Contact constraint enforcement using the Tribol interface physics library

MFEM Community Workshop 2023

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Tribol

Contact interface physics library

https://github.com/LLNL/Tribol

- Current Tribol team:
  - SR Wopschall
  - EB Chin
  - K Weiss
- Code is written in C++
  - Dependencies on **mfem** and **axom**
- Features C and Fortran API compatibility
- Tribol is integrated into many codebases:
  - ale3d
  - blast
  - diablo
  - serac

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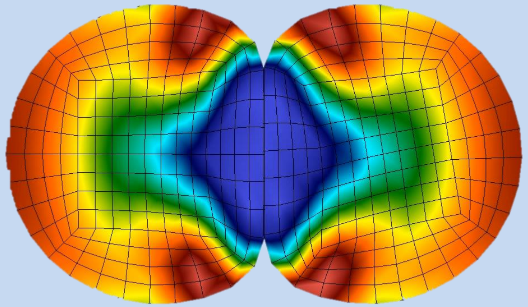
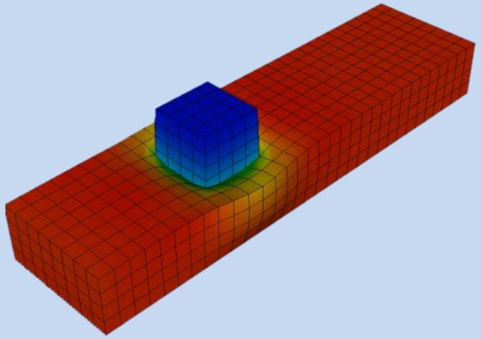
Contact methodologies

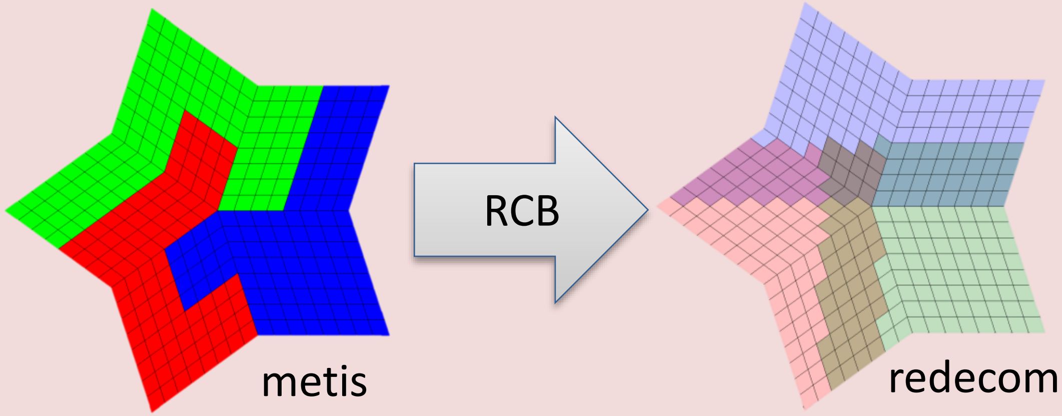


Common plane



Mortar

Domain redecomposer (redecomp)



MFEM interface

Submesh

- Create a surface ParMesh from boundary attributes
- Elements/dofs do not change rank

Low-order refined transfers

- Transfer higher-order mesh data to a refined low-order mesh
- Mass-conservative mapping

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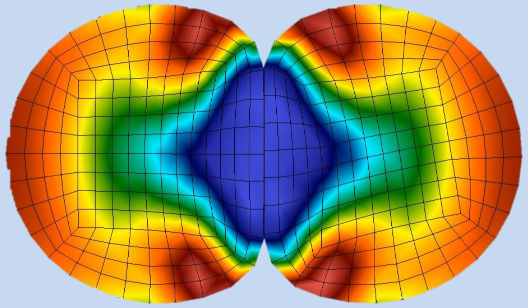

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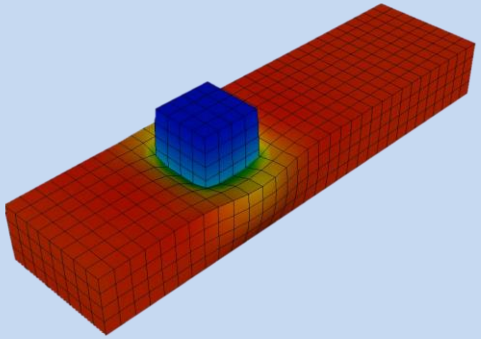

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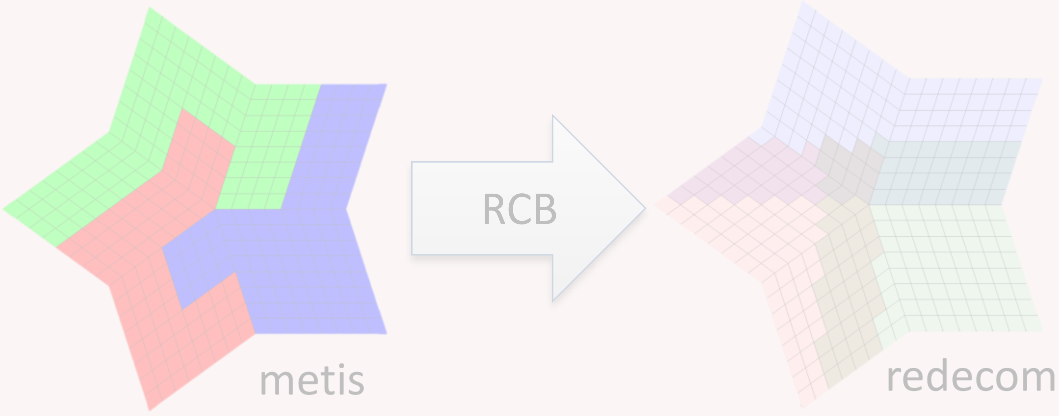

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Tribol contact methodologies

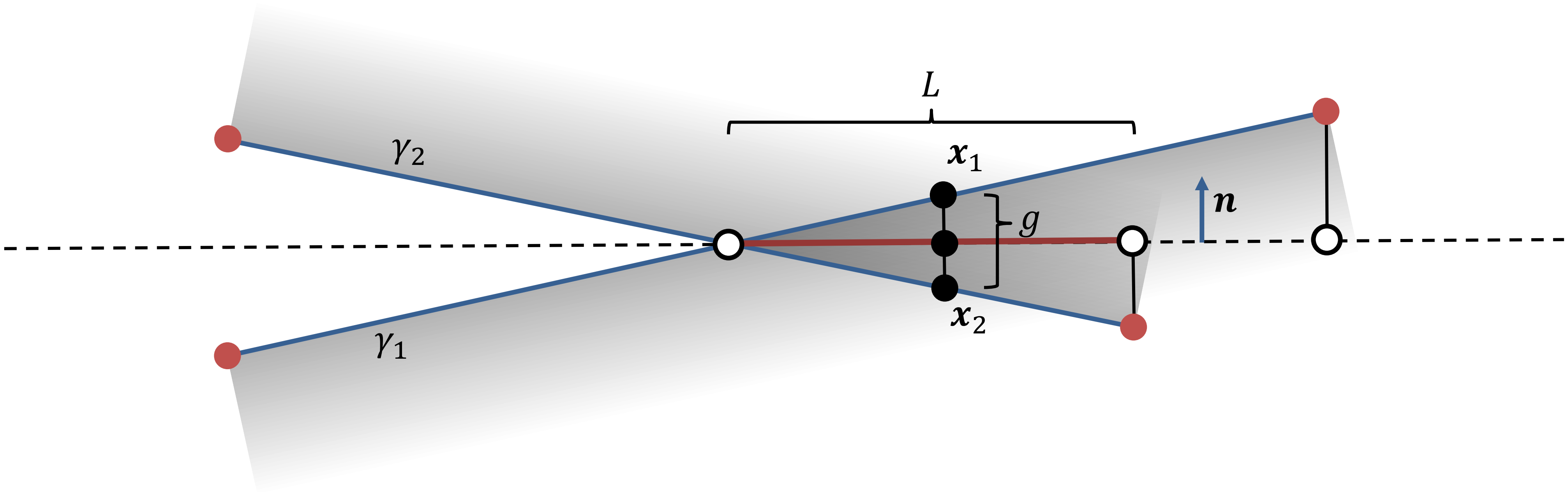
- Contact energy: $\Pi_c = \int_{\Omega_c} p\ g\ dS$

- Pressure (tied contact: enforces $g = 0$ or contact: enforces $g \geq 0$):
  - Penalty
  - Lagrange multiplier
  - Augmented Lagrange

- Gap:
  - How to define?
    - In terms of one surface?
    - In terms of an average over both surfaces?
  - Identifying contact pairs
  - Must also define a normal direction

- Surface of integration:
  - Identifying surfaces in contact (computational geometry)
  - Domain
    - One surface of the pair?
    - Average of both surfaces?
    - Both surfaces?
  - Integration rule
    - Segmentation?
    - Element-based?
    - Nodal? (i.e. node-to-surface contact)

Tribol contact methodologies: common plane



Contact force on pair: $f = \kappa g L$

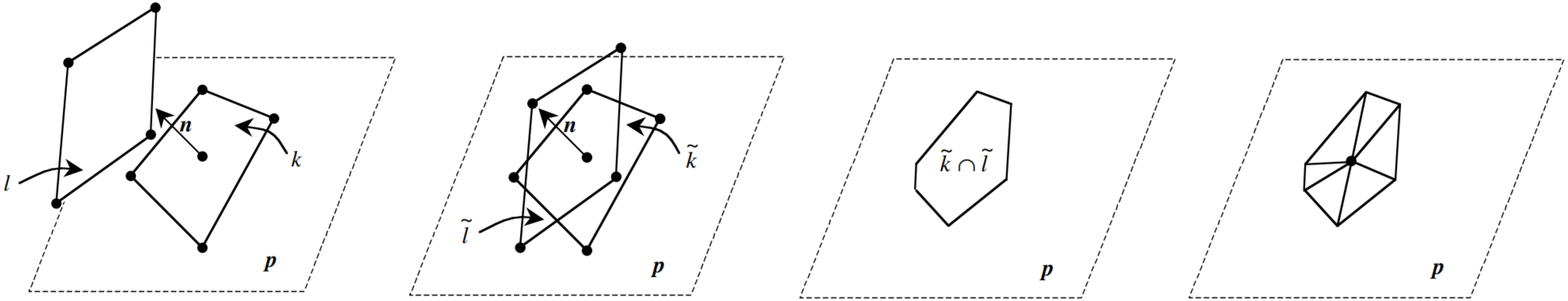
- κ: penalty parameter (force/area)
- $g = (\boldsymbol{x}_2 - \boldsymbol{x}_1) \cdot \boldsymbol{n}$: gap at overlap centroid
- $\boldsymbol{n}$: unit normal of common plane (average of each normal in pair)
- L: length of pair overlap

Tribol contact methodologies: mortar

Puso and Laursen, Comput Methods Appl Mech Engrg (2004)

Contact force on node B on side i from p_A: $\quad f_{AB}^{i} = p_A \boldsymbol{n}_A \int_{\gamma} N_A^1 N_B^i \, ds$

- p_A: pressure value on node A (non-mortar side; side 1)
- $\boldsymbol{n}_A$: nodally averaged unit normal vector on non-mortar side
- $\int_{\gamma} N_A^1 N_B^i \, ds$: mortar integral
  - If $i = 2$, integrand usually isn't smooth over domain of integration
  - Use segmentation to define integration domain and rule:



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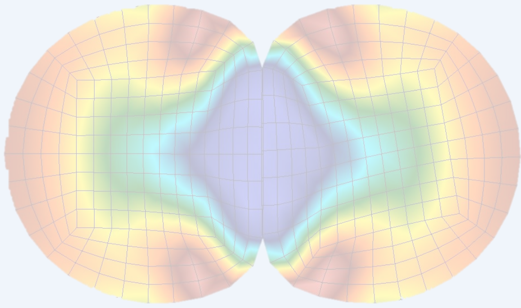
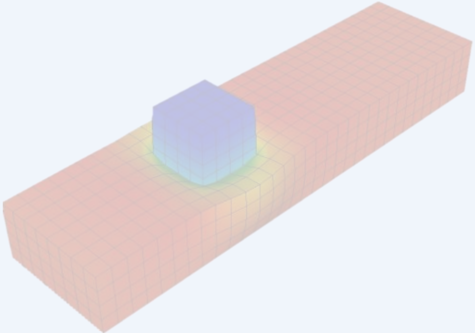


Common plane



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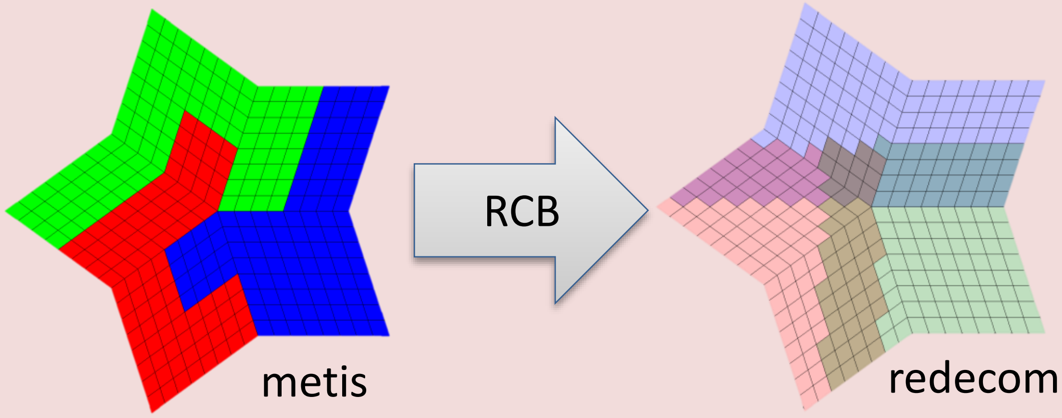
Domain redecomposer (redecomp)



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Domain redecomposer

Tribol’s contact algorithms

SERIAL

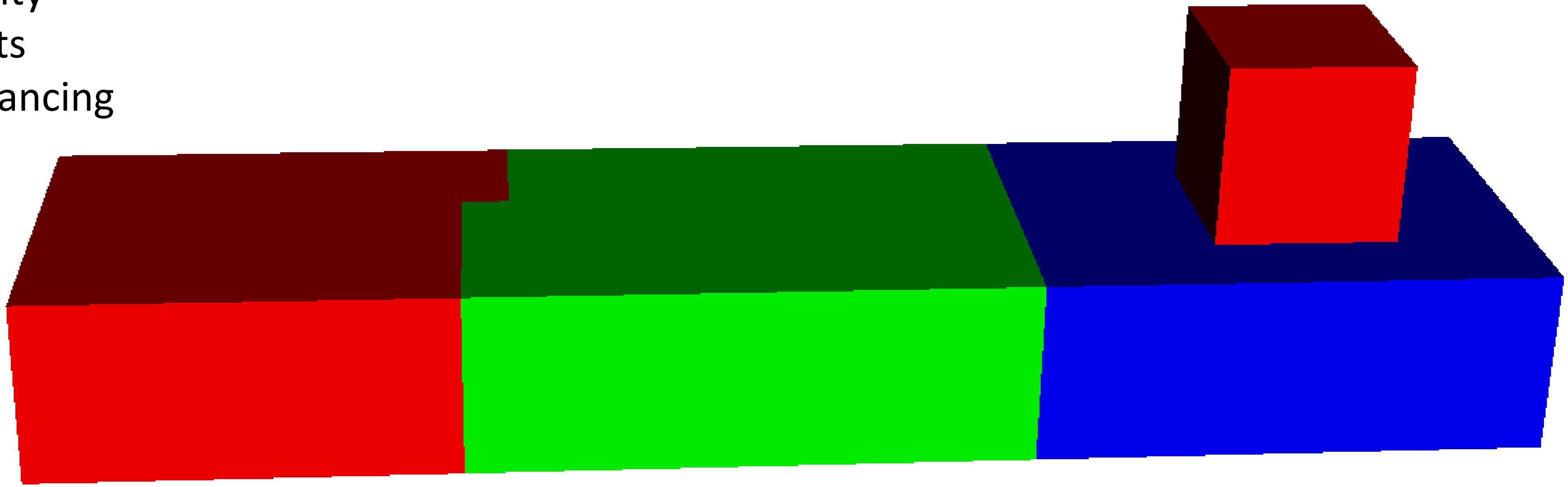
Domain redecomposer
(redecomp)

Typical MFEM problem of interest

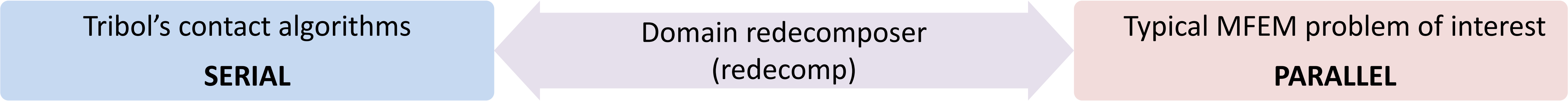
PARALLEL

- Why redecompose?
  - Increase code modularity
  - Spatial proximity
  - Ghost elements
  - Problem rebalancing

Contact ironing problem
Metis decomposed domain



Domain redecomposer



Tribol’s contact algorithms

SERIAL

Domain redecomposer
(redecomp)

Typical MFEM problem of interest

PARALLEL

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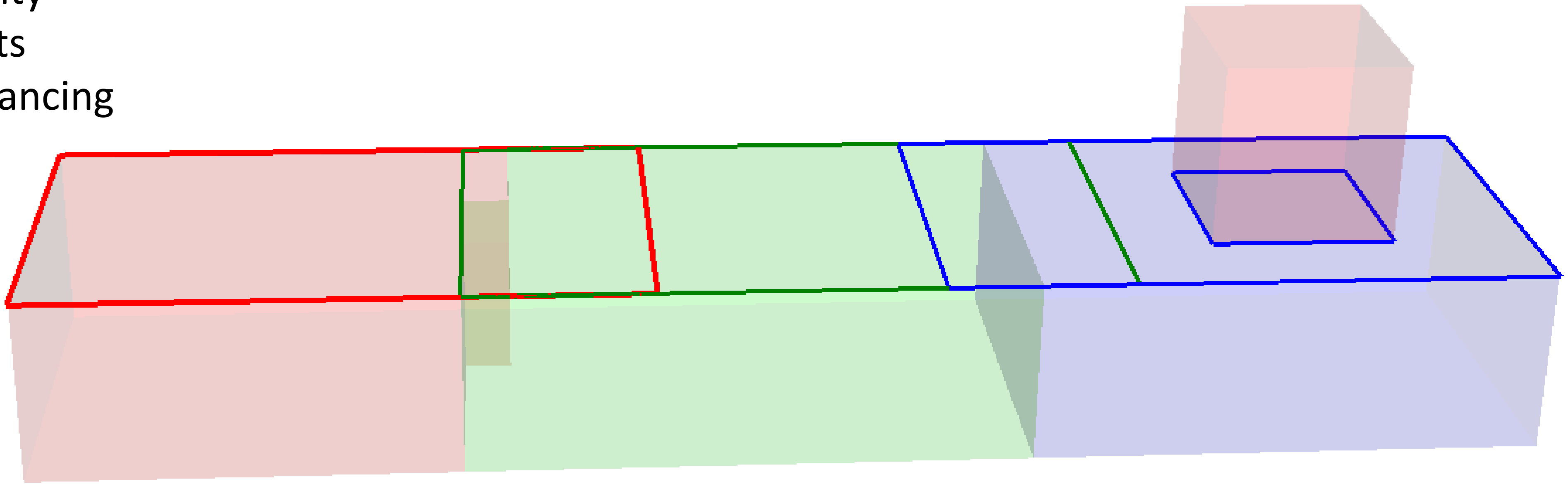
Contact ironing problem
Redecomposed domain (outline)



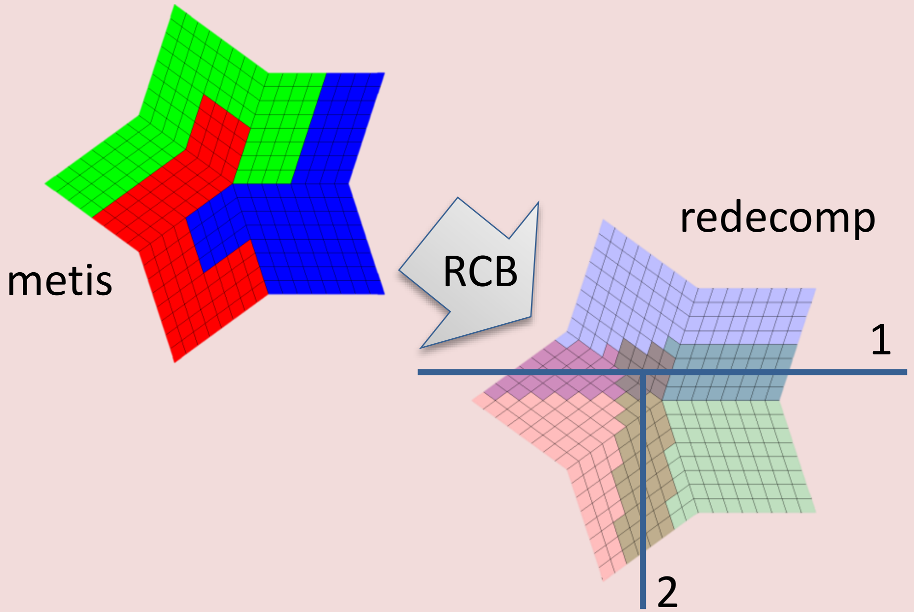
Using the domain redecomposer

See the src/redecomp directory in the Tribol repo

1. Create a RedecompMesh object

   Requires

   - An MFEM ParMesh
   - (Optional) RCB options

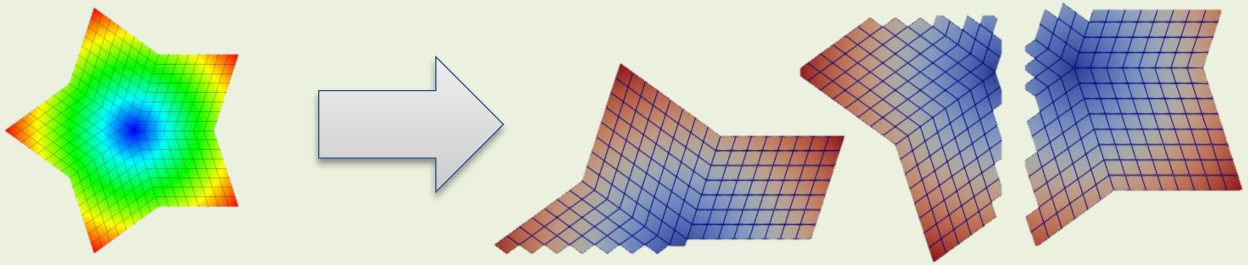


Moving grid functions and quadrature functions

2. Create a RedecompTransfer object

   Optional arguments (optimizes grid function transfer)

   - ParFiniteElementSpace on ParMesh
   - FiniteElementSpace on RedecompMesh



Moving matrices

2. Create a MatrixTransfer object

   Arguments

   - Test and trial ParFiniteElementSpace on ParMesh
   - Test and trial FiniteElementSpace on RedecompMesh

Using the domain redecomposer

- Example problems
  - src/examples/domain_redecomp.cpp
    - Create a redecomp mesh, transfer grid functions, and transfer quadrature functions to/from a ParMesh
  - src/examples/multidomain_redecomp.cpp
    - Same as the previous example, but with one RCB decomposition over multiple ParMeshes
  - src/examples/matrix_redecomp.cpp
    - Compute mass matrix on a redecomp mesh then move and assemble on a linked ParMesh

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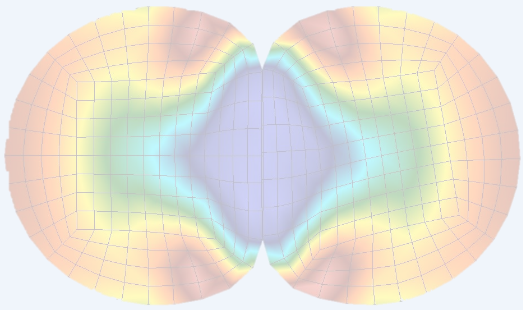
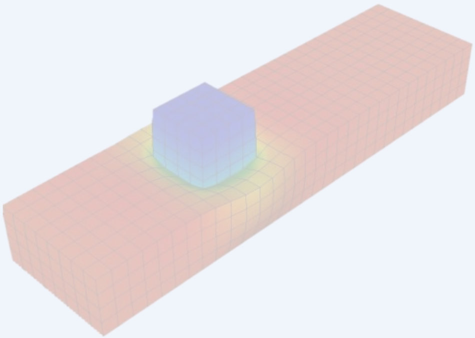
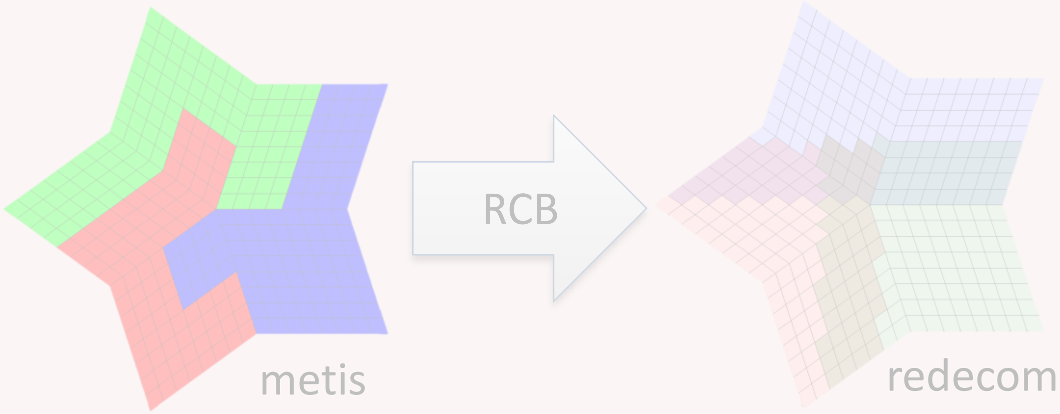


Common plane



Mortar

Domain redecomposer (redecomp)



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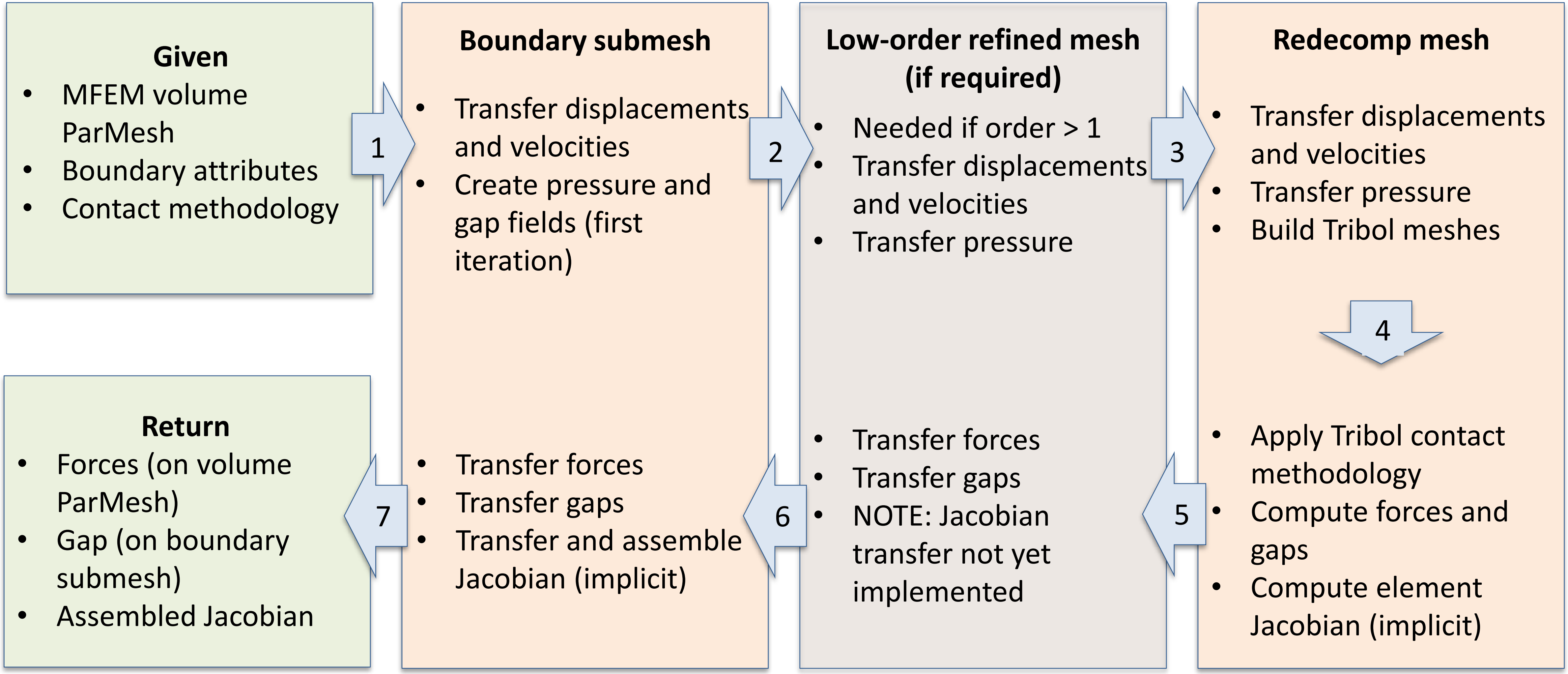
Tribol MFEM interface



Given

- MFEM volume ParMesh
- Boundary attributes
- Contact methodology

1

Boundary submesh

- Transfer displacements and velocities
- Create pressure and gap fields (first iteration)

2

Low-order refined mesh (if required)

- Needed if order > 1
- Transfer displacements and velocities
- Transfer pressure

3

Redecomp mesh

- Transfer displacements and velocities
- Transfer pressure
- Build Tribol meshes

4

- Apply Tribol contact methodology
- Compute forces and gaps
- Compute element Jacobian (implicit)

5

- Transfer forces
- Transfer gaps
- NOTE: Jacobian transfer not yet implemented

6

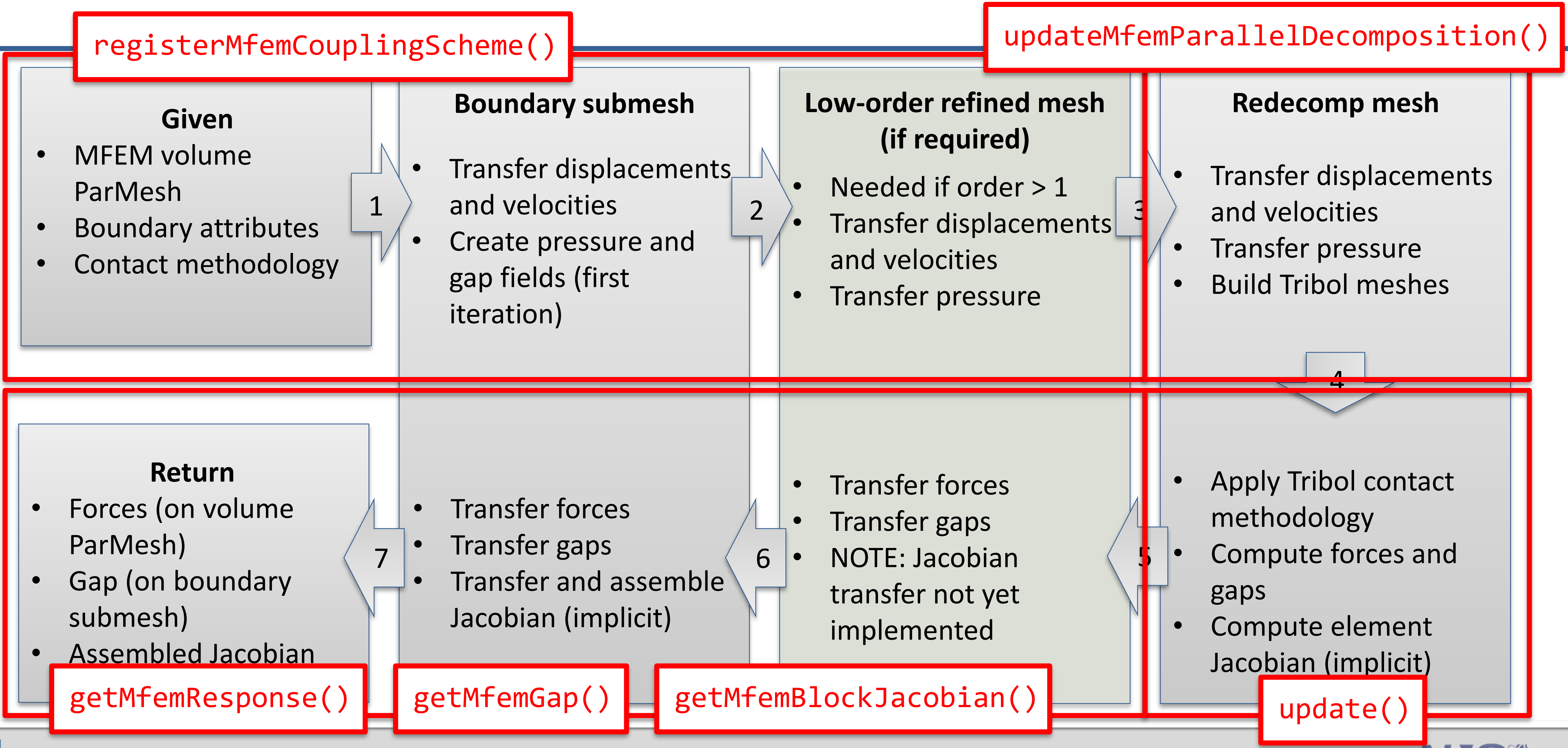
- Transfer forces
- Transfer gaps
- Transfer and assemble Jacobian (implicit)

7

Return

- Forces (on volume ParMesh)
- Gap (on boundary submesh)
- Assembled Jacobian

Tribol MFEM interface



`registerMfemCouplingScheme()`

Given

- MFEM volume ParMesh
- Boundary attributes
- Contact methodology

Boundary submesh

- Transfer displacements and velocities
- Create pressure and gap fields (first iteration)

Low-order refined mesh (if required)

- Needed if order > 1
- Transfer displacements and velocities
- Transfer pressure

`updateMfemParallelDecomposition()`

Redecomp mesh

- Transfer displacements and velocities
- Transfer pressure
- Build Tribol meshes

- Apply Tribol contact methodology
- Compute forces and gaps
- Compute element Jacobian (implicit)

`update()`

- Transfer forces
- Transfer gaps
- NOTE: Jacobian transfer not yet implemented

`getMfemBlockJacobian()`

- Transfer forces
- Transfer gaps
- Transfer and assemble Jacobian (implicit)

`getMfemGap()`

Return

- Forces (on volume ParMesh)
- Gap (on boundary submesh)
- Assembled Jacobian

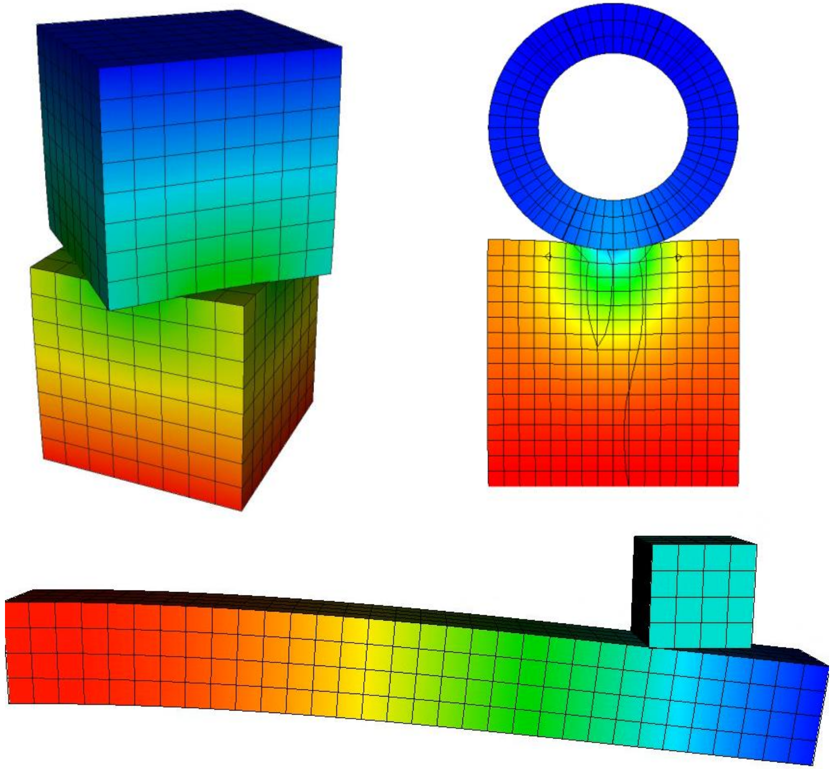
`getMfemResponse()`

Tribol MFEM interface

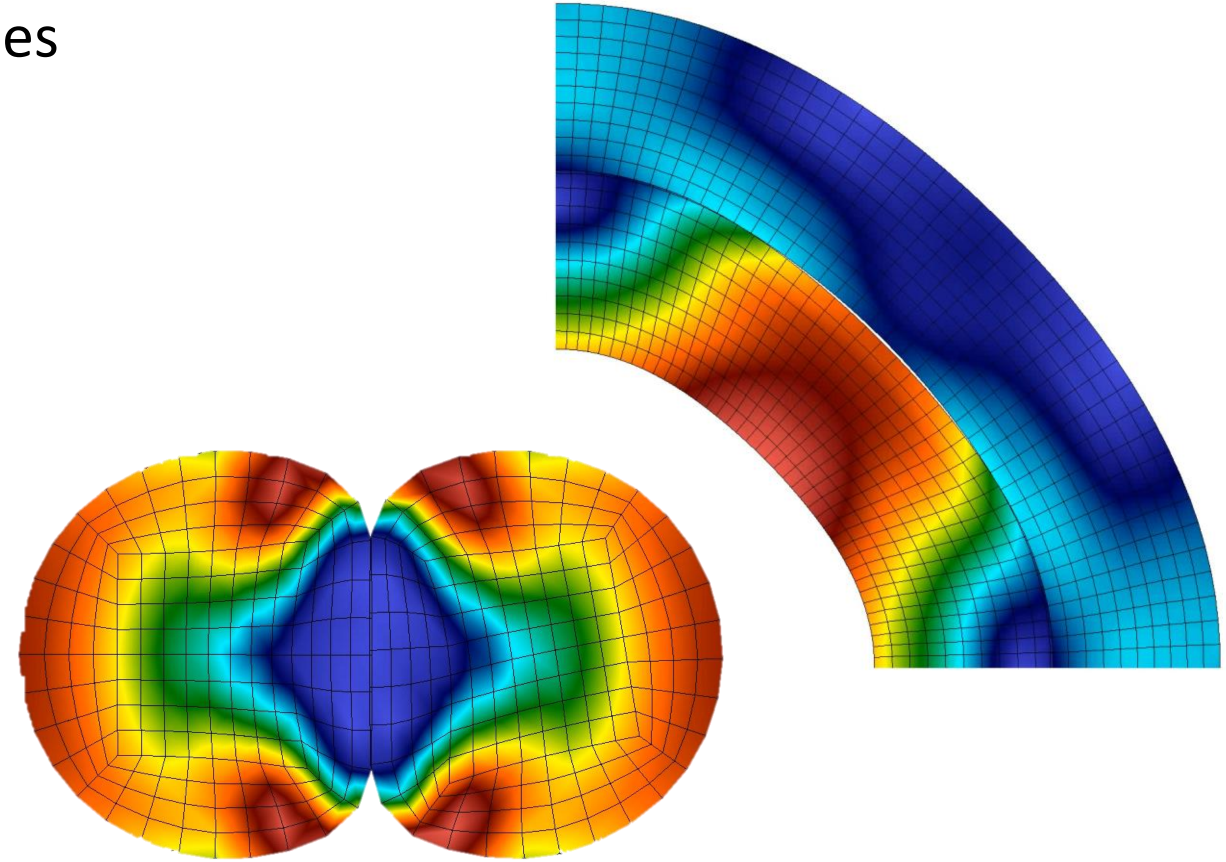
- Example problems
  - `src/examples/mfem_common_plane.cpp`
    - Simple two block impact problem
    - Common plane + penalty contact enforcement, hyperelastic solid, explicit finite elements
  - `src/examples/mfem_mortar_lm_patch.cpp`
    - Two block contact patch test
    - Mortar + Lagrange multiplier enforcement, elastic solid, implicit finite elements

Tribol MFEM interface

- Ongoing integration with multiphysics codes



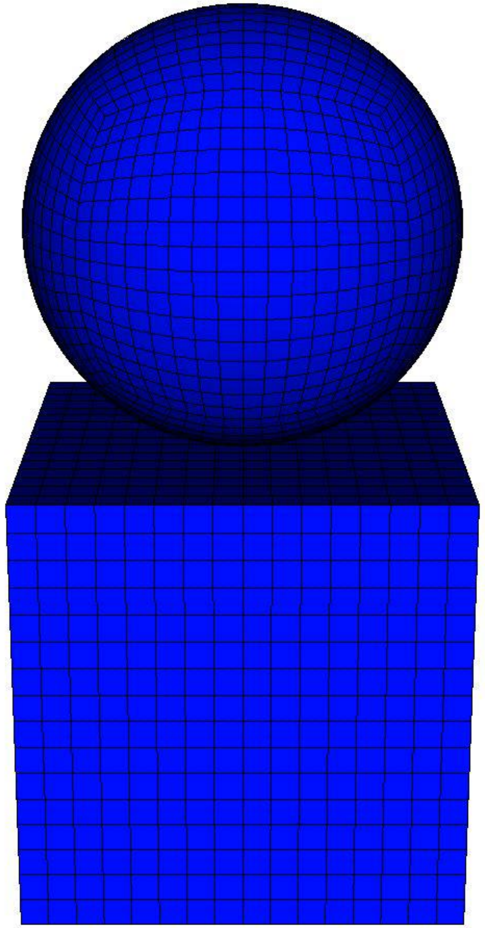
Serac (implicit mortar)

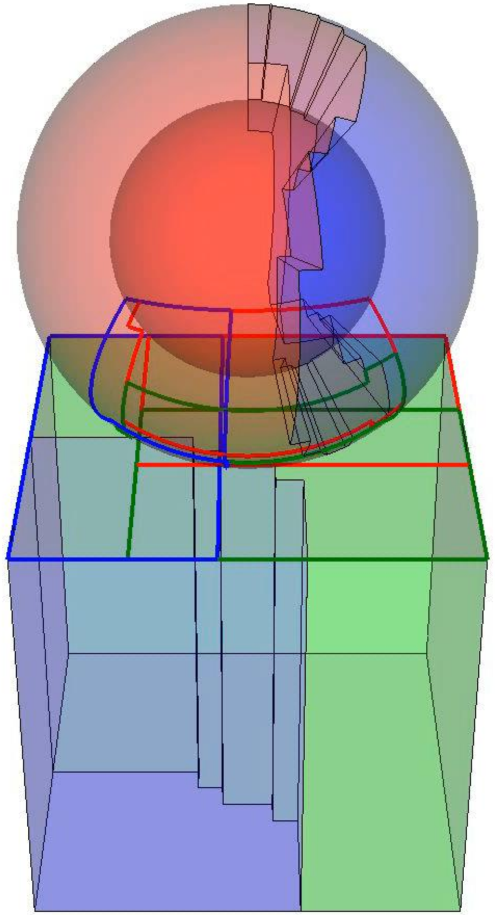


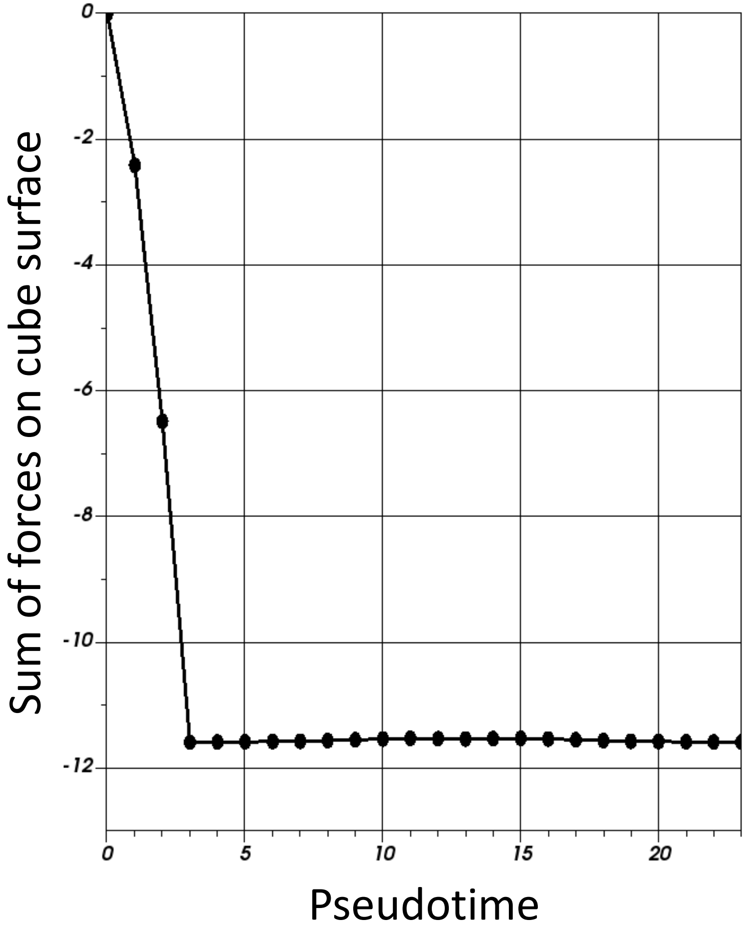
Blast (explicit common plane)

Example problem: quasistatic twisting sphere

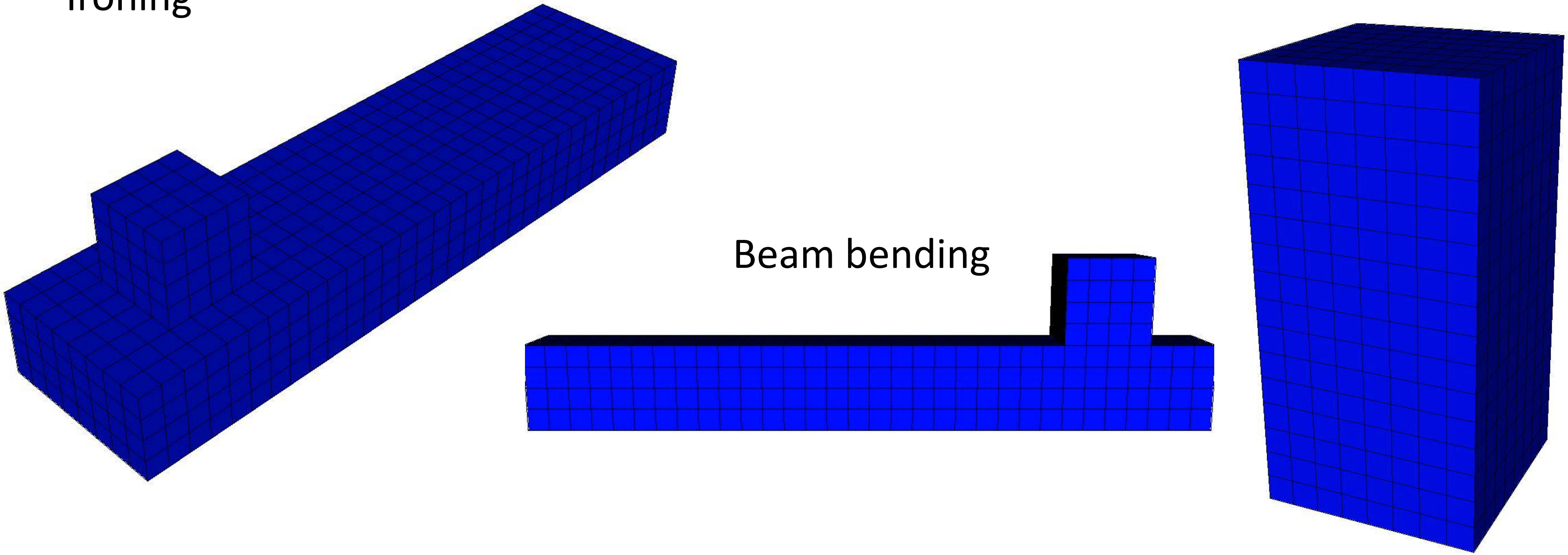
Serac implicit mortar, hyperelastic solid, 3 MPI ranks







More example problems



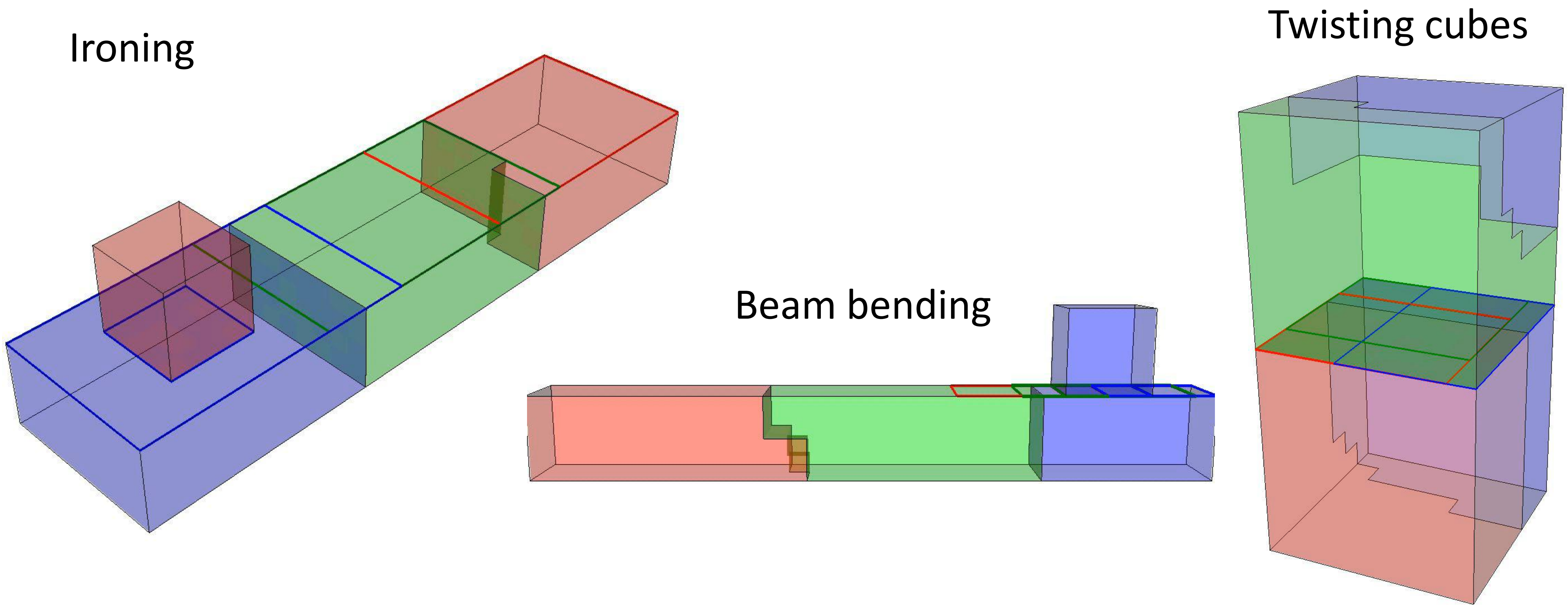
Ironing

Beam bending

Twisting cubes

More example problems

□ □ □ Surface redecomposition on-rank domains 🟥 🟩 🟦 MFEM on-rank domains



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Summary and conclusions

- Three main components of the Tribol interface physics library
  - Common plane and mortar methods
  - Domain redecomposer for MPI parallel contact
  - MFEM interface for simplifying Tribol usage with MFEM data structures
- Code is available on github: https://github.com/LLNL/Tribol
  - Serac integration (see https://github.com/LLNL/serac) coming soon (see PR #982)
- Coming next
  - GPU porting
  - Improved mortar contact algorithms
  - New/improved interface physics capabilities
  - Other code improvements
- **Thank you!**

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