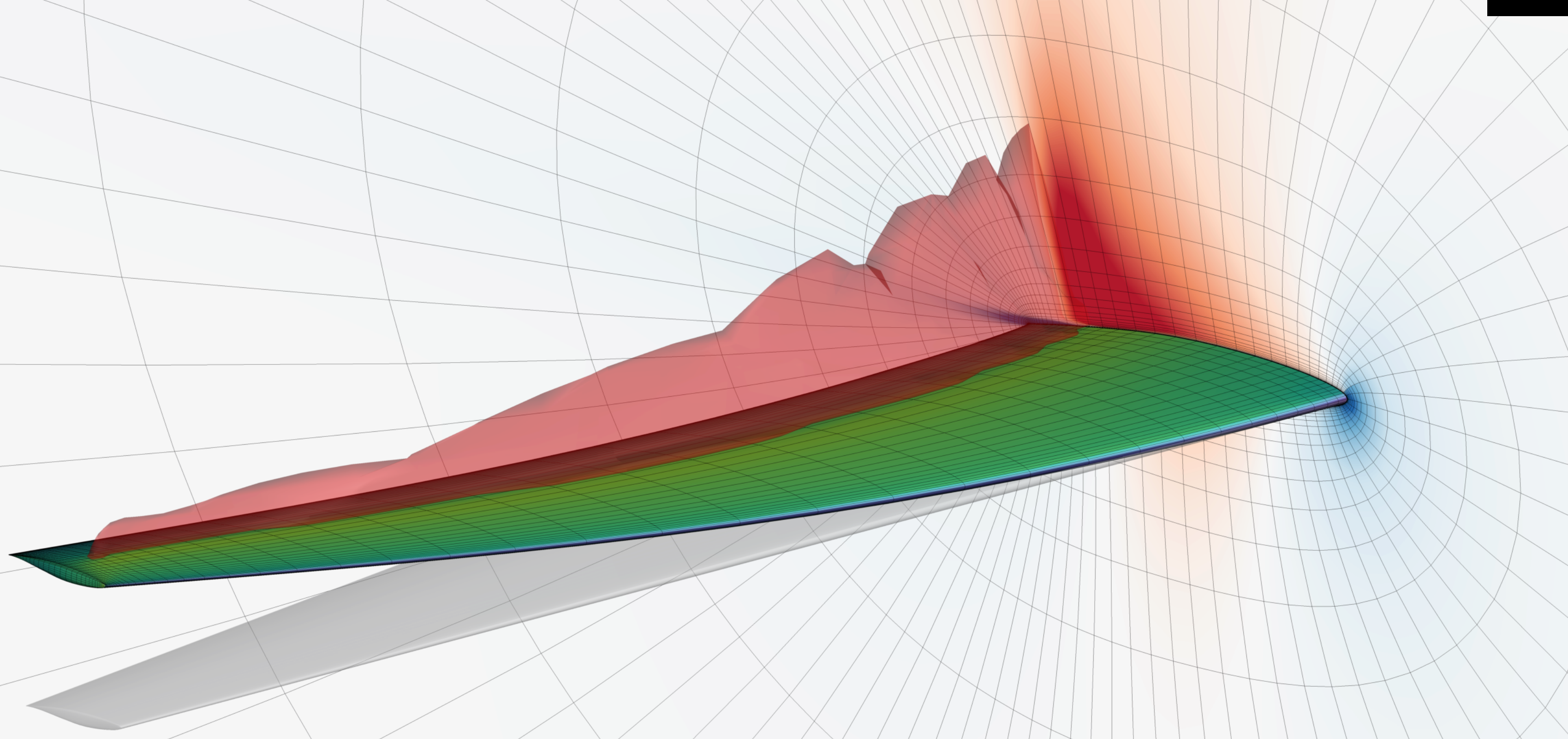
A Modular Multiphysics Simulation Framework Using OpenMDAO

Presenter Video



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We study multidisciplinary design optimization (MDO)

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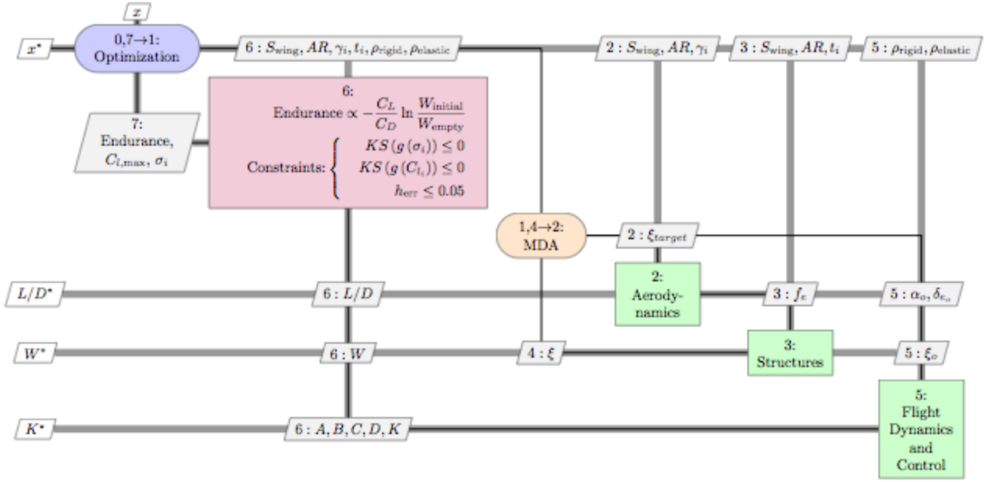
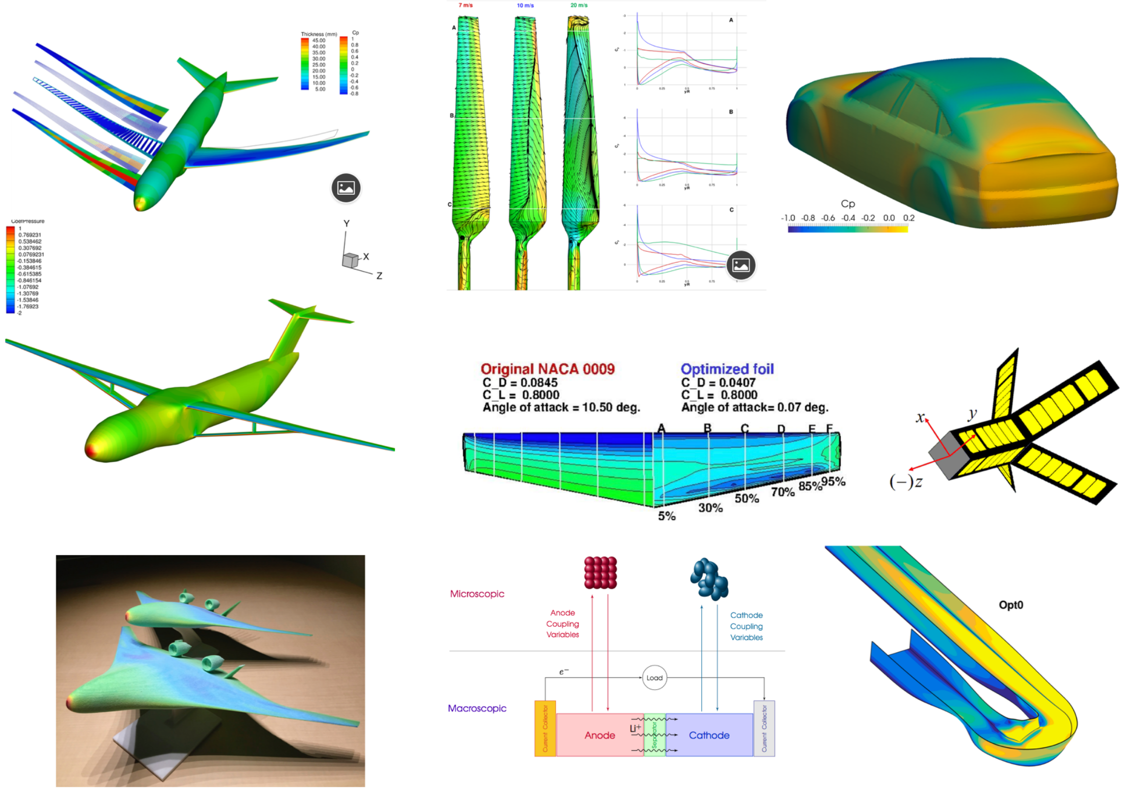
Research in the MDO Lab is divided into two main thrusts

Fundamental MDO algorithms



$$\frac{\partial R}{\partial u}\frac{du}{dr} = \mathcal{I} = \left[\frac{\partial R}{\partial u}\right]^T \left[\frac{du}{dr}\right]^T$$

Applications of MDO



Optimized 973 aerodynamic shape and structural sizing design variables

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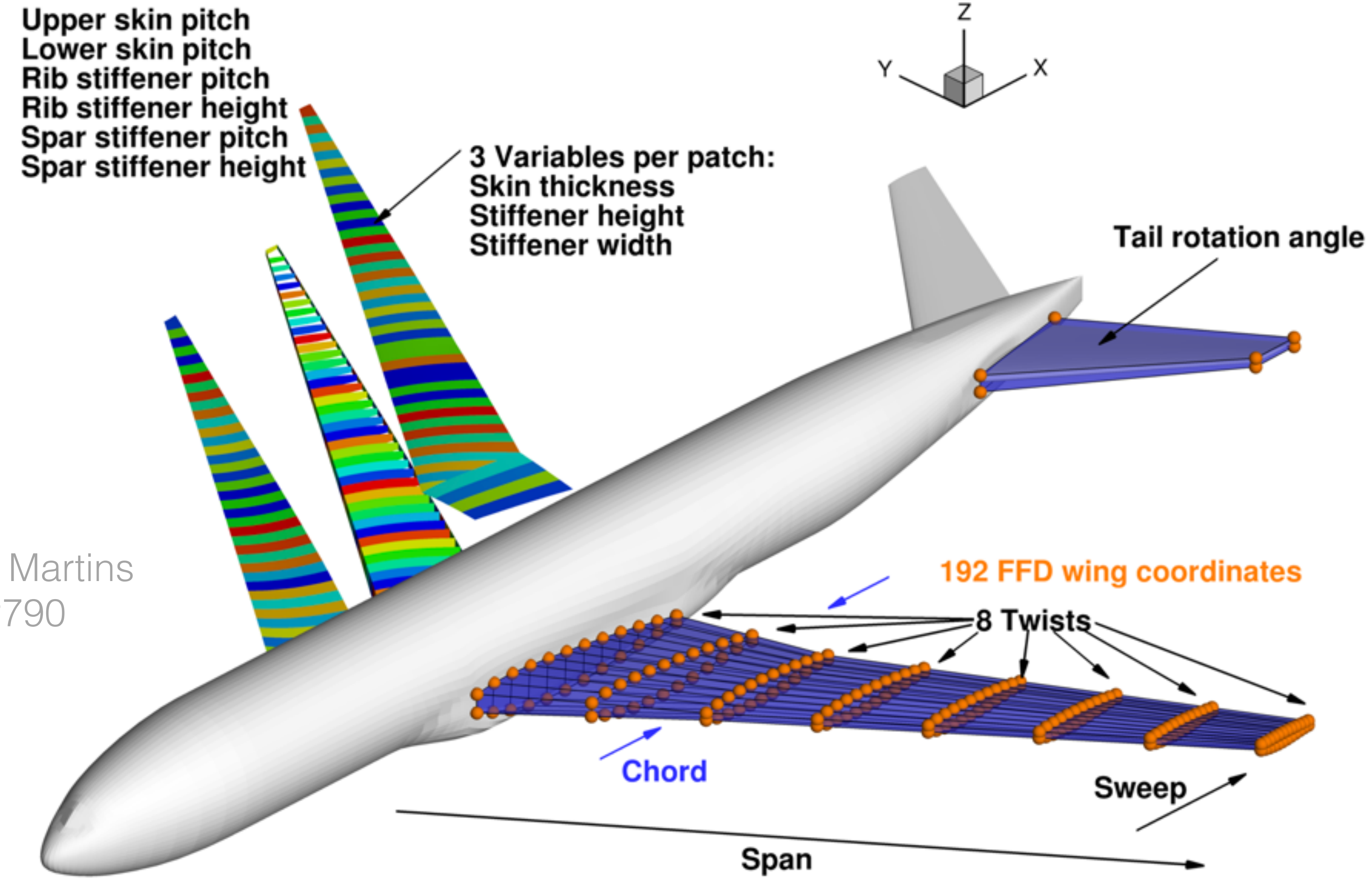

Kenway and Martins
AIAA 2015-2790

The Python interface to ADflow can be generalized to other CFD solvers

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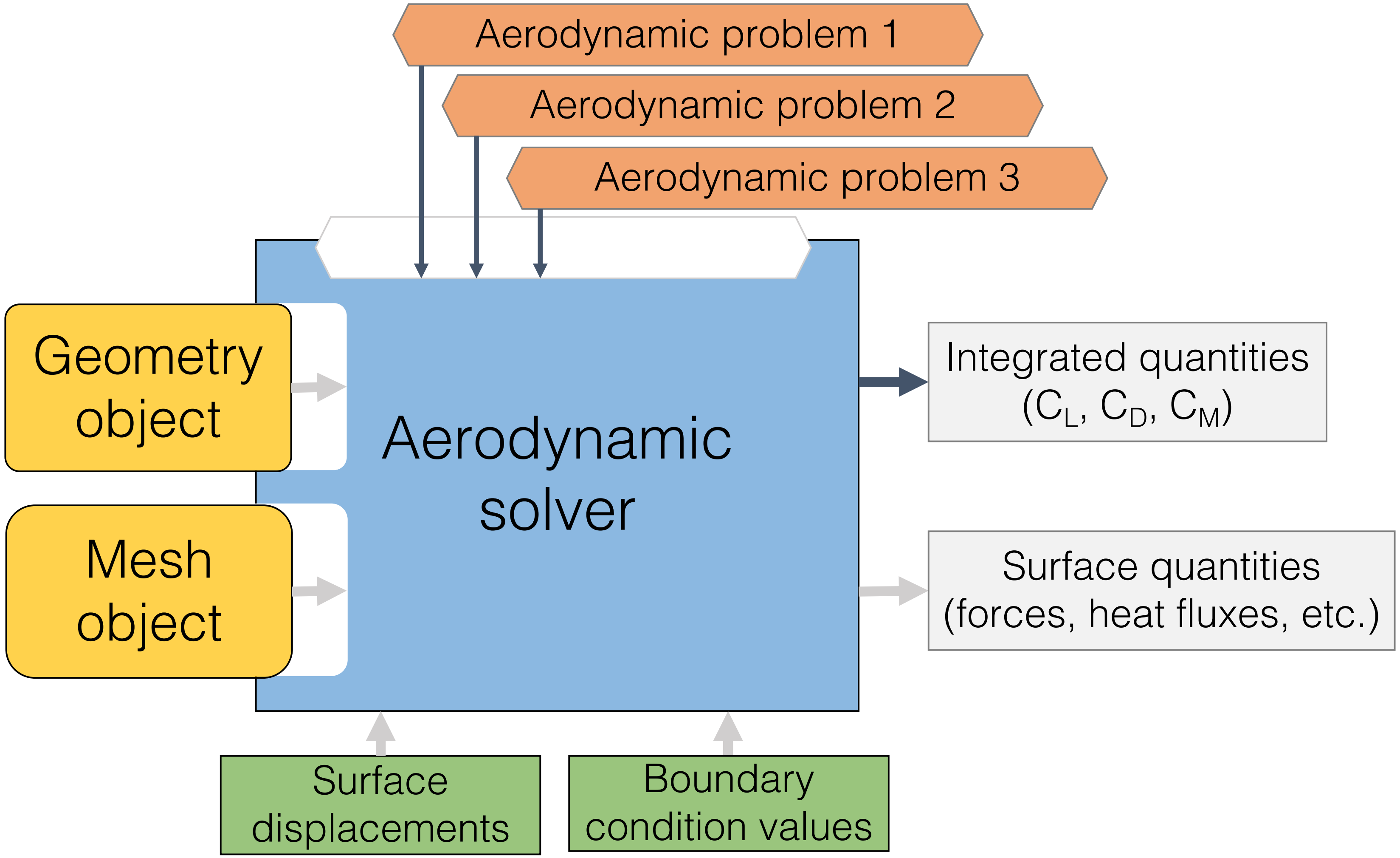

The MACH framework API is solver agnostic

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The MACH framework API can work with multiple aerodynamic and structural solvers

Previous aeropropulsive and aerothermal studies from the MDO Lab used ad-hoc implementations

Coupling multiple disciplines for analysis alone is challenging, and setting up the coupled derivative problem is extremely difficult

However, it is difficult to extend our approach to additional disciplines

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Previous aeropropulsive and aerothermal studies from the MDO Lab used ad-hoc implementations

Coupling multiple disciplines for analyses is difficult on its own, yet it is not enough for gradient based optimization

The complexity grows exponentially with each additional discipline

OpenMDAO provides a flexible solution for gradient based optimization

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OpenMDAO handles the data transfer between disciplines, and efficiently solves the coupled derivative problem

Building complex models in OpenMDAO with high-fidelity simulations is still challenging

Computational performance and parallelism must be tuned carefully

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OpenMDAO MultiPhysics (MPHYS) is a multidisciplinary simulation framework

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It provides the OpenMDAO model structure required to build complex models using high-fidelity simulations

Computational performance and parallelism comes built in

While the primary goal is models with high-fidelity simulations, MPHYS is also useful for multifidelity models

CFD 2030: MDAO limited by
"one-off laborious, non-standard interfaces"

MPHYS provides a modular framework

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MPHYS defines a minimal common API for each solver

Developers can build OpenMDAO wrappers for their solvers
that conform with this API

With these common interfaces, MPHYS models are plug-and play:
the solvers and transfer schemes are interchangeable

Two different aerodynamic solvers can use the same problem interface

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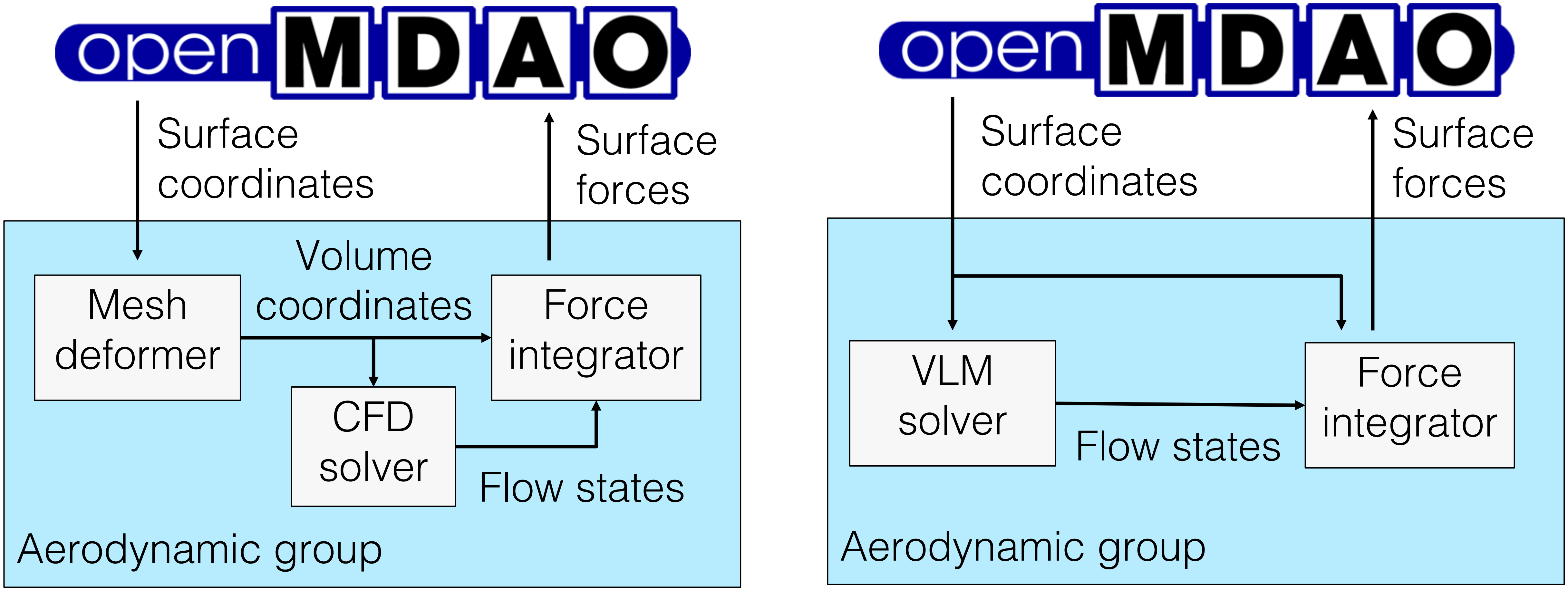

We can swap aerodynamic groups

MPHYS provides the machinery for computational efficiency

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The allocated memory for the solvers can be reused throughout the model

Multiple flight conditions can be analyzed in serial or in parallel, without incurring an increased computation or memory cost

The abstracted parallelism in MPHYS reduces the complexity of each individual runscript

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MPHYS defines 3 main groups in the OpenMDAO model hierarchy

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Multipoint: Contains all scenarios analyzed
with the same combination of solvers and fidelity levels

Scenario: Contains all the groups required on the scenario level,
such as the solver group and the optional functionals groups

Solver: The non-linear coupled analysis group,
which is the lowest-level group provided by MPHYS

Solvers can add a group for each level in MPHYS

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Multipoint: Solvers can add groups that perform computations that are shared across all scenarios under this multipoint group, e.g., computation of the initial mesh, modal decomposition, etc.

Solver: The main solver group will be added to this level, which will be iterated until the MDA converges

Scenario: Groups at this level perform expensive function evaluations, which are executed one time after the main solver loop converges

Breakdown of a single point aerostructural model

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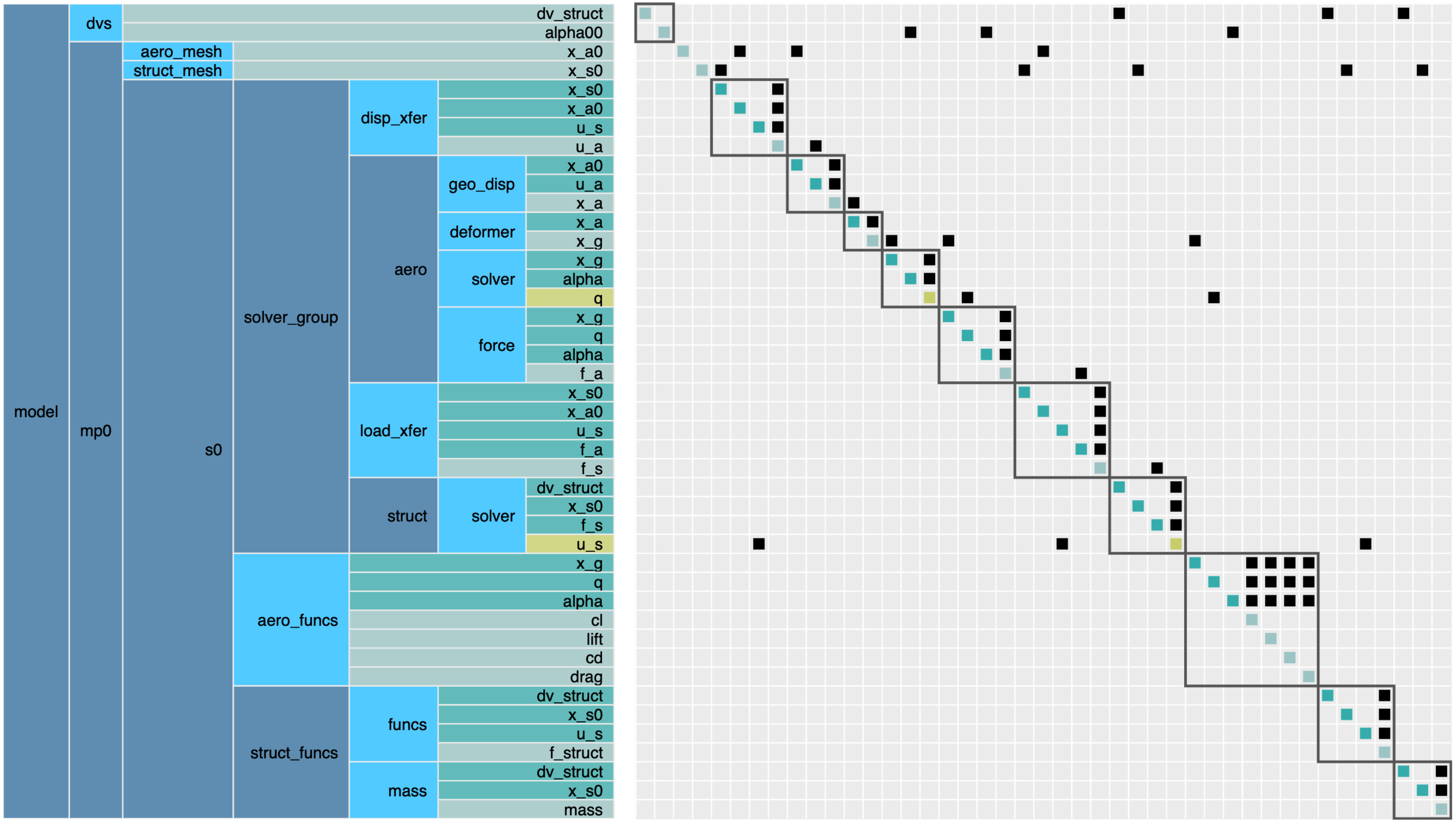

MPHYS Multipoint is the top-level group users interact with in the runscript

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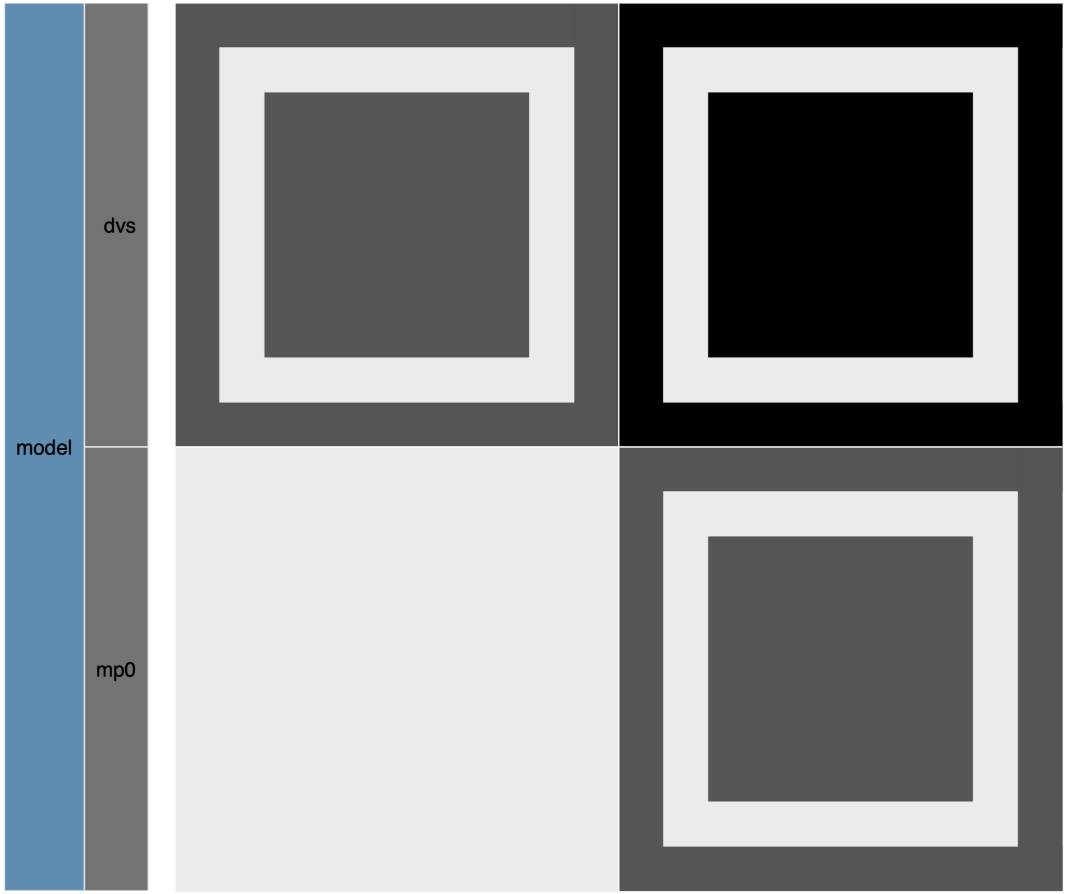
Users can add components and groups to the top-level model

MPHYS Multipoint group contains all MPHYS objects

Additional OpenMDAO groups can be added before or after the multipoint group



Users add scenarios to the multipoint group

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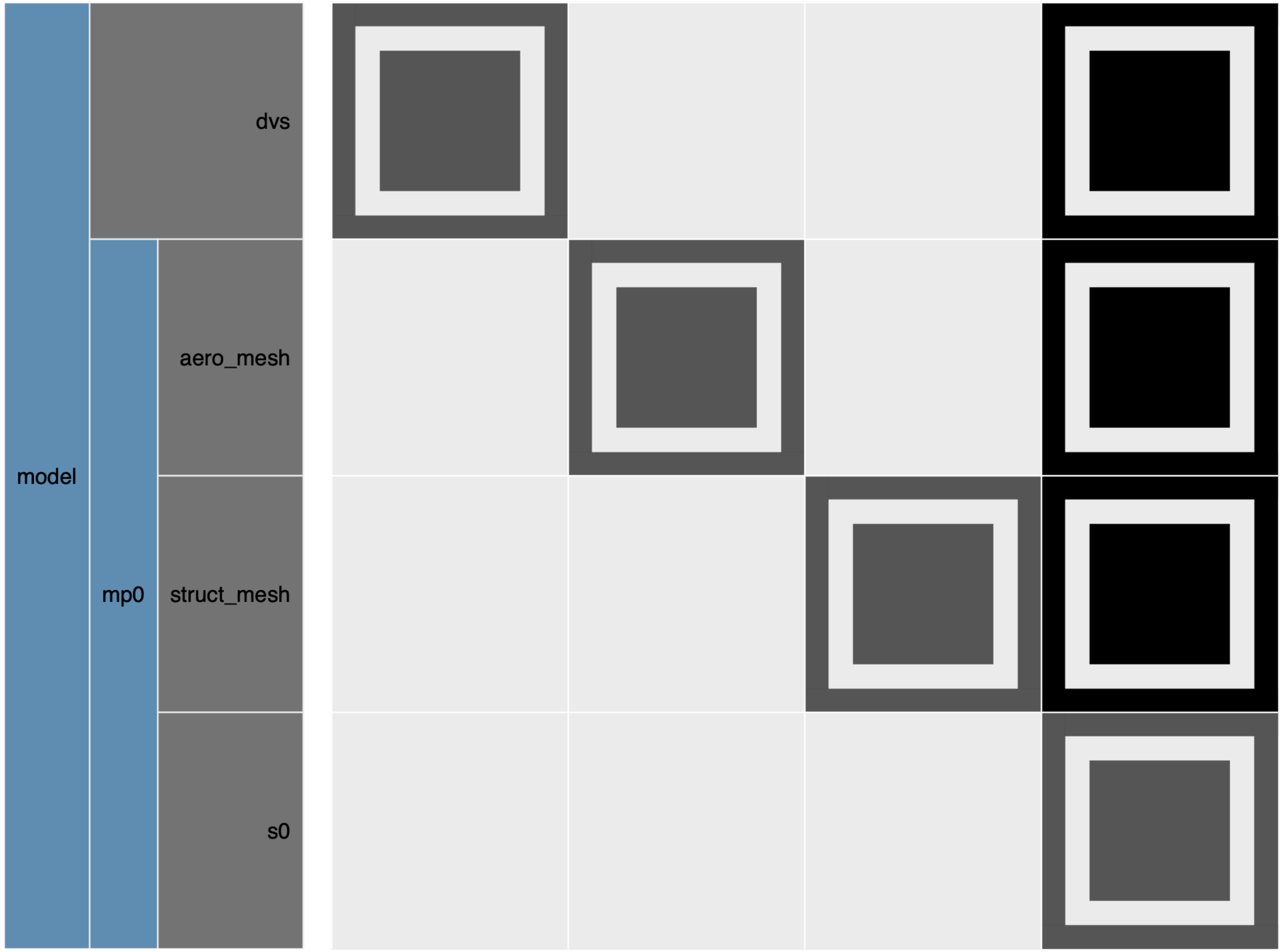
Multipoint group automatically adds the multipoint-level groups for each solver, e.g., aero_mesh and struct_mesh for this case

Each scenario user adds is appended after these groups, e.g., s0 for this case



Each scenario group contains a solver loop and optionally functionals

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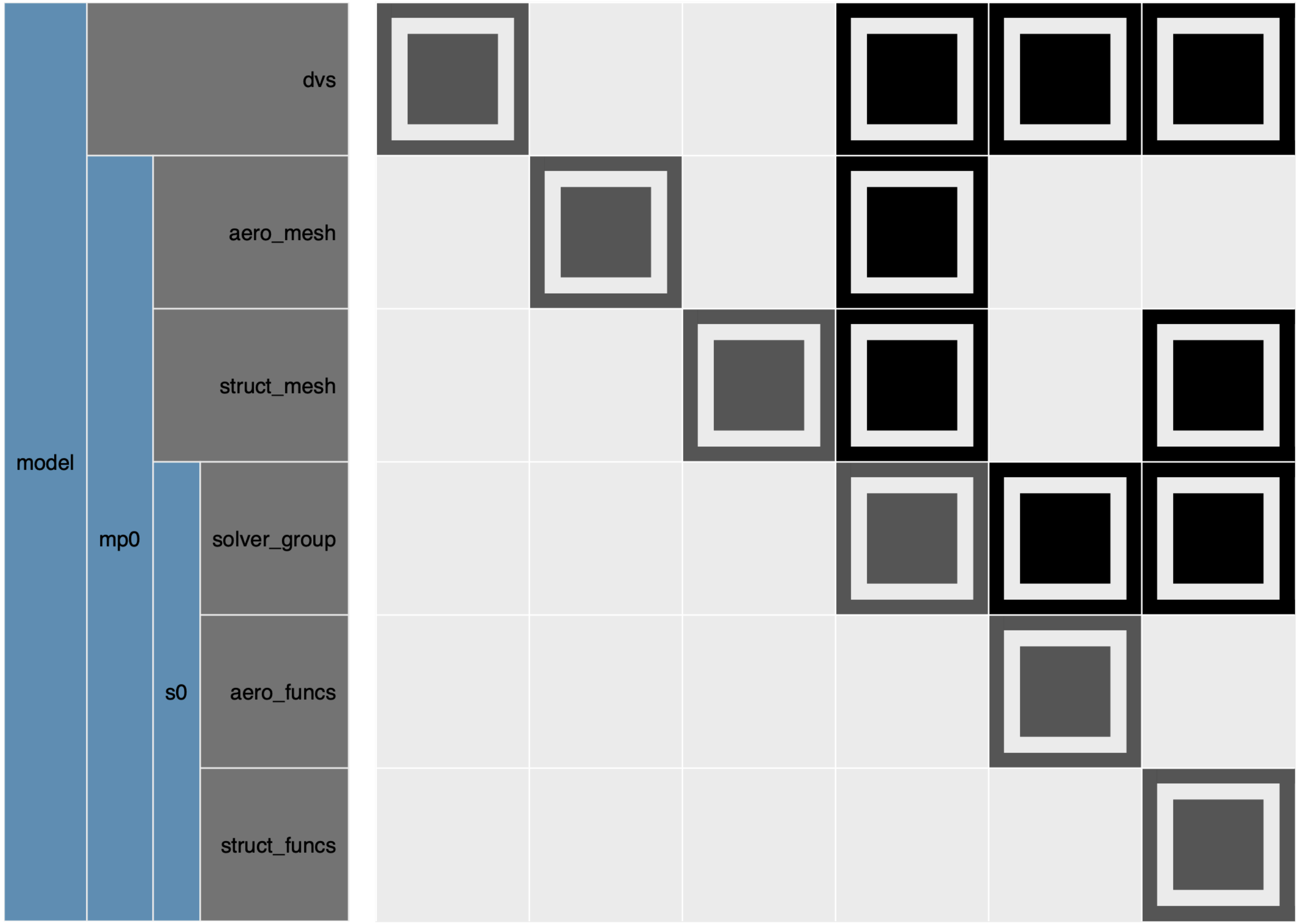
Solver group contains the MDA components that will be converged during each run

The scenario-level groups are used for expensive function evaluations for each discipline



Solver group contains all the discipline solvers and the transfer schemes

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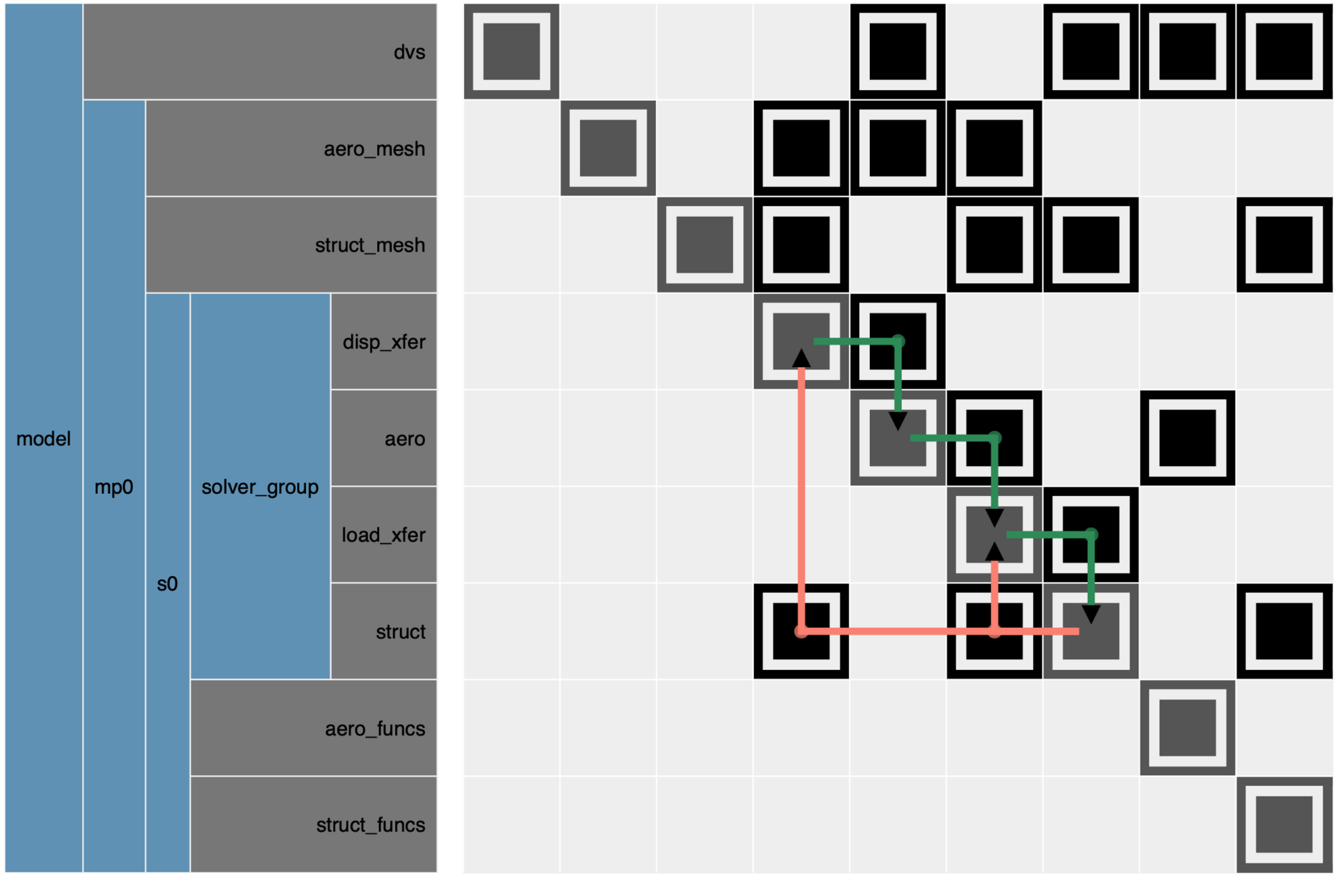
For aerostructural simulations, the dependency of aerodynamics to structural displacements are converged on the solver level

The scenario-level groups are executed once after the solver group converges



MPHYS only defines a minimal API that is used to connect disciplines

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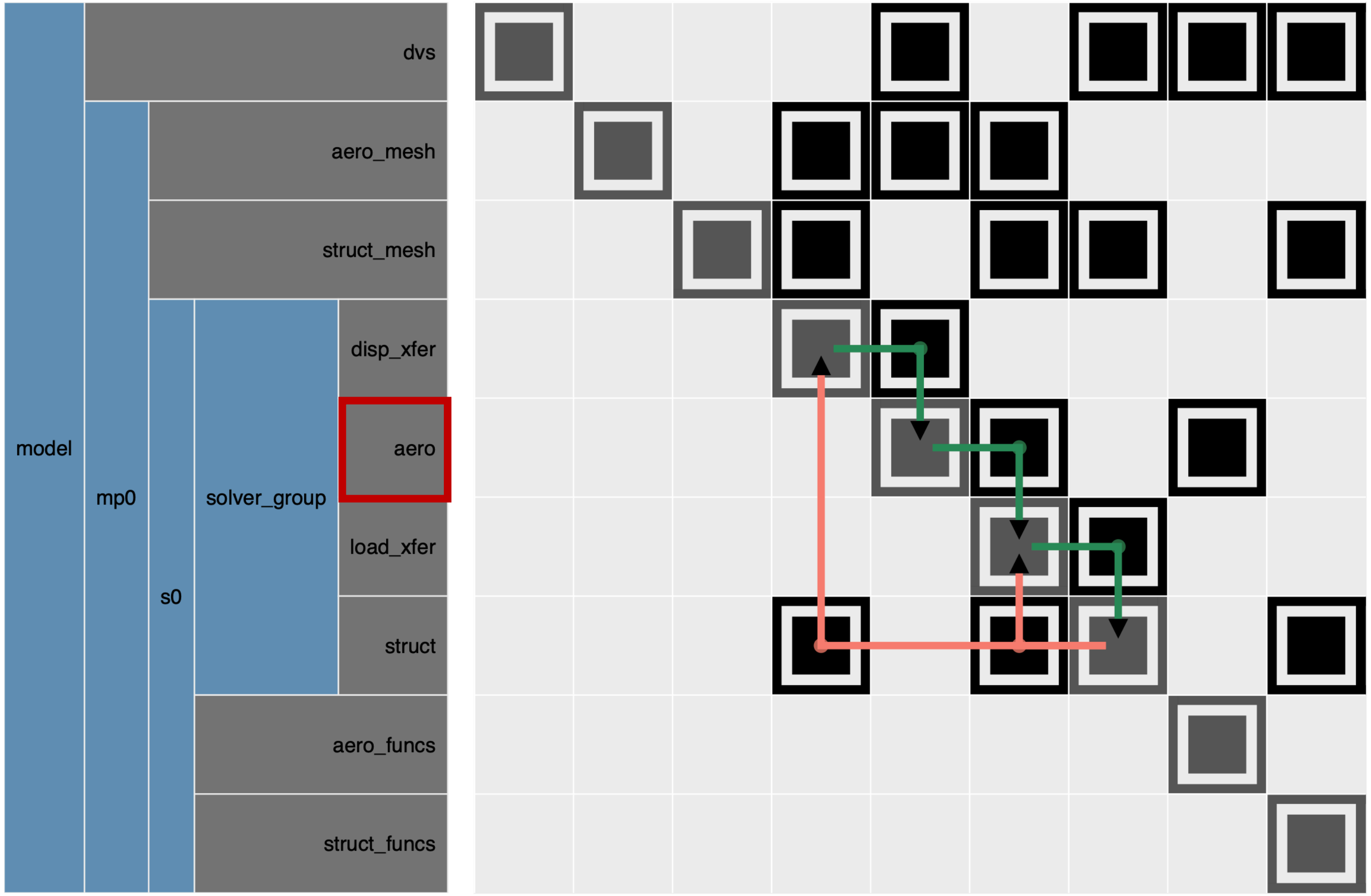
Each discipline group can use a custom internal structure



The aerodynamic problem interface is the surface geometry, and the nodal forces

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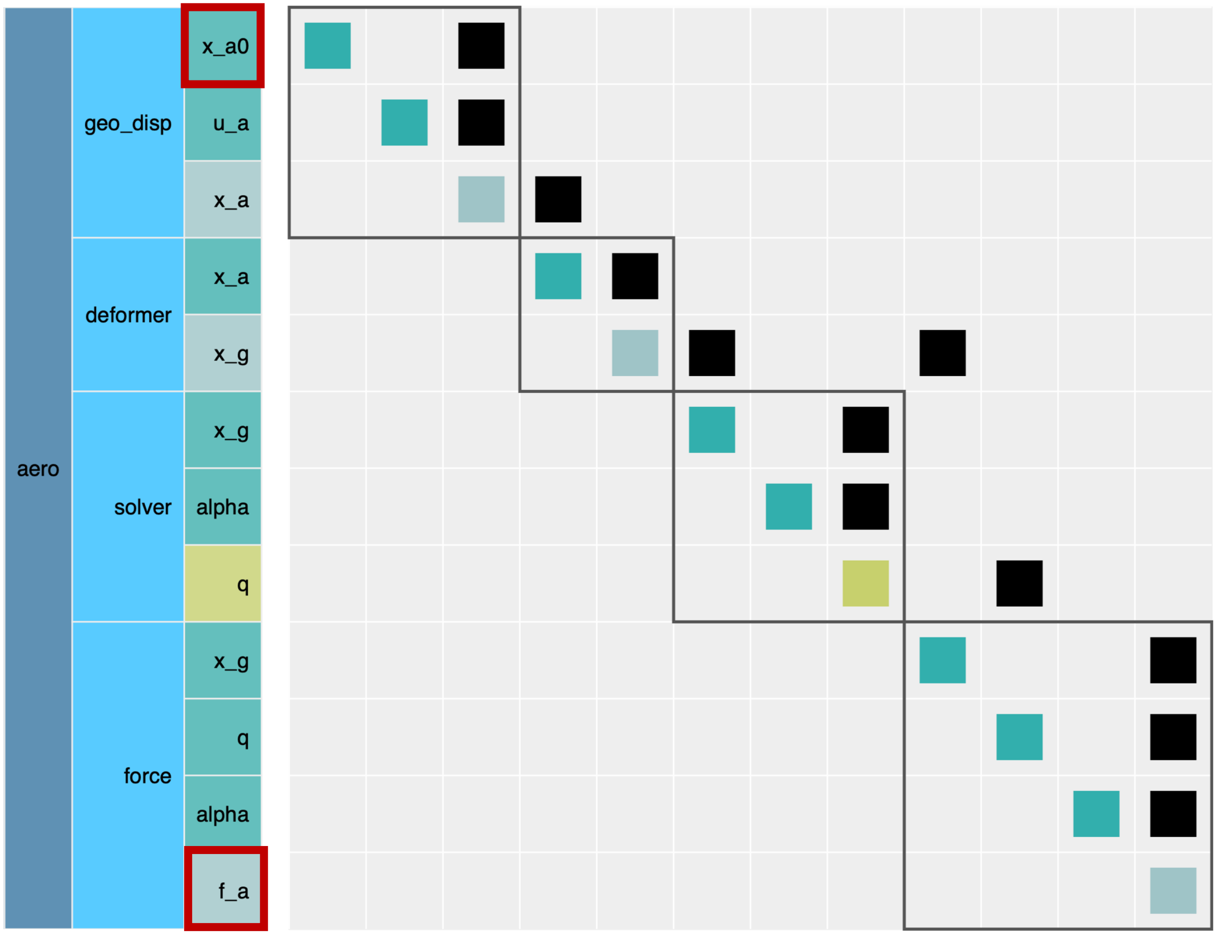
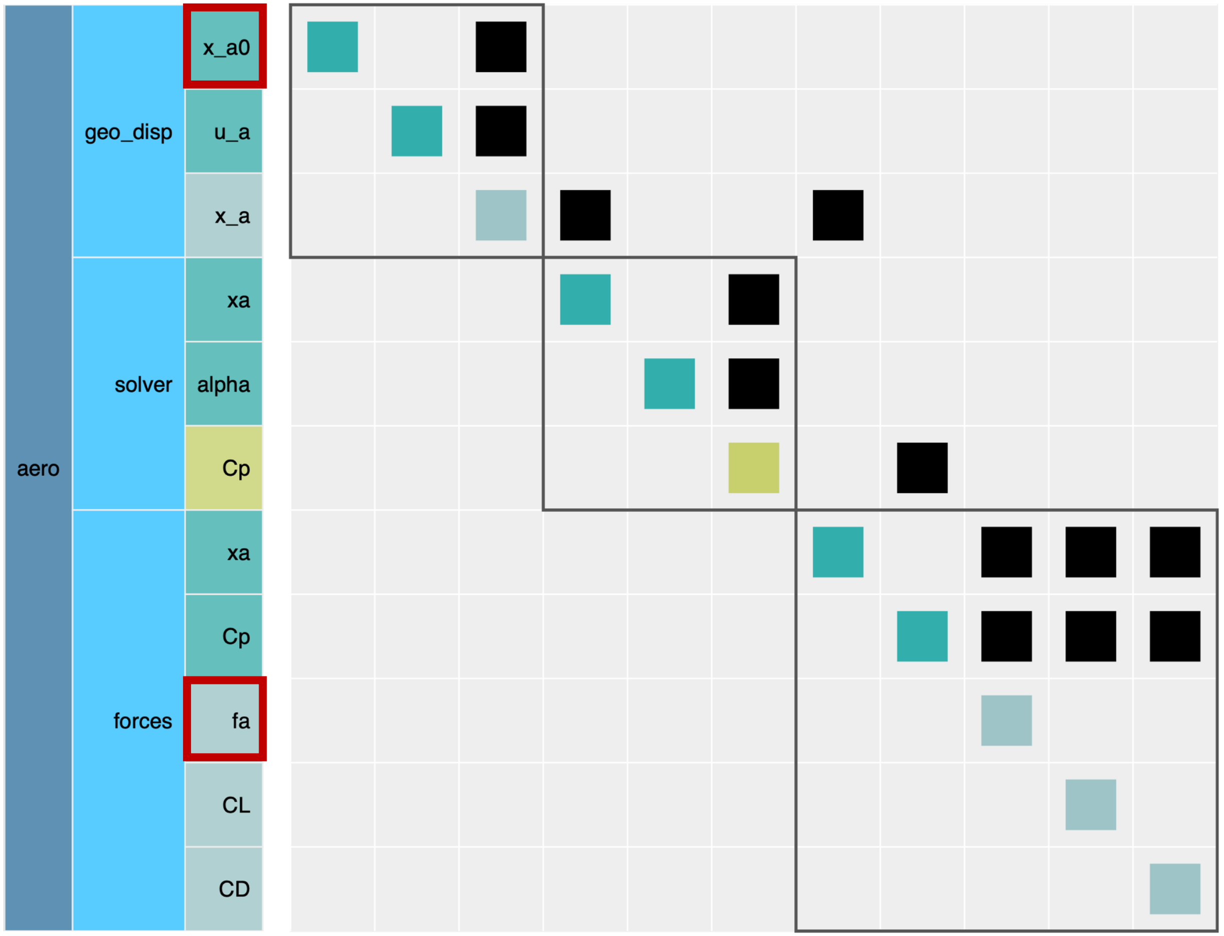
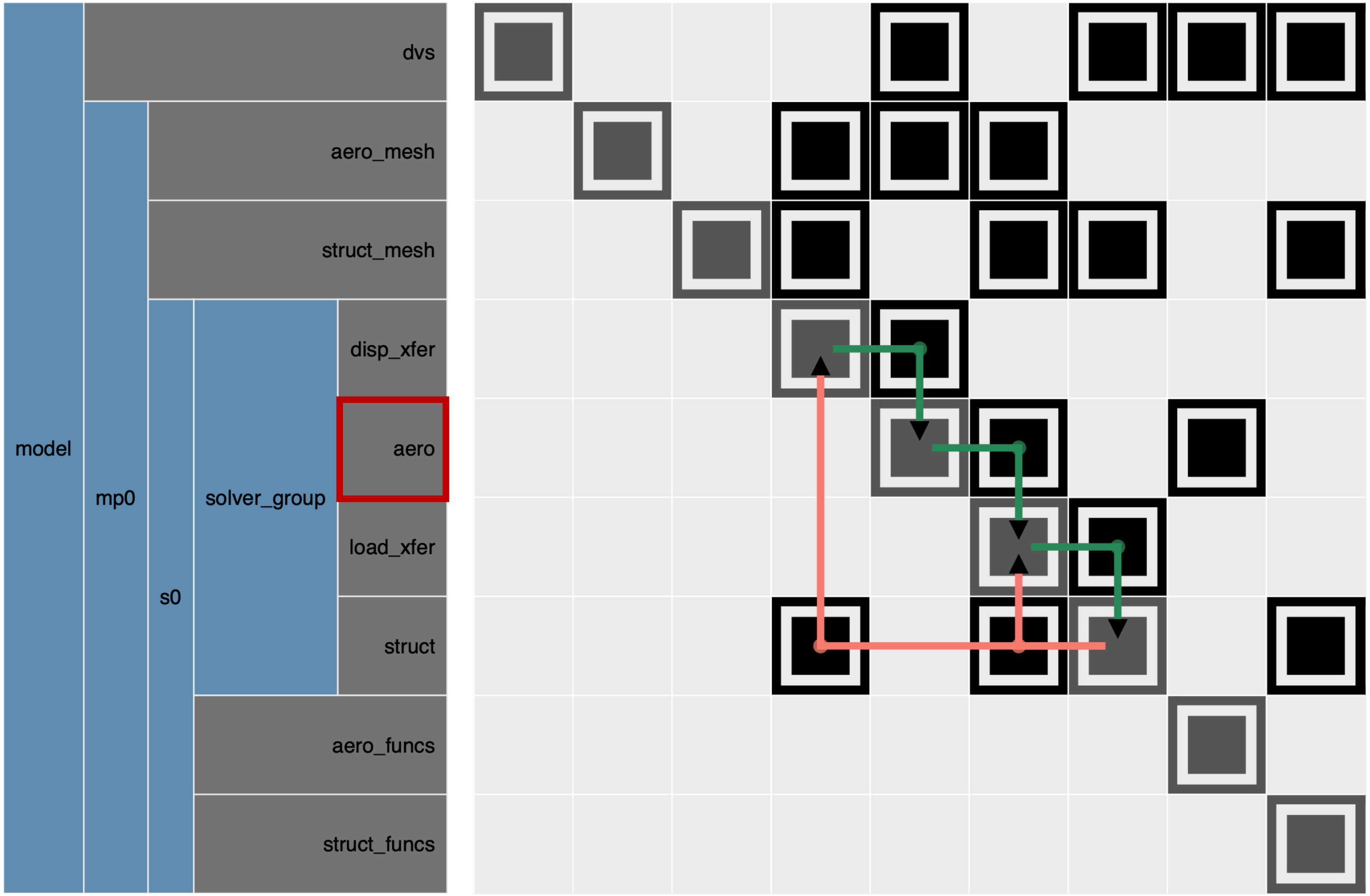
ADflow (RANS CFD)



VLM Solver



The discipline solvers are interchangeable as a result of the MPHYS API



Users can add multiple multipoint groups, which contain multiple scenarios

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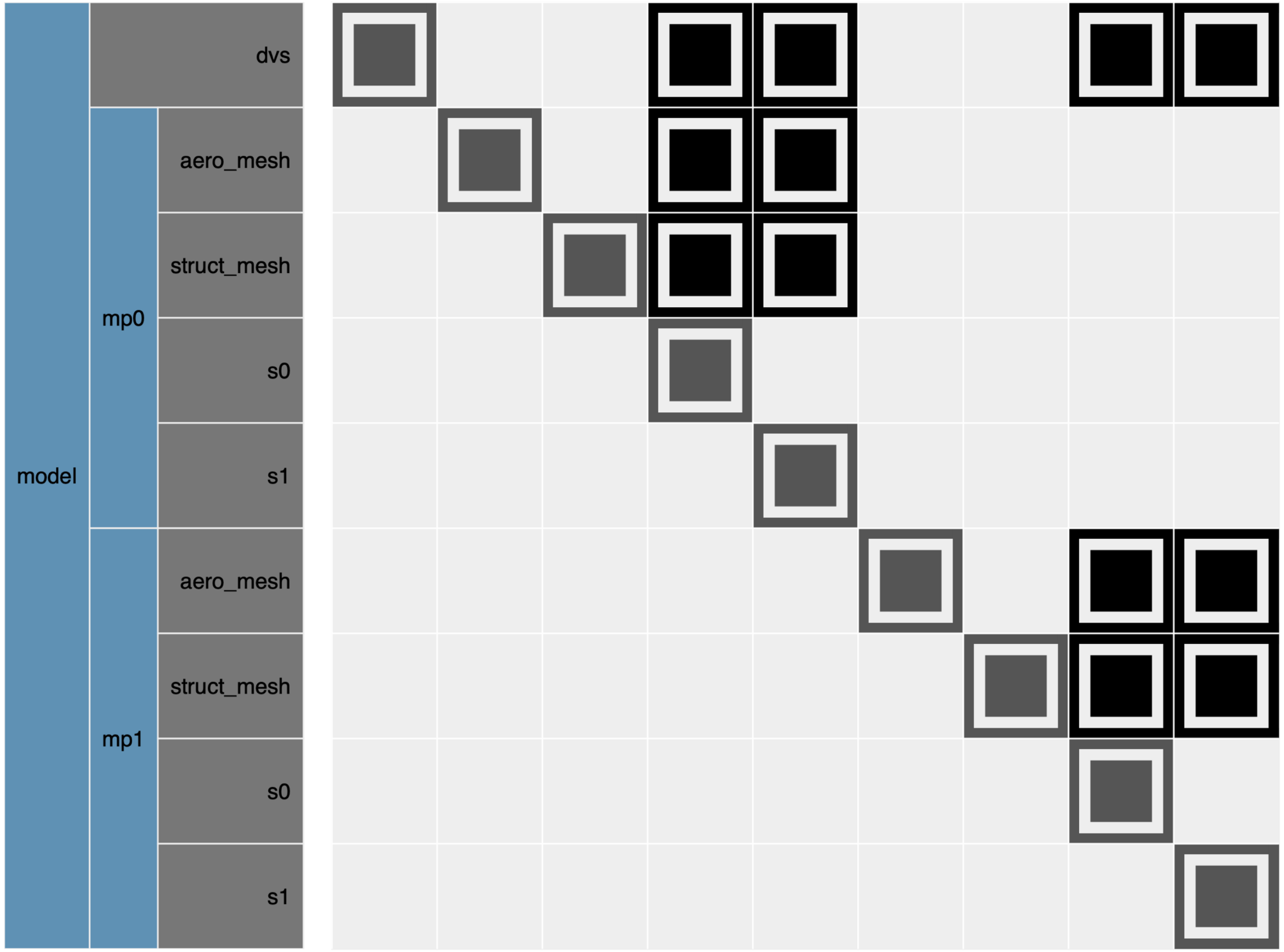
An example model with
2 multipoint groups,
each containing 2 scenarios

Different multipoint groups are used to add different combinations of solvers



Parallelism can be customized both at the multipoint and scenario level

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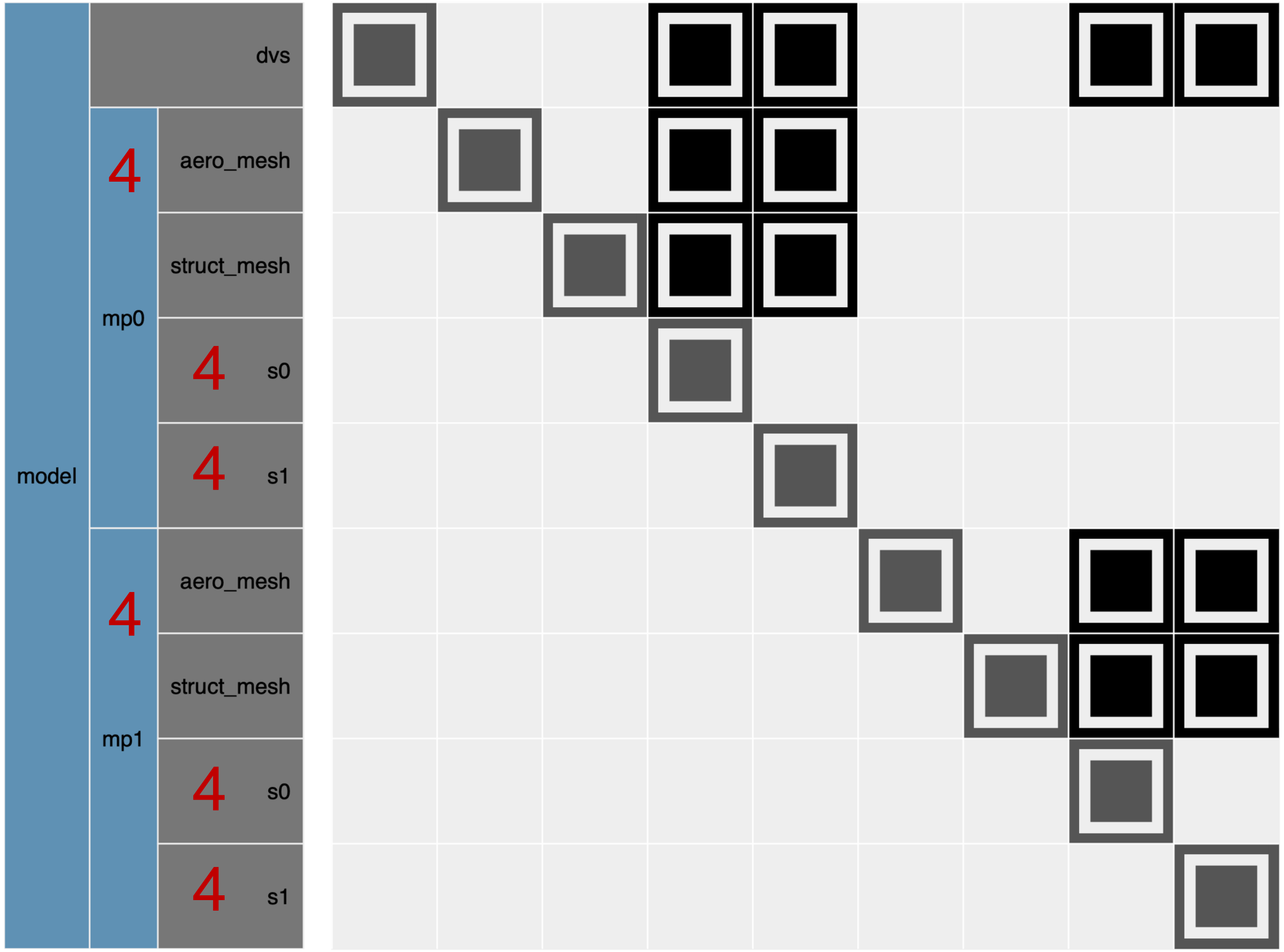
Every scenario in every multipoint group can use the full set of processors and can be executed back to back

The solver memory for this case is reused between different scenarios when the same solvers are used

Red numbers highlight the number of processors used for each group



Parallelism can be customized both at the multipoint and scenario level

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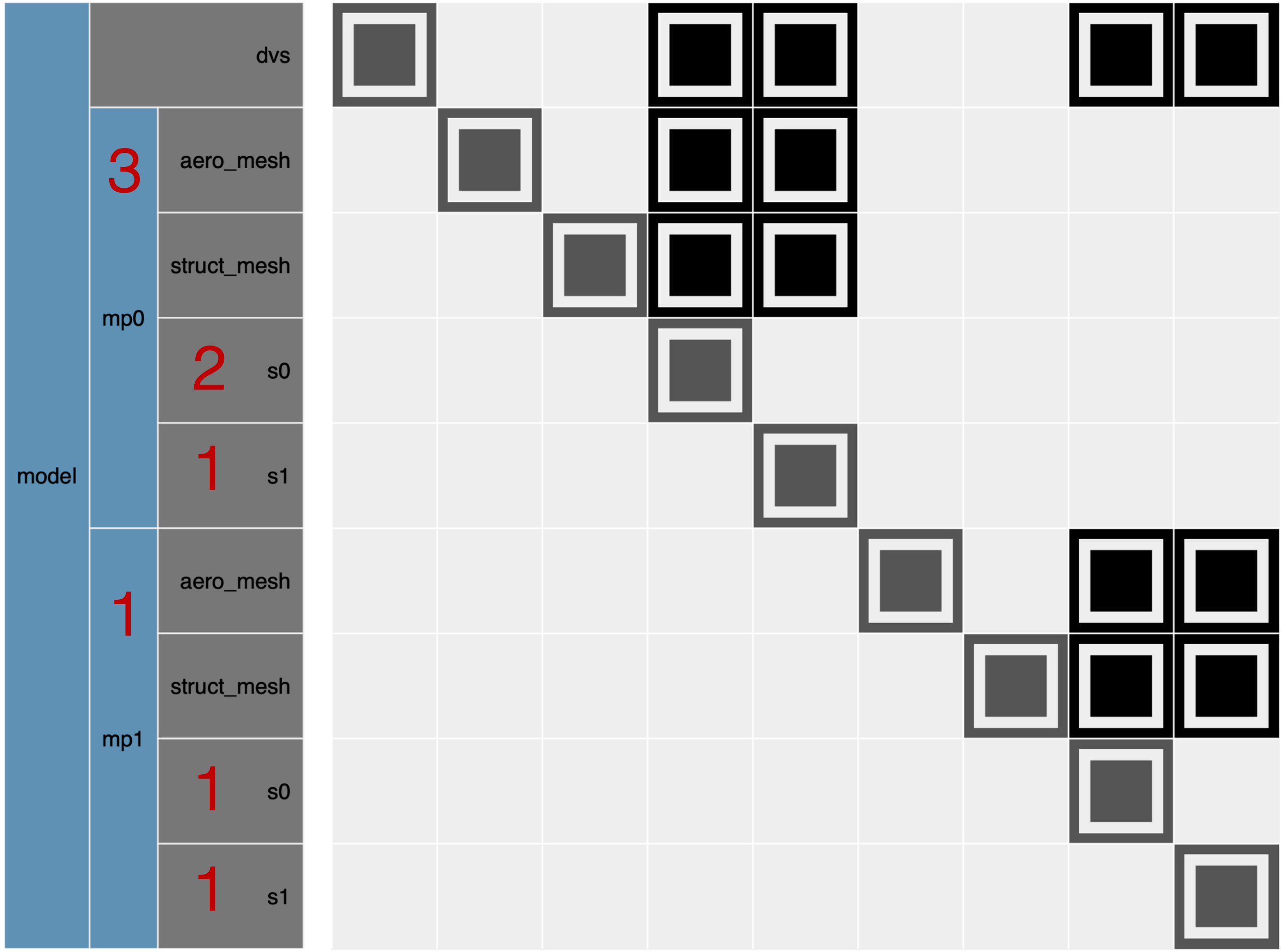
The full set of processors can also be divided among the multipoint groups

Similarly, each scenario in each multipoint group can use a portion of the full set of processors

Red numbers highlight the number of processors used for each group



These features enable users to build complex models using high-fidelity tools

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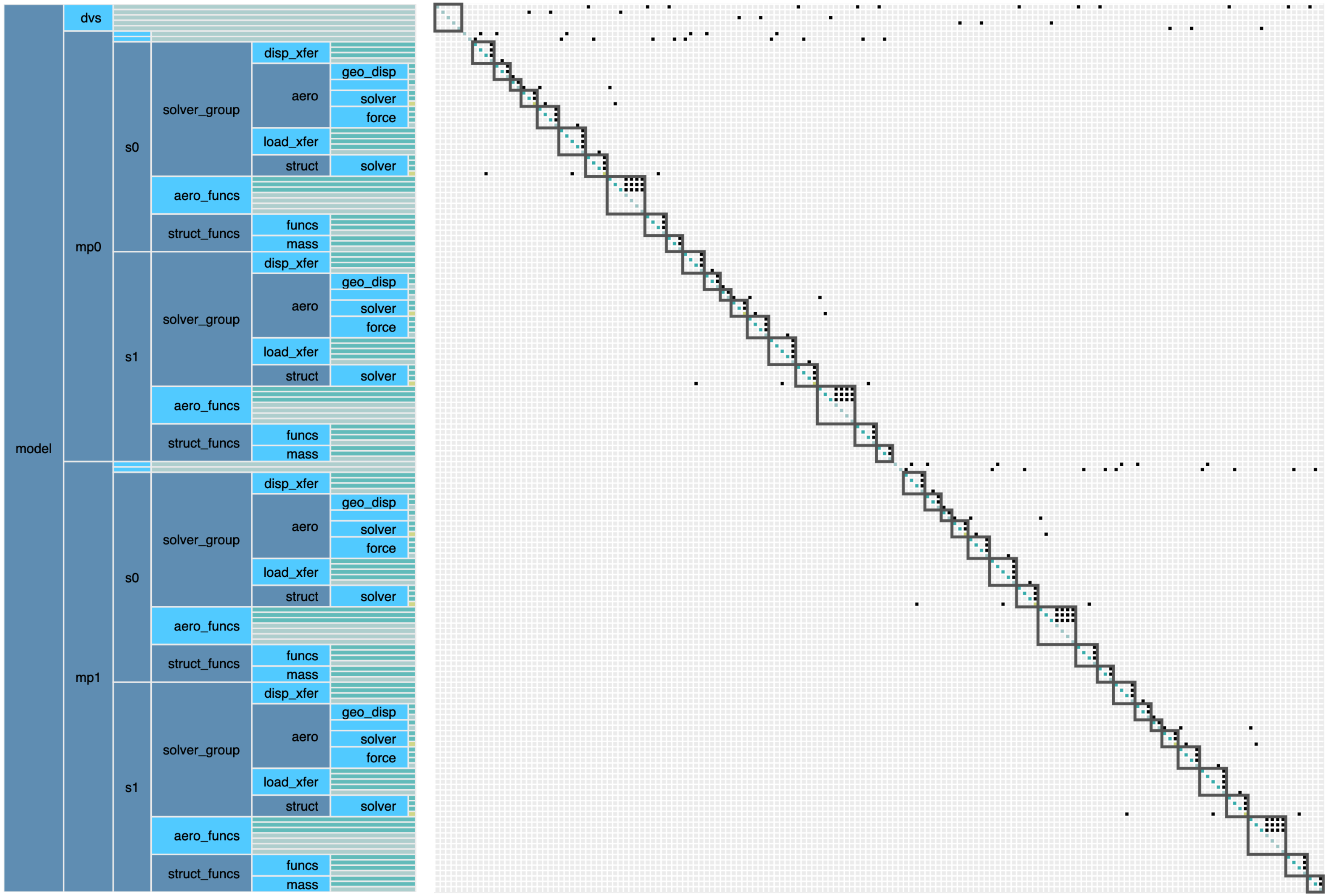

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MPHYS can perform aerostructural simulations using combinations of solvers

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Aerodynamics: ADflow (RANS CFD) and a VLM solver developed at LARC

Structure: TACS (High-fidelity FEM) and a modal solver

Transfer: MELD and Rigid Link Transfer (RLT)

We can do aerostructural analyses and basic optimizations with 8 different combinations

Availability of multiple solvers create new possibilities for design optimization

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If solvers provide derivatives, they can be included in optimizations

Even without gradients, they can be used to analyze the design, which was optimized using another solver

Different combinations of solvers can be tested for each flow condition; e.g., VLM for maneuver loads and RANS CFD for cruise cases

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Work underway to add more solvers and design tools

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MPHYS wrappers are being developed for FUN3D and SU2

Plans include the addition of NASTRAN,
and simple beam and wing-box models

Also working on including geometry parameterization tools:

- Free form deformation (FFD)
- Vehicle Sketch Pad (VSP)
- Engineering Sketch Pad (ESP)

We are also adding more disciplines, such as propulsion and thermal models

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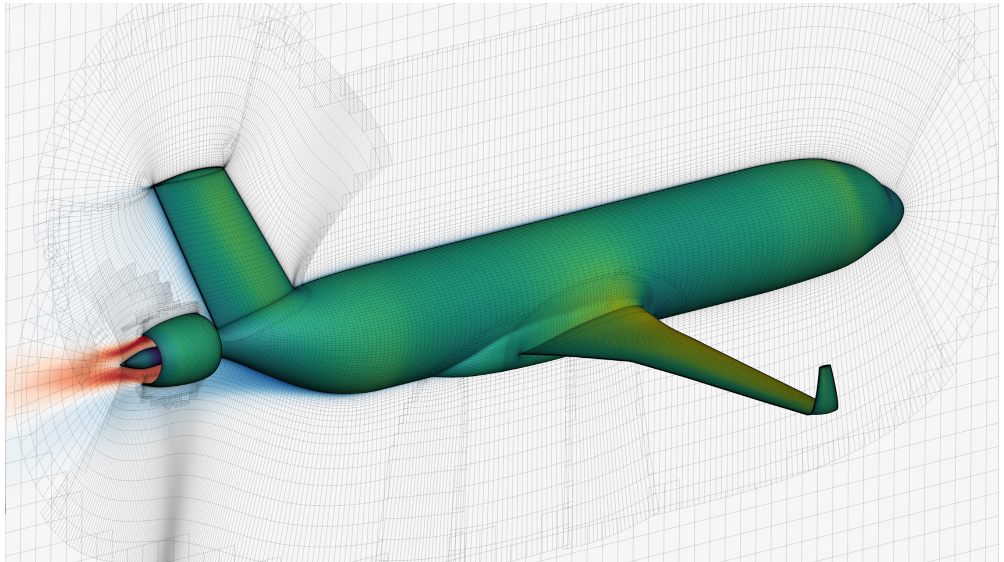
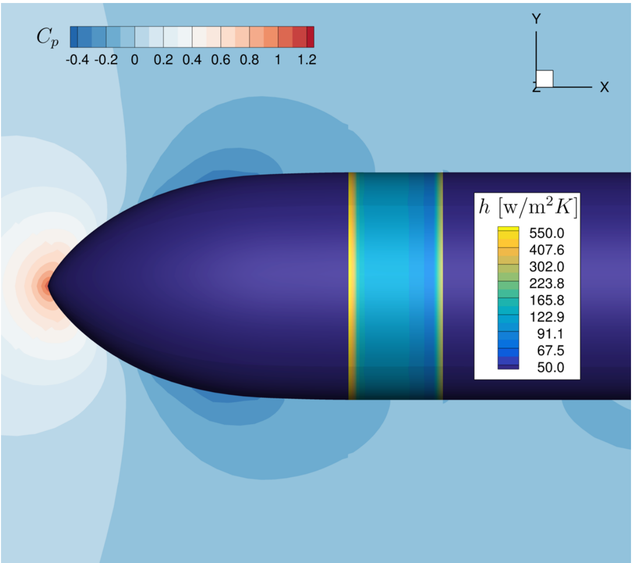
Goal is to perform all future aeropropulsive and aerothermal studies using MPHYS

This will also enable extending the aerostructural design studies to additional disciplines

Yildirim et al.
AIAA 2019-3455





Anibal et al.
AIAA 2020-2115

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MPHYS provides a multiphysics simulation framework in OpenMDAO

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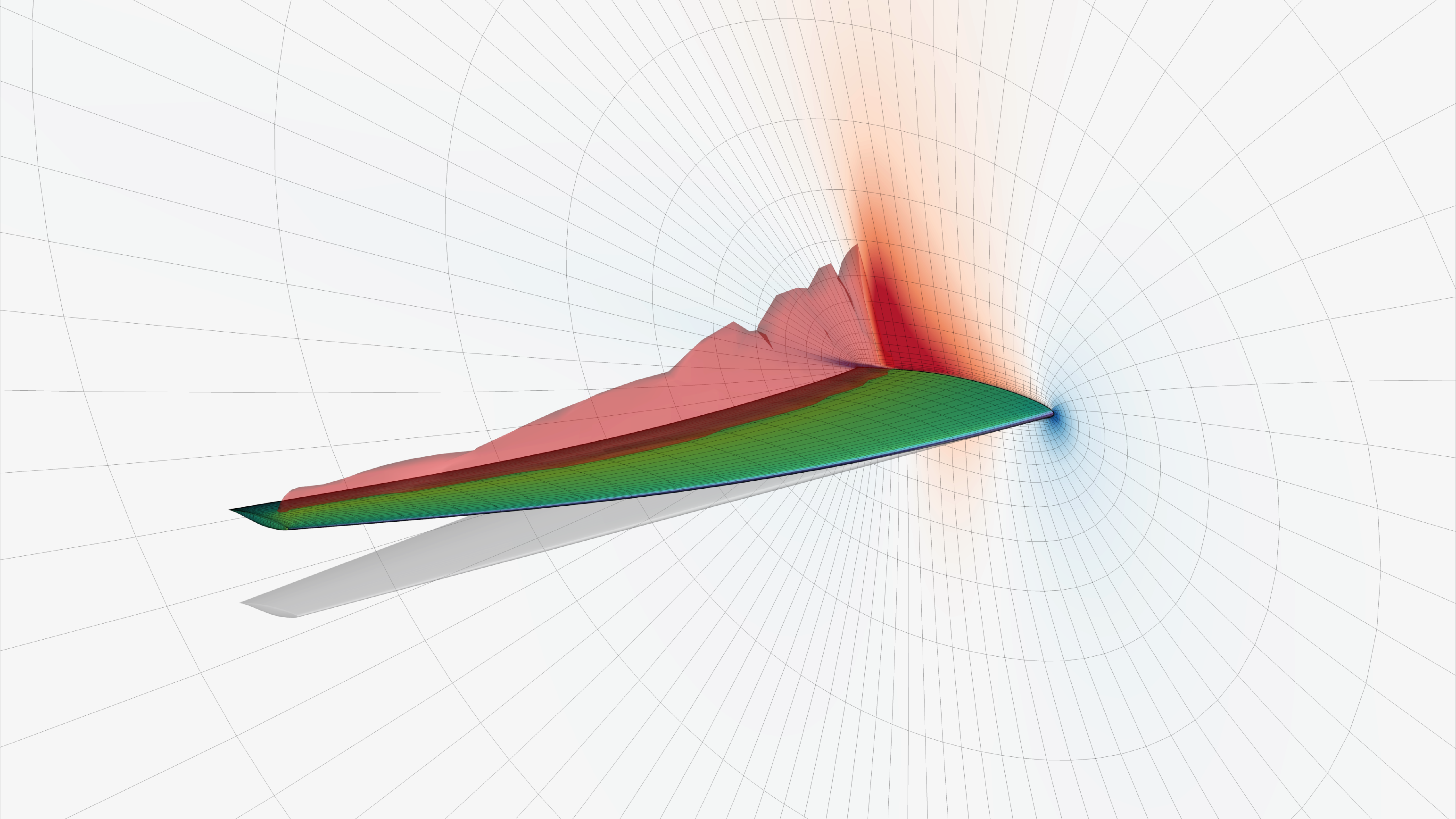
It streamlines the inclusion of high-fidelity simulations in OpenMDAO models

Users interact with a simplified interface; parallelism is abstracted, and computational performance is optimized by developers

The standard API defined for each discipline enables a plug and play approach, where the solvers are interchangeable

MPHYS enables extending the models to additional coupled disciplines



Thank you!

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Q&A Session: MDO-07, Emerging Methods, Algorithms, and Software Development in MDO II

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Open-source tools:

https://github.com/
- mdolab/ADflow
- gjkennedy/funtofem
- gjkennedy/tacs
- OpenMDAO/OpenMDAO

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