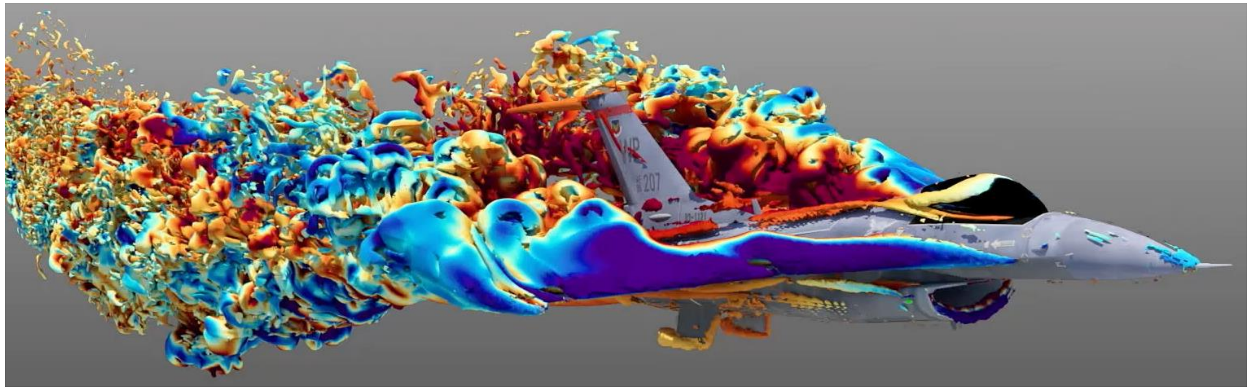


A Vision for High Fidelity Multi-Disciplinary Simulation Built Surrogates Influencing the Design and Assessment of Military Systems

National Defense Industry Association
Systems and Mission Engineering Conference
6-8 December 2021

DOD HPC MODERNIZATION PROGRAM

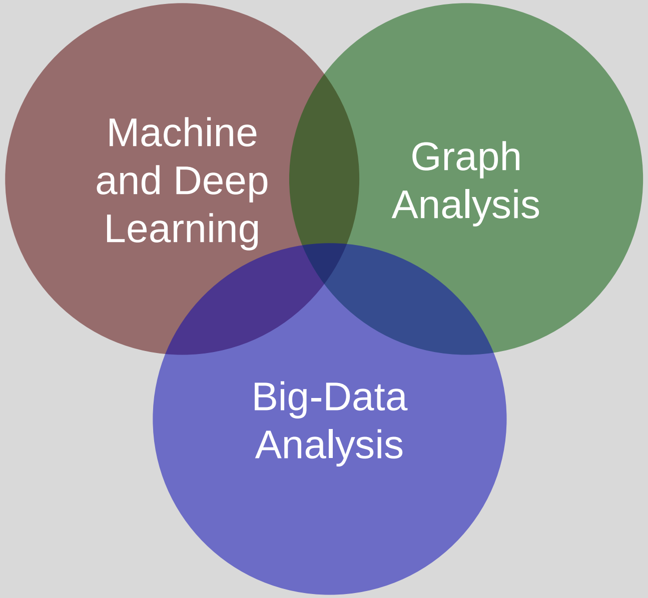
Dr. Scott A. Morton, Associate Director for CREATE
DoD HPCMP, US Army ERDC/Information Technology Laboratory
Scott.a.morton3.civ@mail.mil

Definition: High-End Computing *(HEC)*

Compute-Intensive		Data-Intensive	
Difficult	**Easy**	**Difficult**	**Easy**
Tightly-coupled *100s to 1000s of nodes in lock-step*	**Embarrassingly parallel** *independent task / node*	**10s to 1000s of accelerators**	**Few accelerators**
Fast / low-latency network	**Slow / high-latency network**	**10s to 1000s of information feeds**	**Few information feeds**
Fast / large memory and storage	**Slow / small memory and storage**	**Large graphs**	**Small graphs**
		Large data sets	**Small data sets**
High Performance Computing	**Basic Computing**	**High Performance Data Analysis**	**Basic Data Analysis**

High-End Computing (HEC) = **High Performance Computing (HPC)** + **High Performance Data Analysis (HPDA)**

Data-Intensive Methods: a computer science approach to understanding phenomena and exploiting uncovered information



- Building artificial intelligence (AI) models *(machine and deep learning)*
- Uncovering relationships *(graph analysis)*
- Understanding large volumes of data *("big data" analysis)*

Definition: Digital Engineering vs. MBSE

- **Model-based systems engineering (MBSE) –** a formalized methodology used to support the requirements, design, analysis, verification, and validation associated with the development of complex systems *(Nataliya Shevchenko, "An Introduction to Model-Based Systems Engineering (MBSE)," Software Engineering Institute (SEI), 21 Dec 2020)*

- **Digital engineering (DE)** – an **integrated digital approach** that uses authoritative sources of systems' **data** and **models** as a **continuum across disciplines** to support life cycle activities **from concept through disposal.** *(Defense Acquisition University)*
  - Integrated digital approach → a monolithic solution that suggests there can be no R&E / A&S divide
  - Data → must be regularly managed/updated/curated at each stage of the process
  - Models → both compute and data-intensive; range from basic analysis to high-end computing (HEC)
  - Availability → accessible to anyone in the design, test, evaluation, sustainment, mission planning pipeline
  - Duration → from concept through disposal (and possibly beyond); decades to centuries
  - Extensity → continuum across disciplines; simultaneous accounting of all assets at all lifecycle stages to facilitate projection of current and future forces in a full range of scenarios, to determine gaps, to advise the characteristics of future platforms, and to build preventive maintenance plans for individual assets

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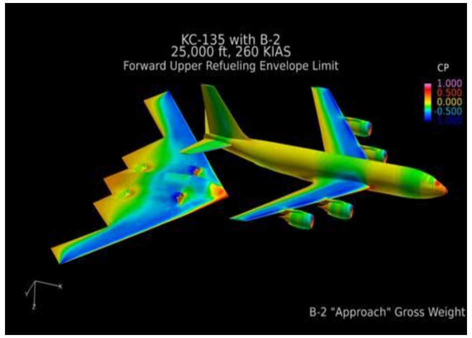
HEC Impacting Digital Engineering

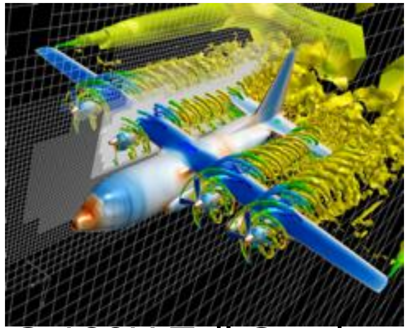
HEC and High Fidelity Physics (Physics Based Analytics-PBA) used for Deficiency Diagnosis

- **Single Point Calc’s (days/100k CPUHrs)**
- **Typically Occurs After Wind/Flight Test discoveries**
- **Fixes can be very costly since the vehicle is far into the design timeline**
- **Payoff for Programs ($M’s)**
- **Postdictive/Early Predictive**



B-2/KC-135 Refuel

Light Weight Prec Munition



C-130H Tail Crack

Increasing Program Relevance and Impact on Program Cost, Schedule, and Performance

Current Simulation Capability/Increasing Resources

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HEC and PBA used earlier in Design to Downselect From a Few Configurations

- Many More Single Point Calcs/ Maneuvers (days/1Ms CPUHrs)
- Targets Specific Flight Cond's Mnvrs for Comparison and Risk Reduction
- Chosen Vehicle Better Meets Req's
- Higher payoff for Programs ($10M's)
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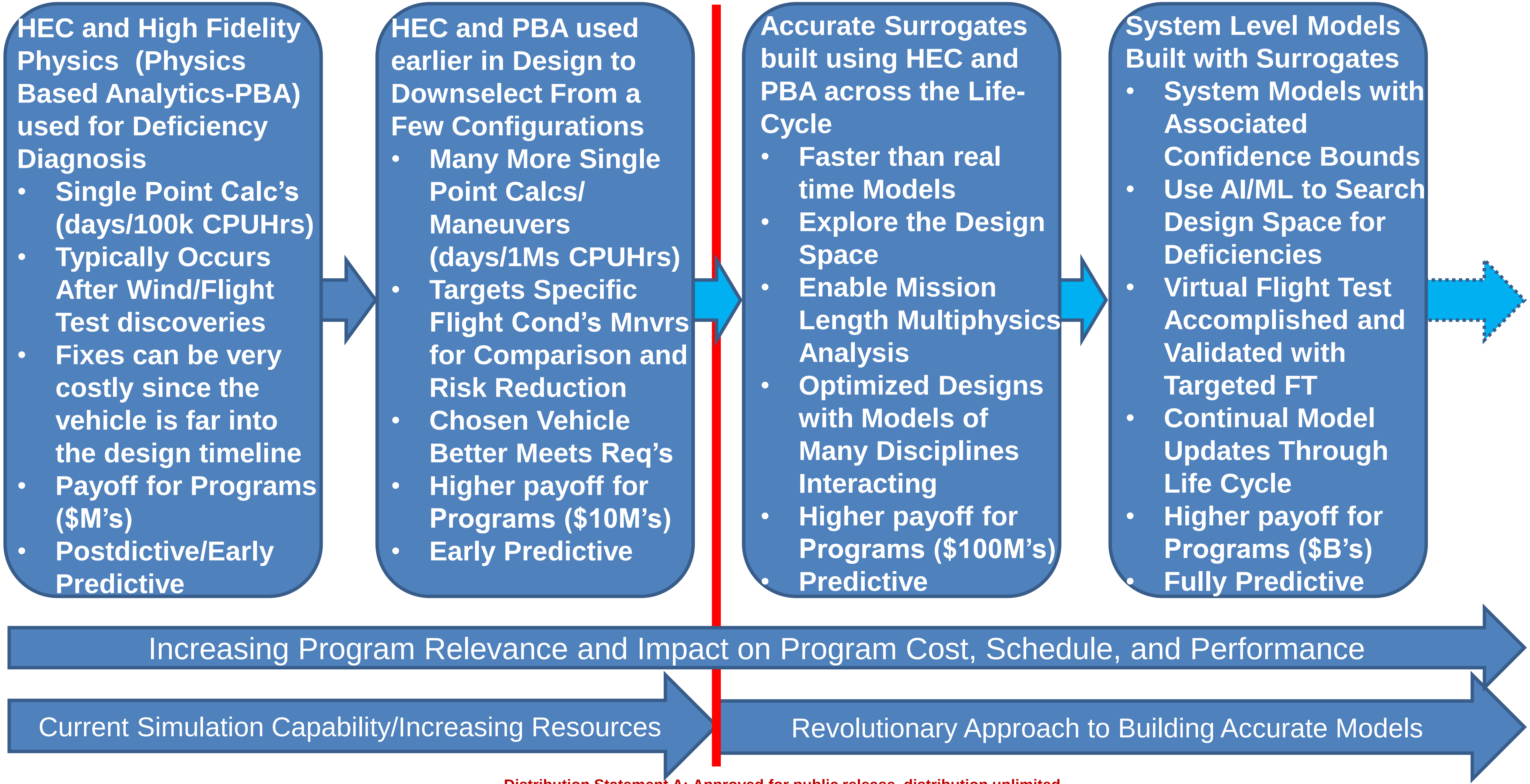
Accurate Surrogates built using HEC and PBA across the Life-Cycle
- Faster than real time Models
- Explore the Design Space
- Enable Mission Length Multiphysics Analysis
- Optimized Designs with Models of Many Disciplines Interacting
- Higher payoff for Programs ($100M's)
- Predictive

Increasing Program Relevance and Impact on Program Cost, Schedule, and Performance

Current Simulation Capability/Increasing Resources

Revolutionary Approach to Building Accurate Models

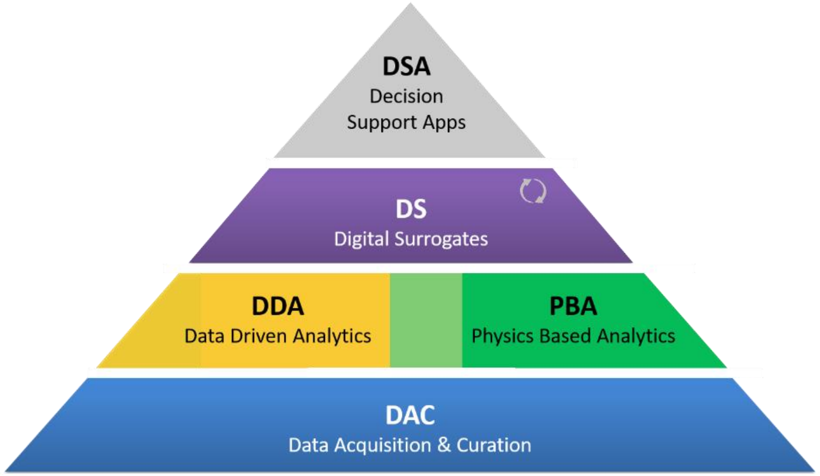
HEC Impacting Digital Engineering



Physics Based Digital Engineering

- **Combat Air Vehicle Example**

- **Look at example Apps, Physics Informed Surrogates, Physics Based Analytics, Data Driven Analytics, and Data Acquisition and Curation**



Physics Based Analytics - Aerodynamics

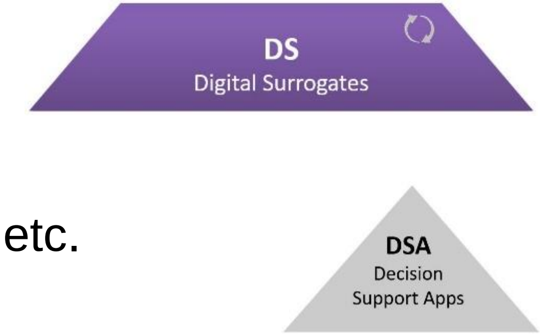
- **Models are built to impact decision making in air vehicle design, development, and sustainment**
  - Examples – Aerodynamics, Stability and Control (S&C), Propulsion, Structures

- **High Fidelity CFD Models typically…**
  - Take supercomputer resources to run depending on the fidelity of the mesh
  - Take flight conditions, surface and external volume meshes with boundary condition attributions as inputs
  - Compute the surface and volume aerodynamics of the vehicle using a finite volume or finite element solution algorithm
  - May be coupled with a structural solver, propulsion module, 6DOF solver, chemistry solvers for non-ideal gases, and conjugate gradient heat transfer solver to compute multiphysics simulations

- **Reduced Order Loads Models typically…**
  - Are derived from simulations using the high fidelity CFD solver, sometimes coupled with other physics models (e.g. S&C 6DOF, Structures, Propulsion)
  - Run faster than real time and can span the air vehicle envelope

Physics Based Analytics – S&C

- **The Stability and Control Model is typically a 6 Degree of Freedom (6DOF) solver that…**
  - Runs faster than real time and spans the vehicle envelope
  - Takes mass properties, vehicle configuration, and desired flight trajectory (e.g. stick inputs) or conditions as inputs
  - Uses information about vehicle aerodynamics, structures, and propulsion and the equations of motion to determine a vehicle's trajectory
  - Can incorporate "feedback control laws"
  - Can easily be improved for accuracy by replacing aerodynamics, structures, and propulsion data as higher fidelity information is known
- **Stability and Control Model can be used for…**
  - Stability and Control analysis and handling qualities
  - Sensitivity studies
  - Mission performance – fuel burn, available payload weight, etc.
  - Driver for "Pilot in the Loop" Simulators



Physics Based Analytics - Propulsion

- **The Propulsion Model has two variants**
  - High fidelity turbomachinery integrated into a CFD solver
  - Engine cycle deck

- **Turbomachinery are geometry/mesh components (e.g. compressor or turbine rotor/stators, combustor) in the flowfield path of a high fidelity simulation tool**

- **The Engine Cycle Deck typically…**

  - Runs faster than real time and spans the vehicle envelope
  - Takes flight conditions, compressor face conditions, exit nozzle conditions, and vehicle configuration as inputs
  - Uses information about the engine and with one-dimensional engine pressure and temperature ratios through the engine stations, along with bleed losses and installation losses, determines compressor face and exit nozzle mass flow, velocity, and temperature data, as well as fuel burn and installed thrust
  - Can be run offline, integrated into a high fidelity simulation tool (FORTRAN or NPSS Model) with pseudo-time accuracy with or without transient behavior, or integrated into an S&C 6DOF Model to provide thrust

Physics Based Analytics - Structures

- **Two variants of Structures Models**
  - Finite Element Structural Model with a High Fidelity Simulation Tool
  - Modal Structural Model
- **The Finite Element Structures Model typically…**

  - Takes from work station to supercomputer resources to run depending on the fidelity of the mesh
  - Takes flight conditions, internal structure meshes with material property attributions, and external loads as inputs
  - Computes the structural deformation, as well as, internal stress and strain of the structure using a finite element solution algorithm
  - It may be coupled with an aerodynamic solver and/or a conjugate gradient heat transfer solver to compute fluid-structure, thermal-structure, or fluid-thermal-structural interactions
- **The Modal Structural Model typically…**

  - Is a linearized Reduced Order Model derived from the Finite Element Model through an eigenvalue analysis
  - Runs orders of magnitudes faster than the Finite Element Model

Physics Based Analytics

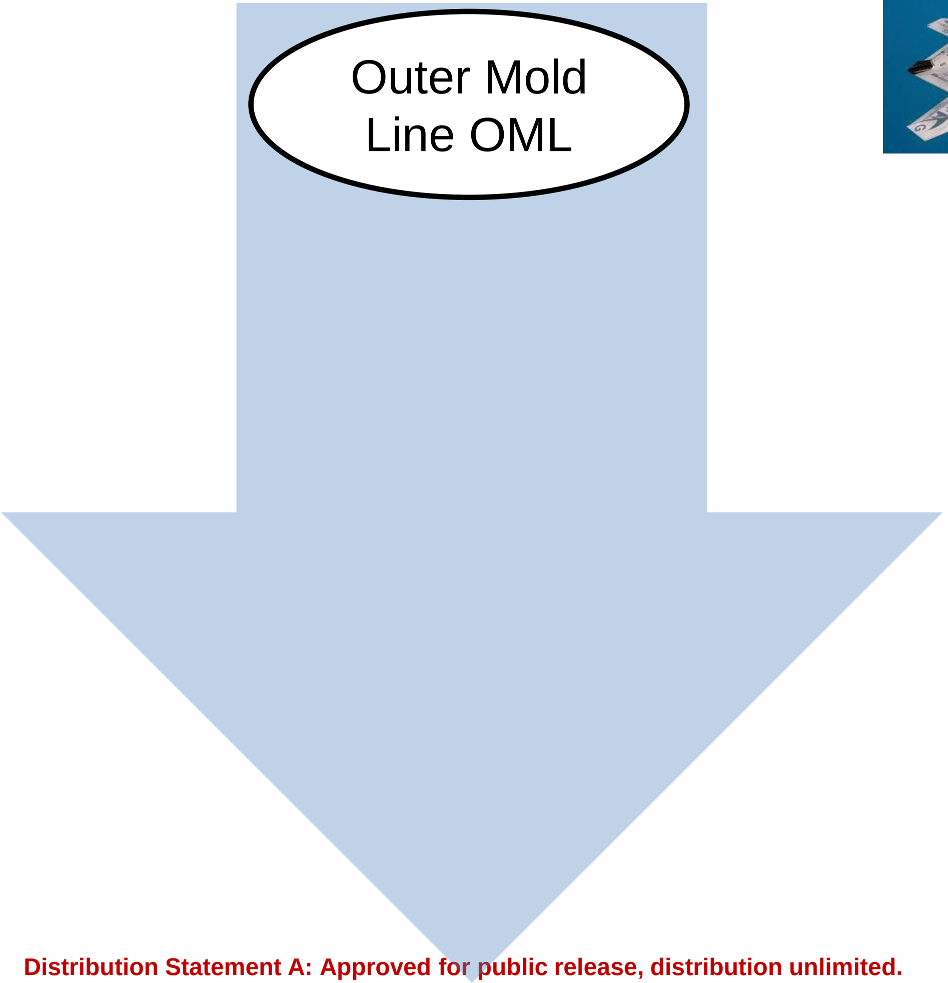
PBA
Physics Based Analytics

DOD HPC MODERNIZATION PROGRAM

- **During the design process we can eliminate poor design choices by increasing the fidelity of the PBAs as more information is known (objects and connection notional)**

Kestrel

Increasing Multi-disciplinary



Increasing Detail/Accuracy

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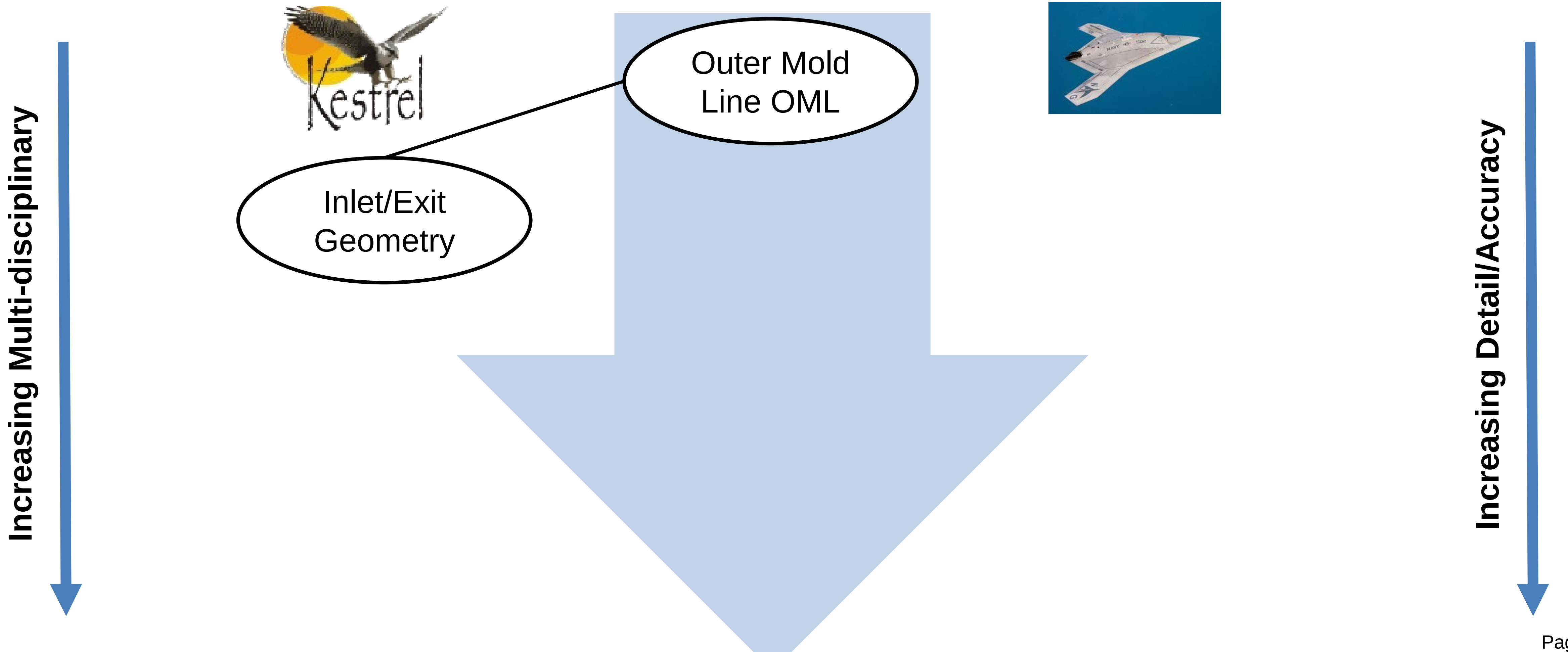

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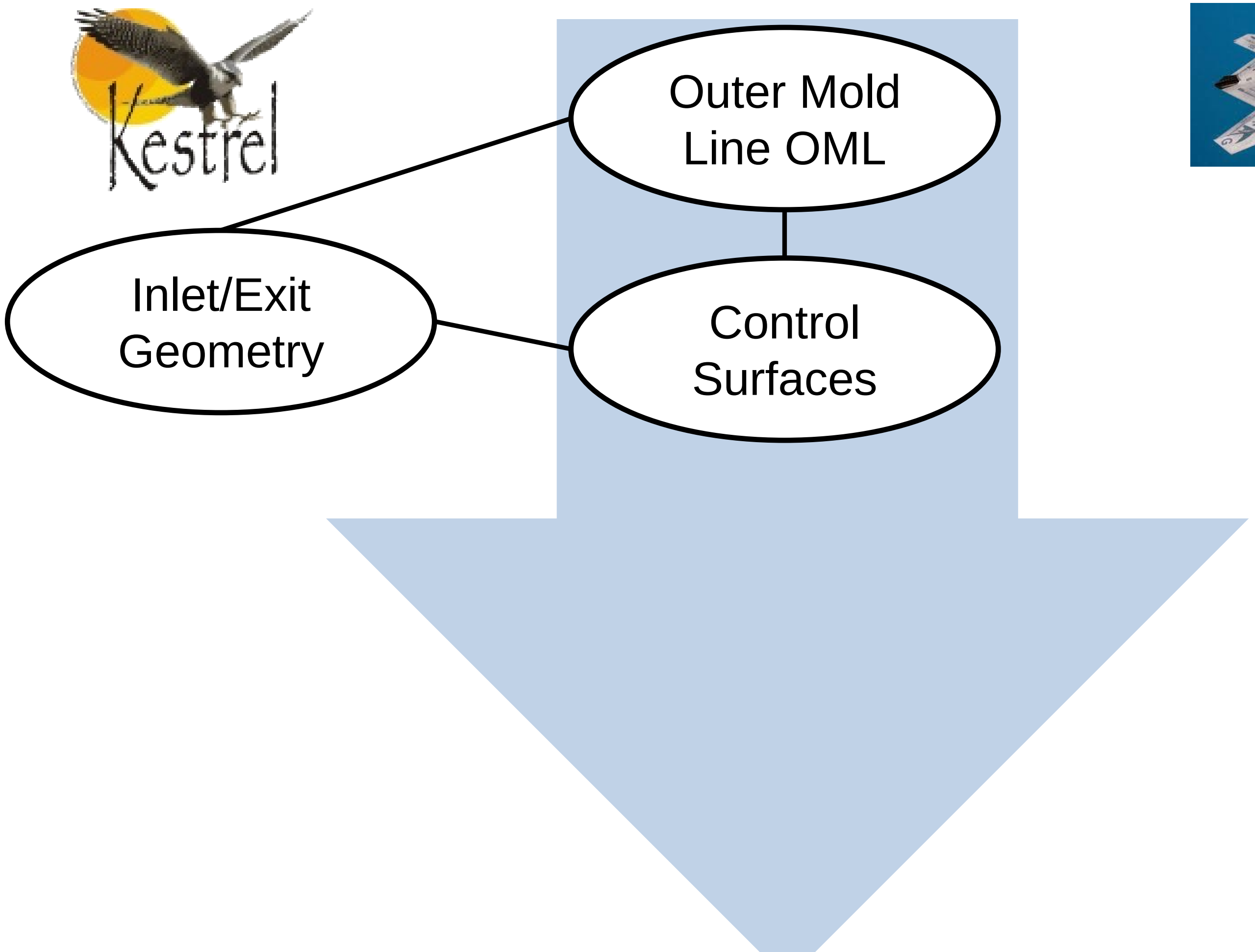

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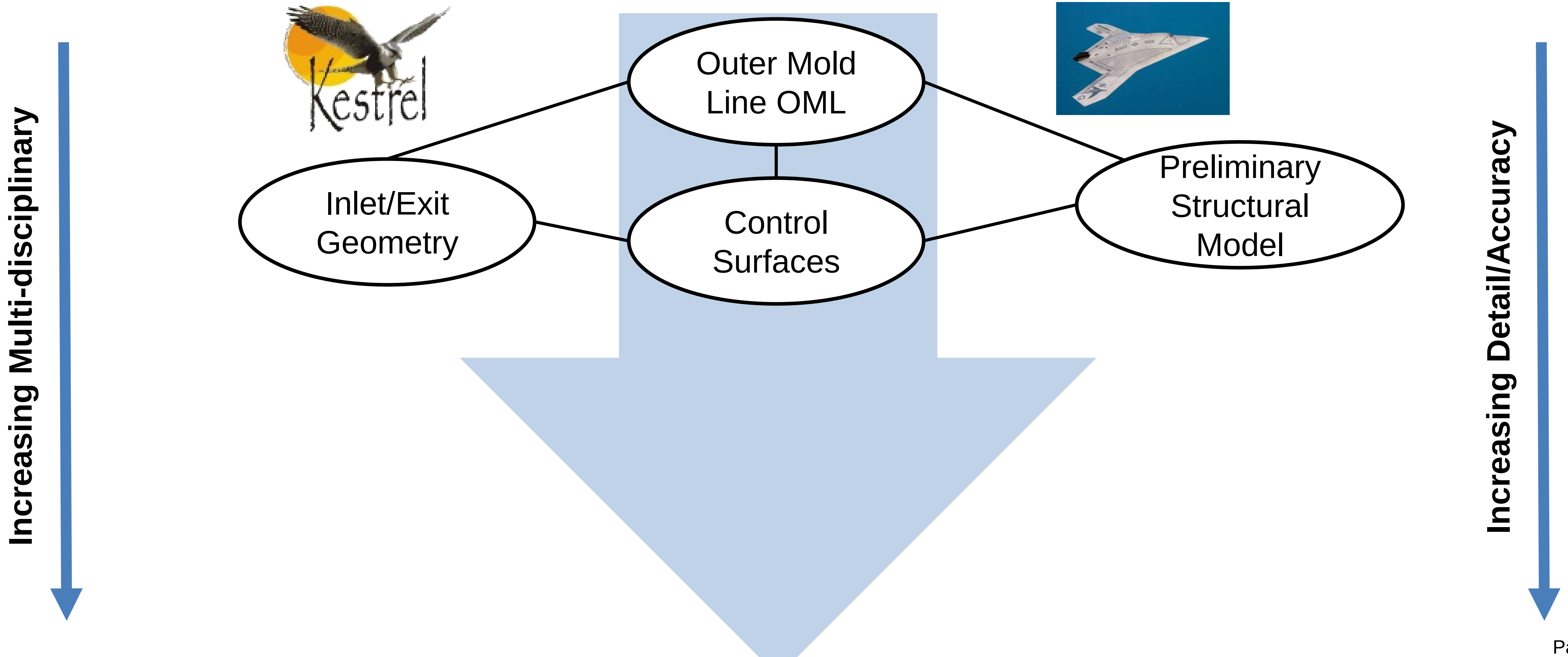

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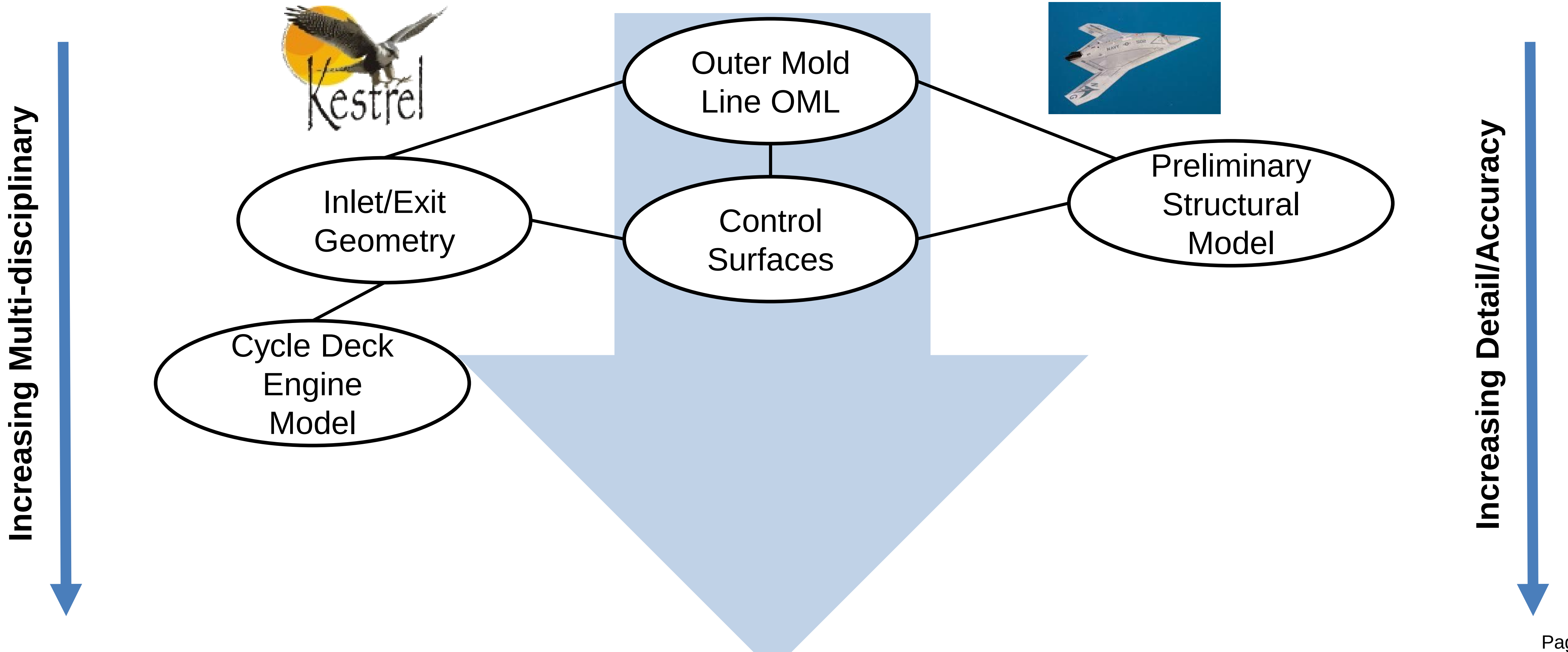

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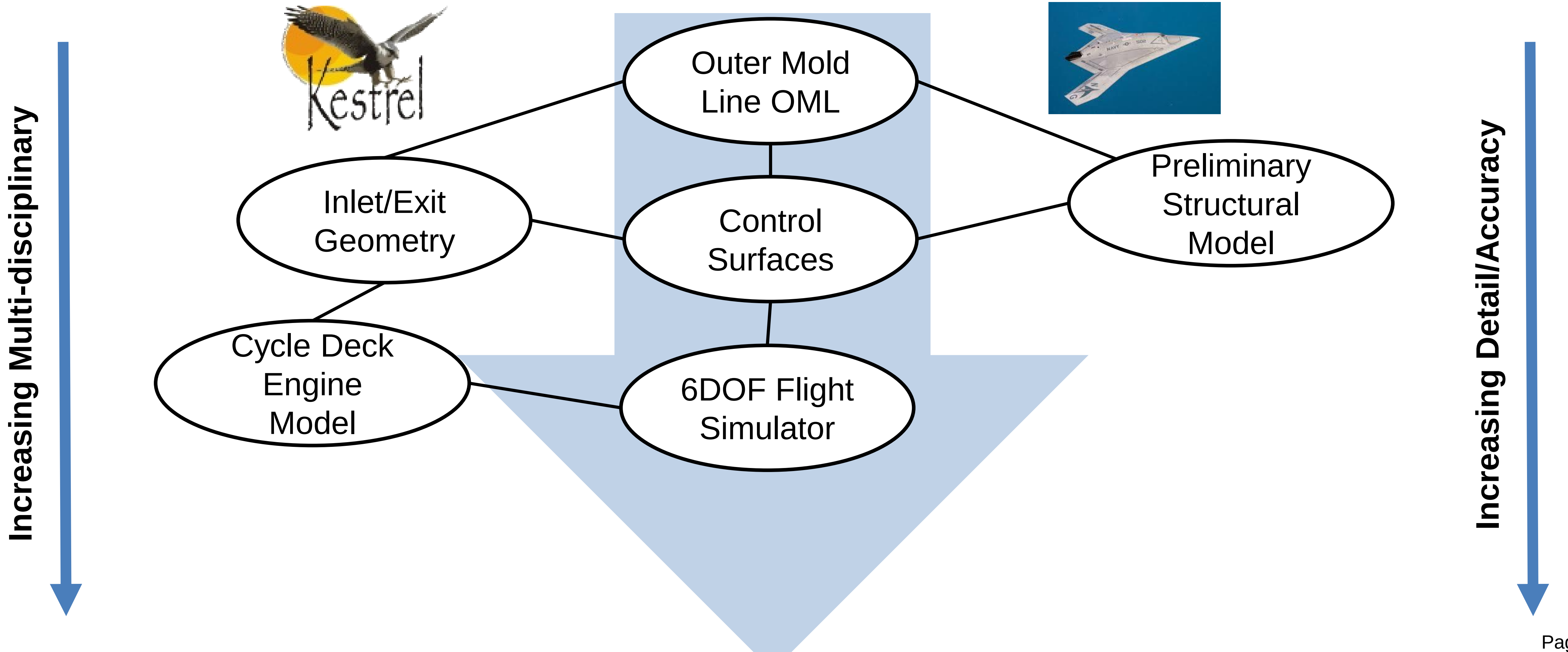

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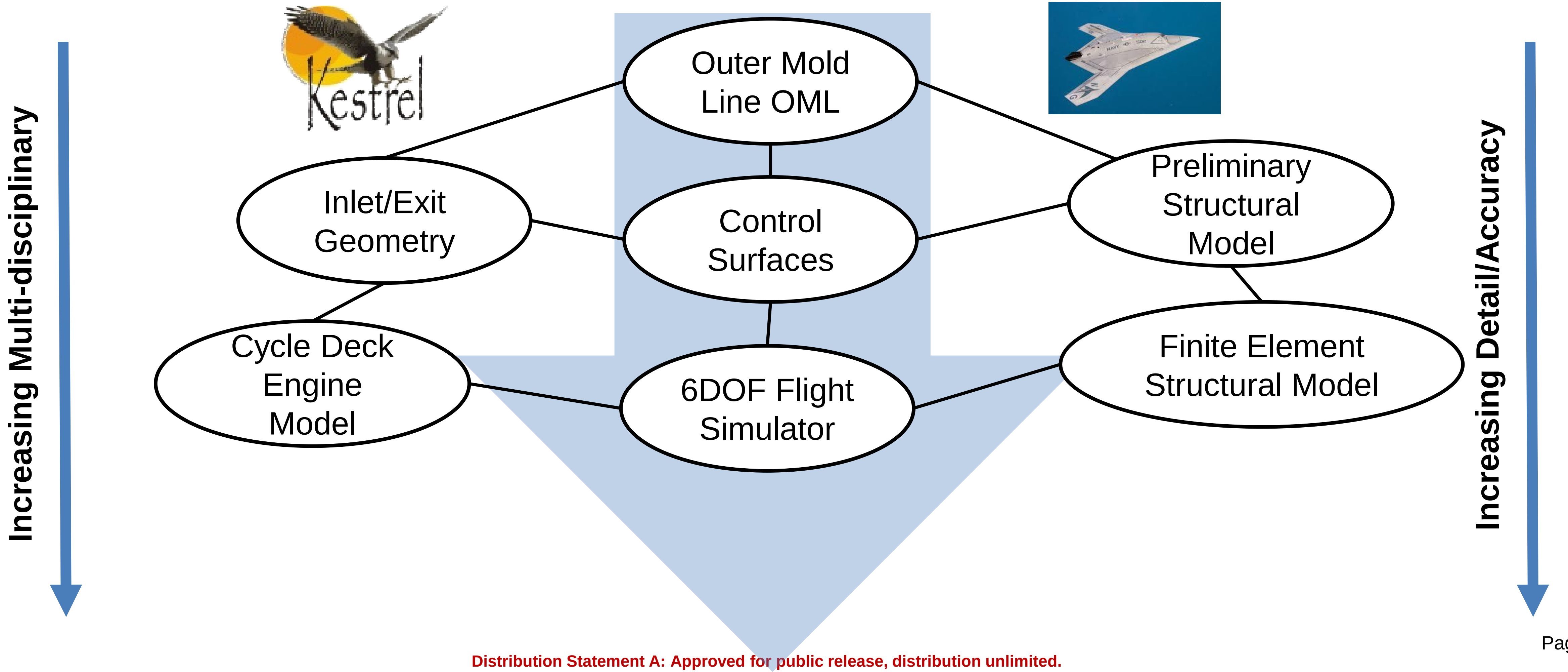

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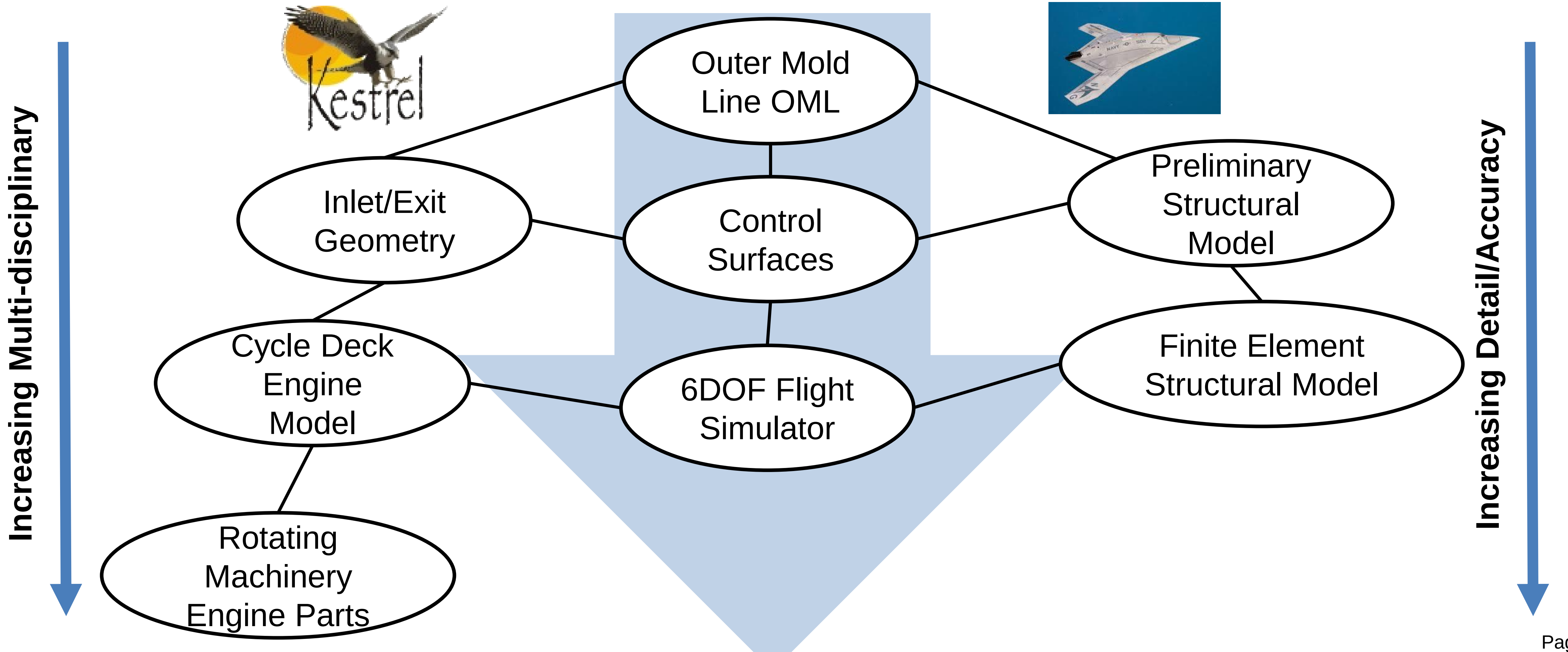

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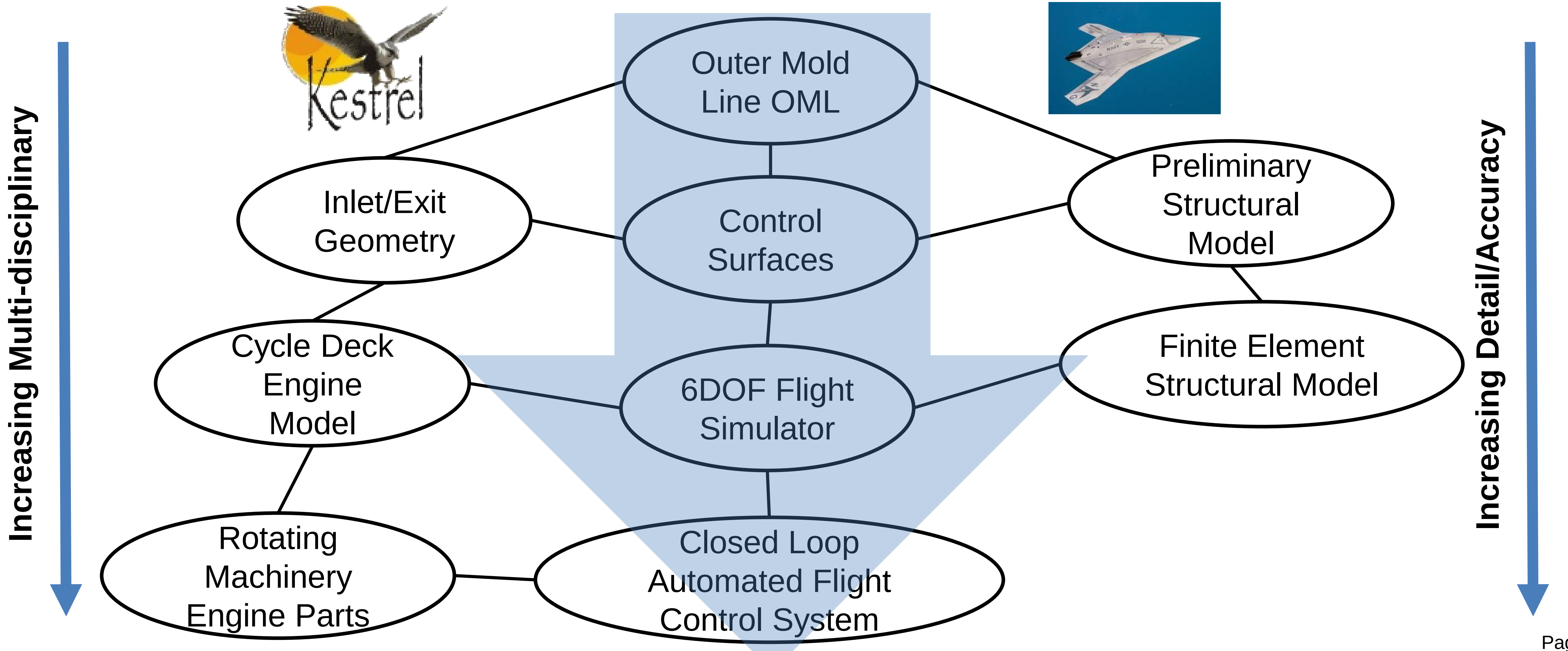

Physics Based Analytics

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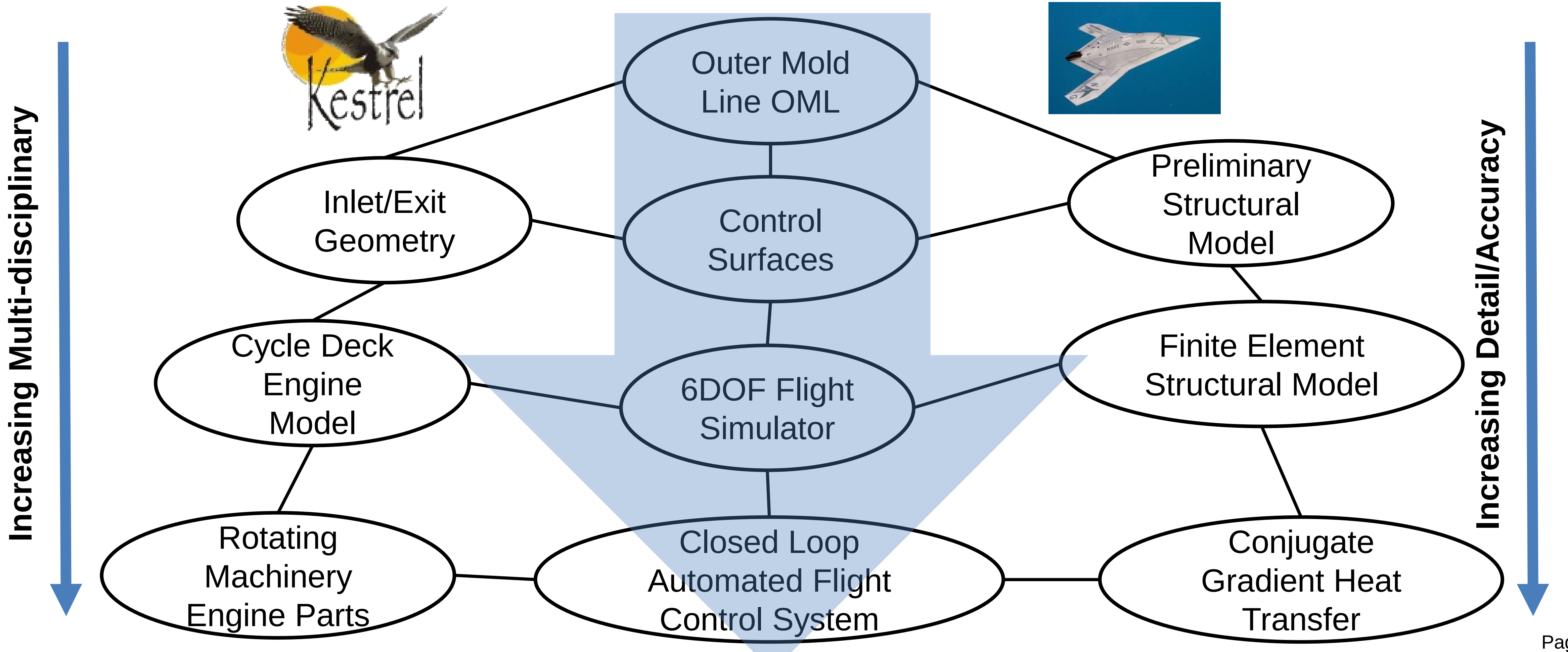
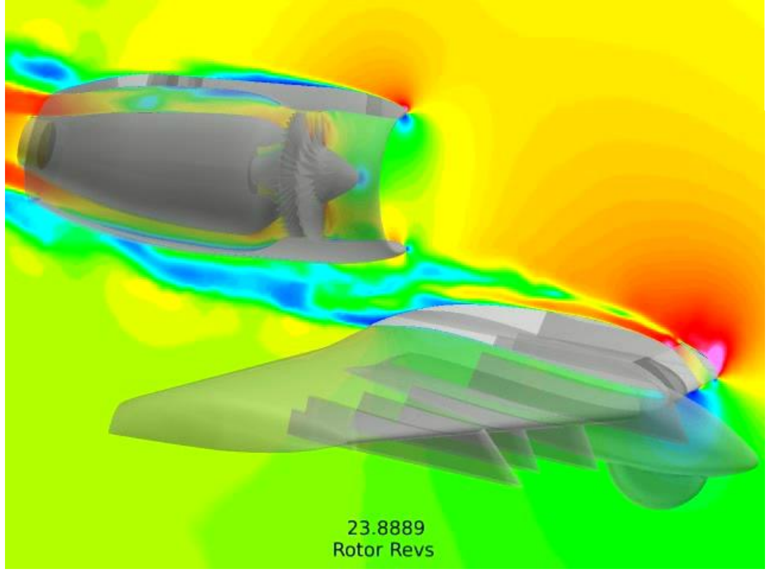
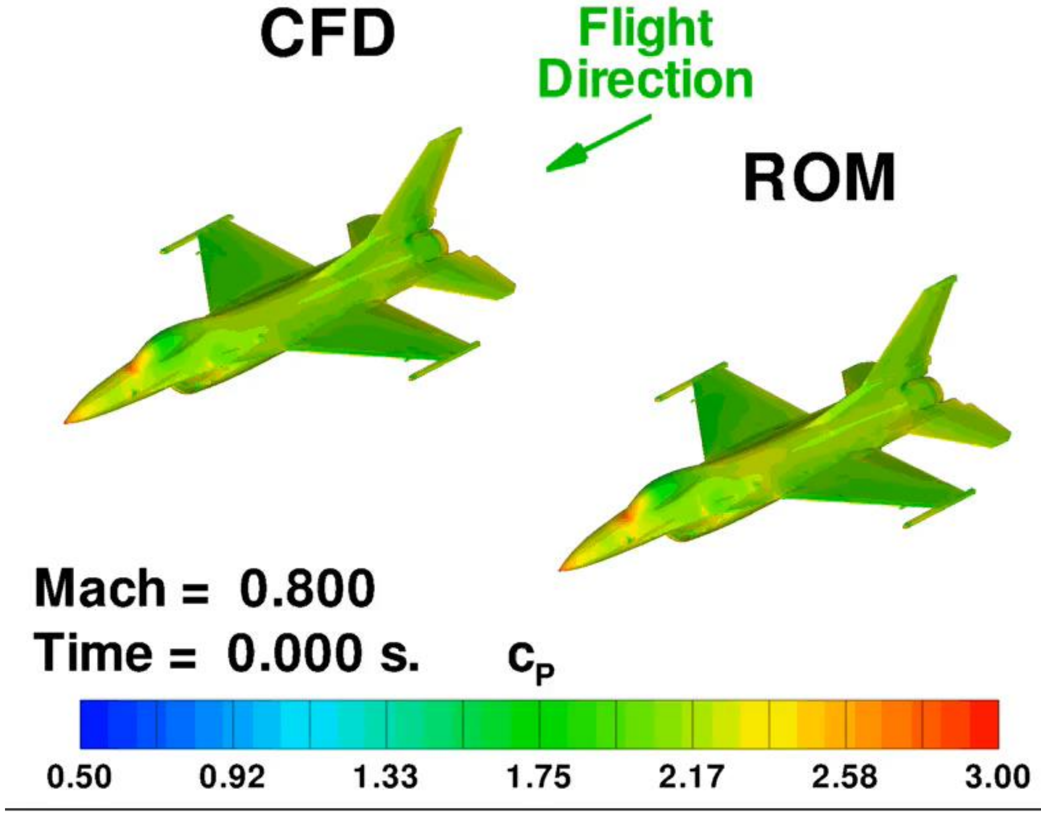


Reduced-Order Modeling

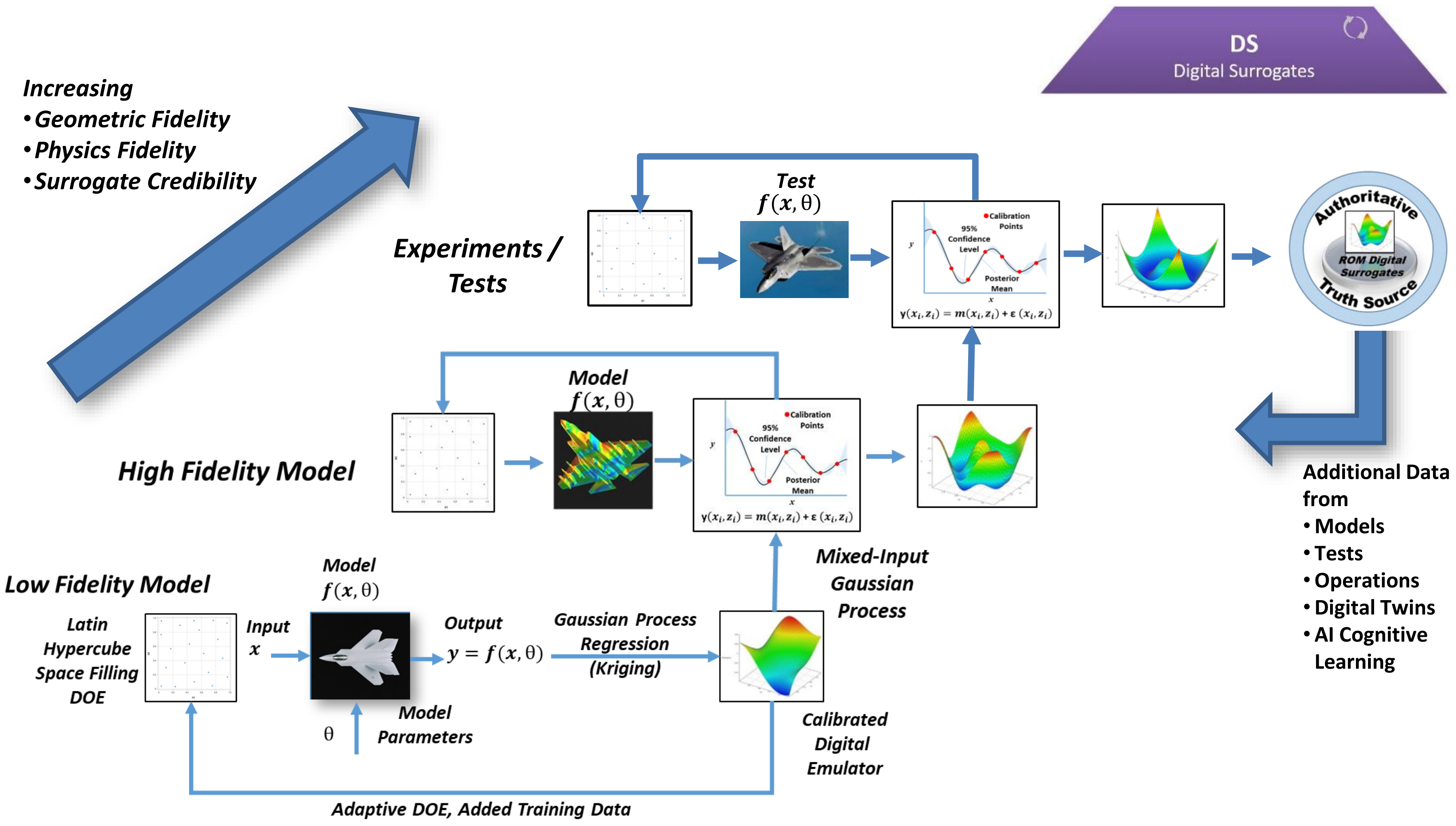
PBA
Physics Based Analytics

DS
Digital Surrogates





Example of Developing an Authoritative Digital Surrogate Reduced Order Model for Aerodynamics



Edward M. Kraft, "Development and Application of a Digital Thread / Digital Twin Aerodynamic Performance Authoritative Truth Source," AIAA-2018-4003. Aviation Systems Conference, Atlanta, GA, June 25-29, 2018

Enhanced Surrogates through Data Driven Analytics

- **Surrogates shown up to this point have been based on PBA**

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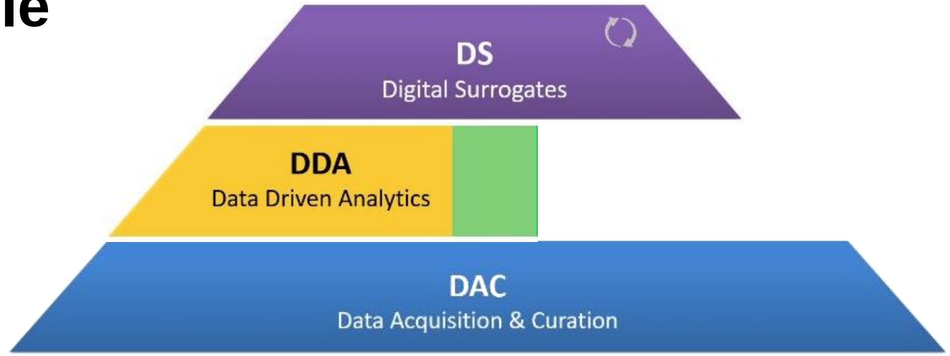
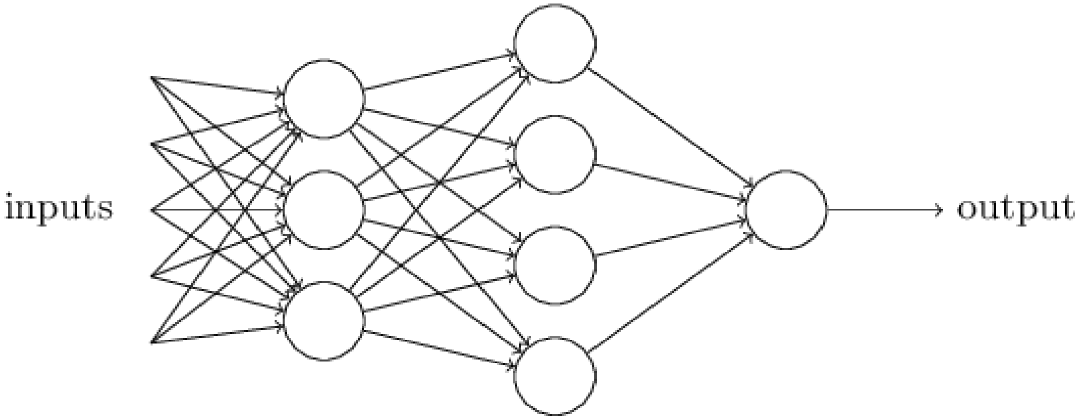
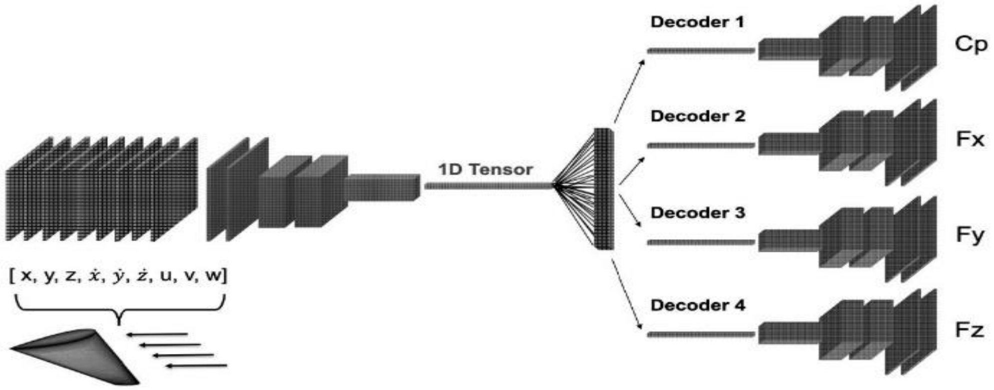


- Machine Learning/Deep Learning (ML/DL) can be used to create surrogates (requires a significant amount of data)





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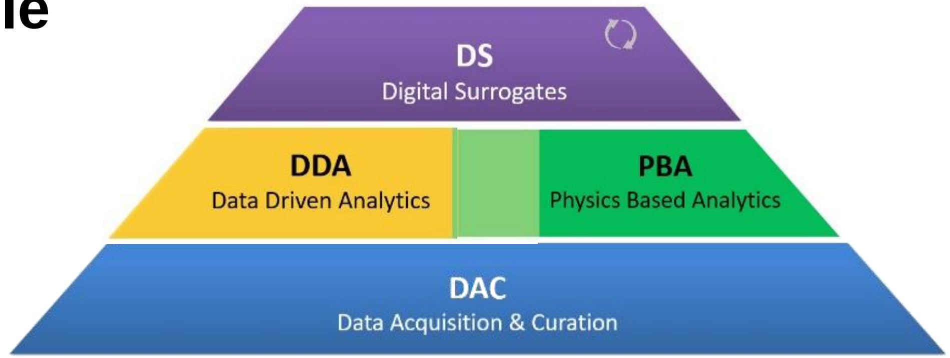

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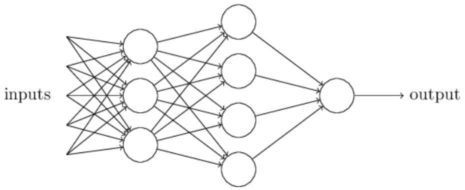

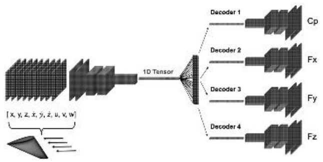

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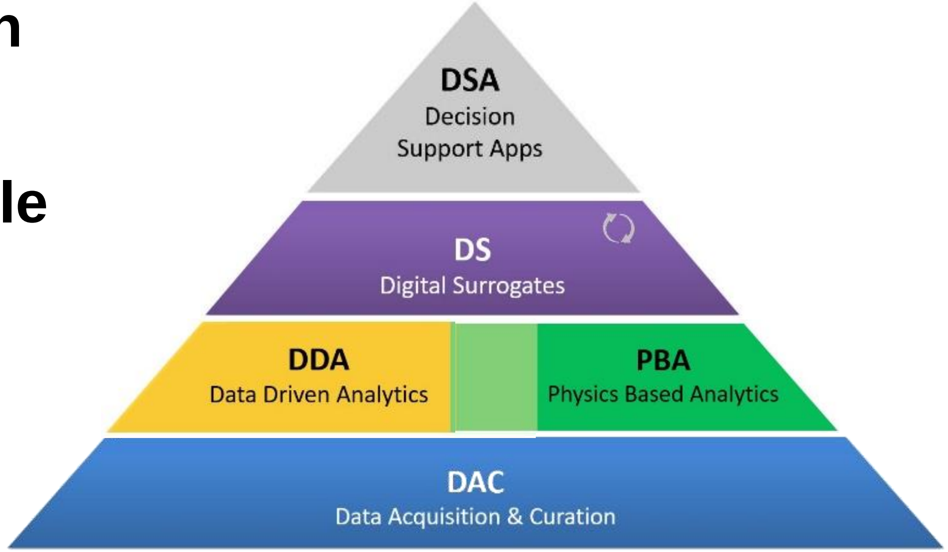

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- The most powerful surrogates are “constrained” by the physics to create a combined DDA/PBA surrogate that accounts for the un-modeled physics/tail number specifics
- Decision Support Apps can be built on this foundation of DDA/PBA – Mission Analysis, Structural Failure Analysis, etc.

Concluding Remarks and Discussion

- **The Physics Based Digital Engineering (PBDE) vision, such as described here, is the inevitable progression of technology (viz., high performance computing, physics, data analytics, and software engineering)**
- **The union of Machine Learning and Digital Surrogate Training via Physics-Based virtual test is what will deliver decision support data at the speed of relevance**
- **Machine Learning and Physics-Based virtual test both require HPC resources that can be reliably delivered by the HPC Modernization Program**
- **This PBDE vision can be applied to next generation combat air vehicle development through its Life-Cycle and specific examples have been shown**
- **Decision Support App software based on physics and system data can be pushed UP the leadership chain to aid in fast, accurate, decision making with high impact**

Acknowledgements

- Material presented in this presentation is a product of the CREATE-AV element of the Computational Research and Engineering for Acquisition Tools and Environments (CREATE) Program sponsored by the U.S. Department of Defense HPC Modernization Program Office
- ***Huge*** thanks to Dr. Robert Meakin, Dr. Saikat Dey, the CREATE-AV Development Team, the CREATE-AV Quality Assurance Team and all of our collaborators for their contributions to this presentation
- Thanks to the CREATE Management Team, the 96th Test Wing RNCS/RNCE, and AEDC for their financial management and facility support and the DoD HPCMP DSRC's for their computational resource support

Questions?