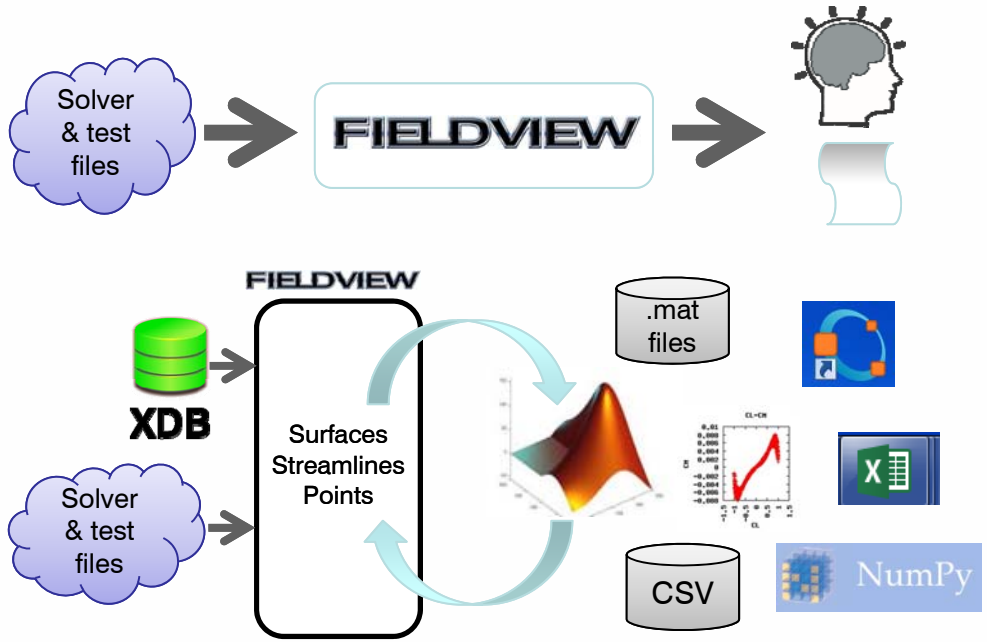
- Using SVD results in Modes an Relative Modal Intensity
  - Data matrix = U∑V*
  - Similar to Eigenvectors and Eigenvalues
- Using DMD results in Dynamic Modes and Eigenvalues
  - Useful for frequency analysis



Spectral analysis of nonlinear flows. Rowley, C. W., Mezic, I., Bagheri, S., Schlatter, P., and Henningson, D. S. No. 1, 2009, Journal of Fluid Mechanics, Vol. 641, pp. 115-127

FieldView 17: Introduces CFD to Matrix Connection

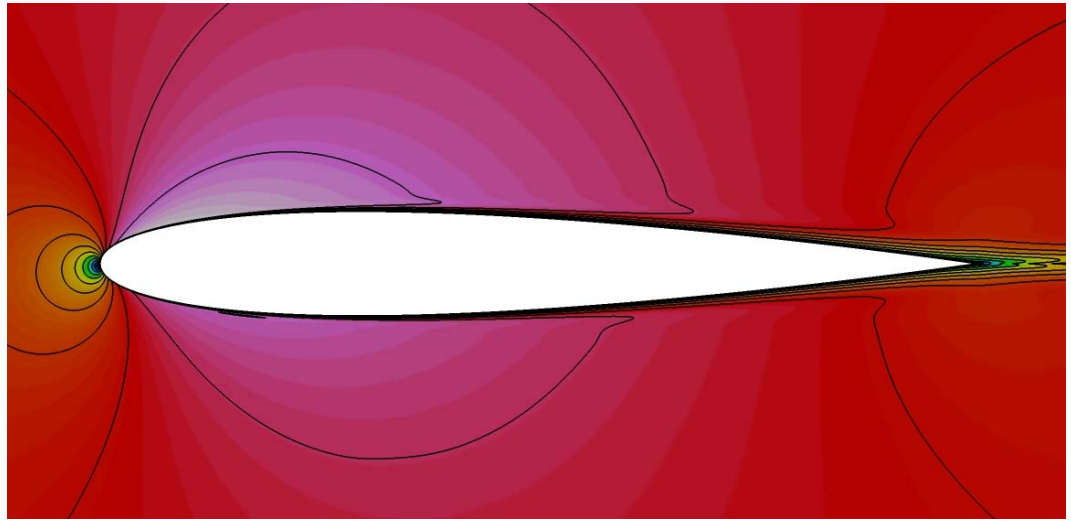
- FieldView has always been good at visualization & extracting data
- We now enable statistics and linear algebra techniques
  - MATLAB, Excel, numpy
  - Direct output to snapshot matrices and CSV format
- To get CFD folks started, we ship:
  - OCTAVE
  - Numpy, matplotlib



FieldView: A waypoint instead of an endpoint

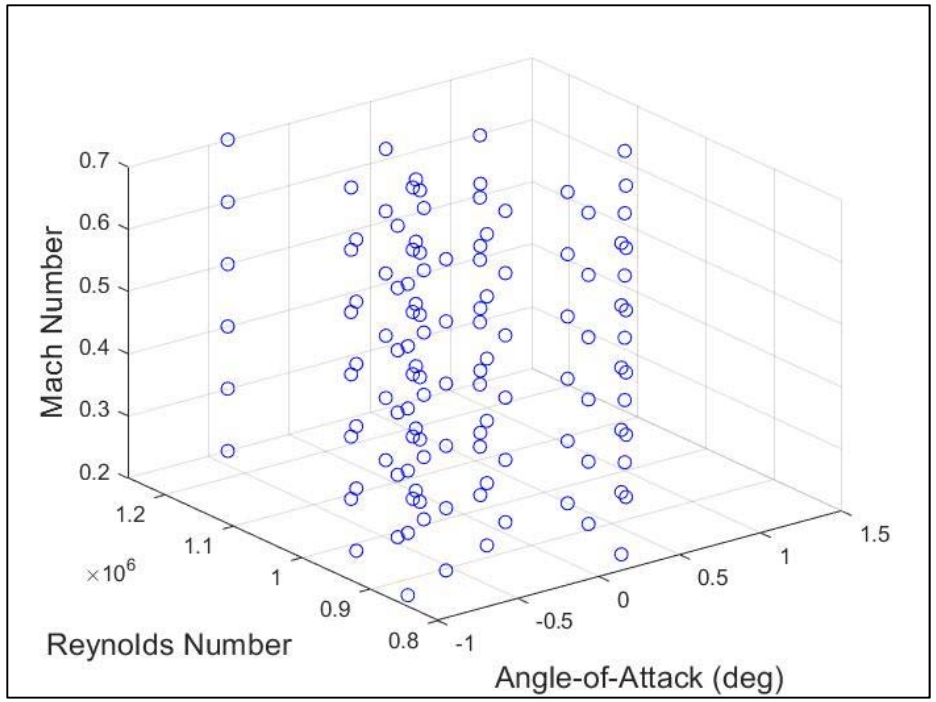
Illustration of Data Analysis Capabilities

- Develop intuition for data analysis capabilities
- NACA 0012 uncertainty quantification example results
- Use modal analysis to *make sense* of data



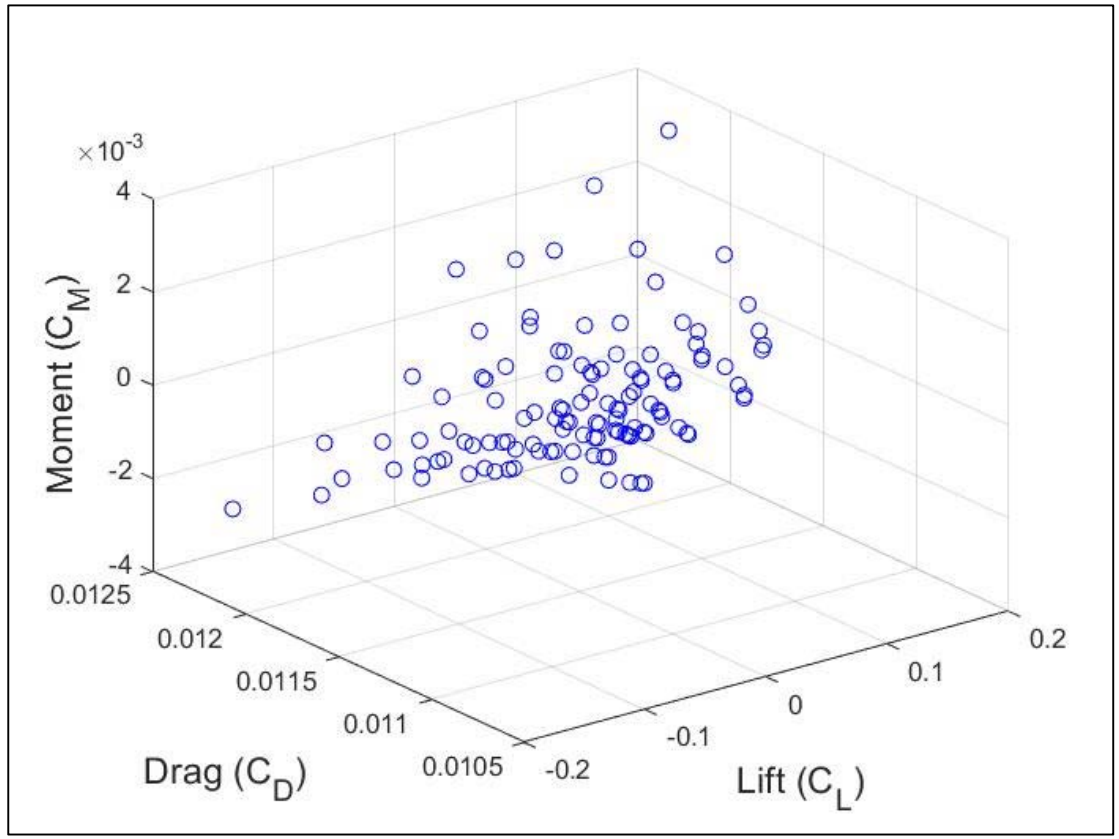
Population of Conditions is Selected for Study

- Input parameter space
  - Epistemic (known range)
    - Mach number
  - Aleatory (known distribution)
    - Reynolds number
    - Angle-of-Attack
- Population includes some ordered characteristics



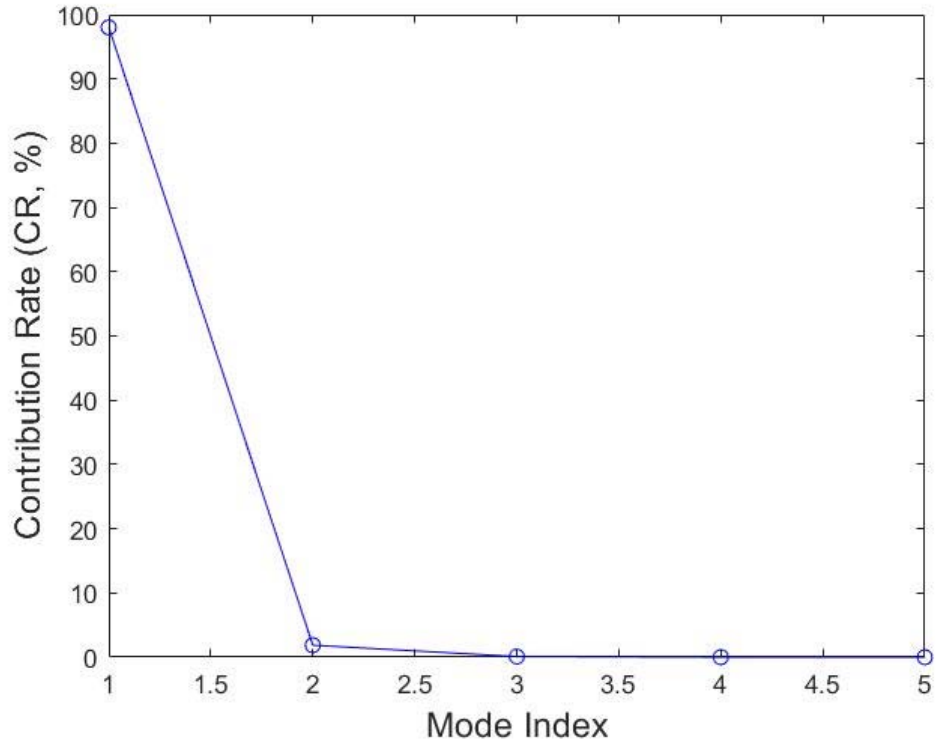
Aerodynamic Predictions Calculated for Input Parameter Space

- State variables
  - Lift
  - Drag
  - Moment
- Nebulous cloud of data
- Minimal insight into physics



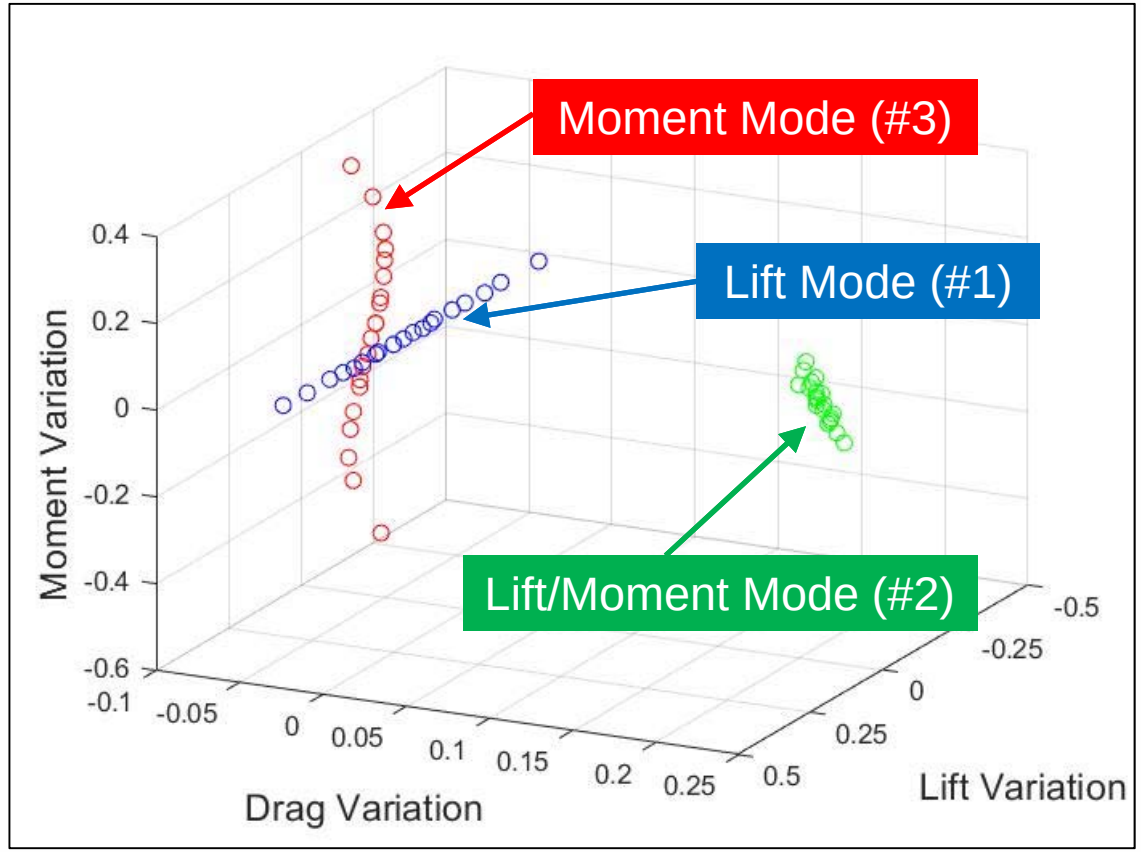
Determine Significant Modes

- Apply singular value decomposition to extract modes
- Mode 1 is nearly 100% of overall behavior
- Modes 2 & 3 compose residual portion of state variable response

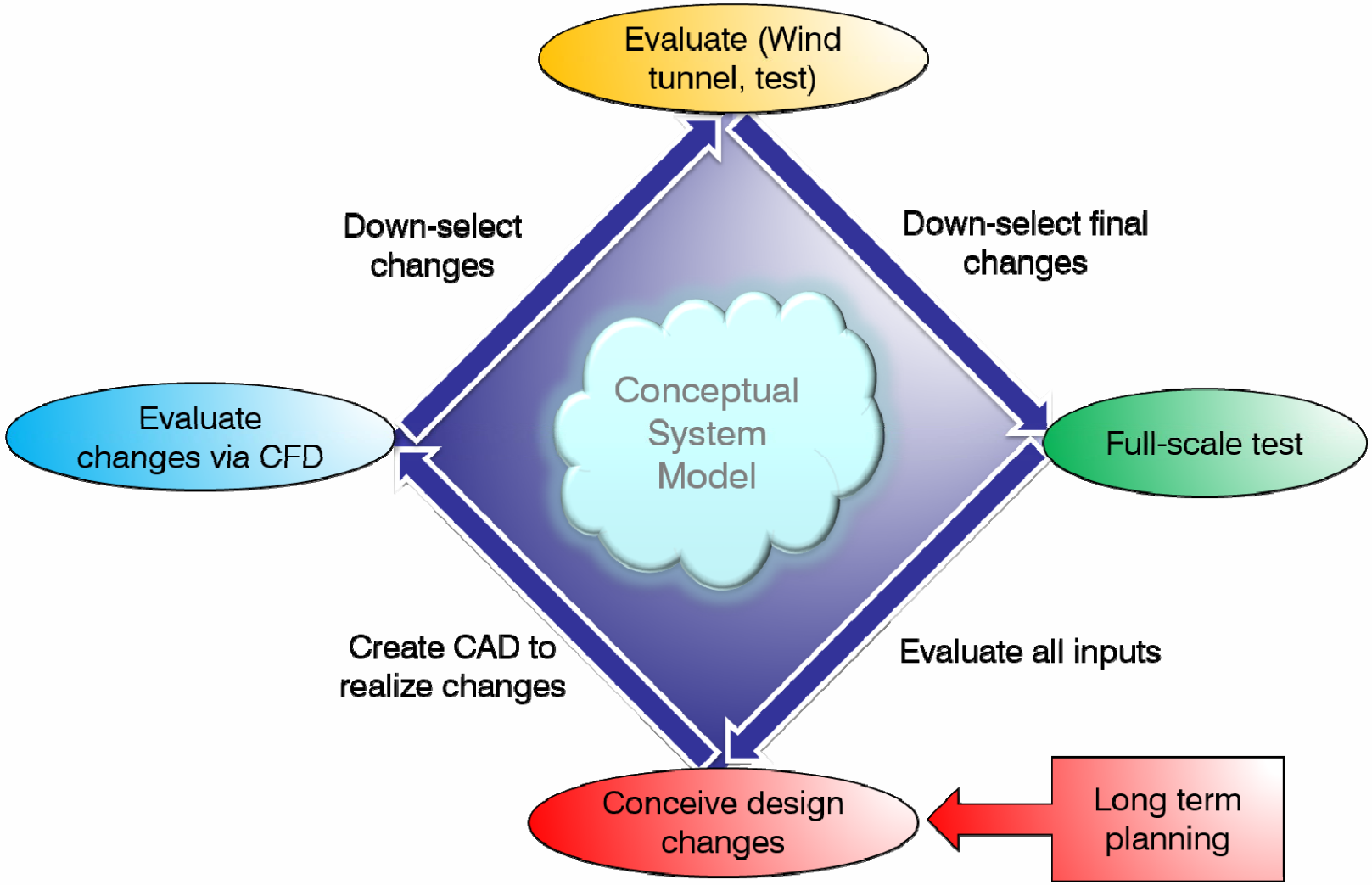


Identify Physical Significance of Modes

- Significantly more ordered
- Mode shapes shown
  - Span lift, drag and moment
  - *Isolated* from Mach effects
- Identify physical functionality for each mode



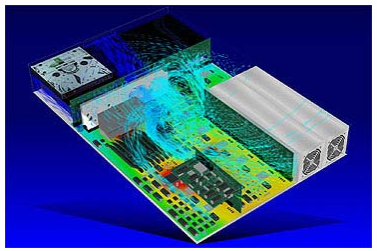
CFD, Experiment and Test



Technology Platform

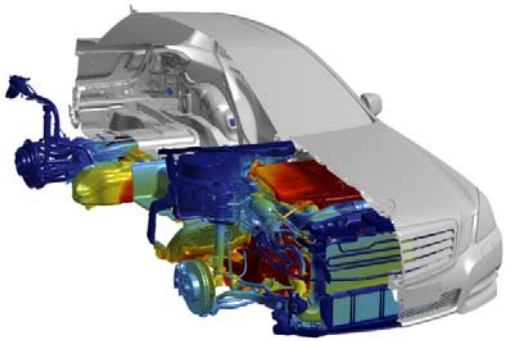
FV Express

OEM Bundled
Node Locked
Reader Subset
Casual Users



FV & HPC FV

Desktop
Node Locked or Floating
Full Functionality
All Readers
Full-Time Sophisticated Users
In situ and XDB Workflows

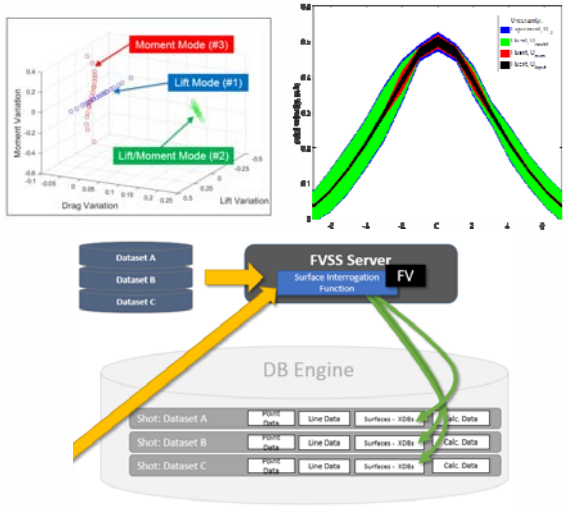


FV Analytics

System Characterization
Linear Algebra Techniques (POD, DMD, PCA, Machine Learning, etc.)

Automated Validation
Web-based, Integrated Database

Uncertainty Quantification
Web-based, Dakota, Database



Technology & User Sophistication