INL/CON-22-70059-Revision-0

ANS MultiApps tutorial

November 2022

Changing the World's Energy Future

Guillaume Louis Giudicelli, Cody J Permann, Derek R Gaston, E. Shemon, Y. Miao, A. Abdelhameed, F. Kong

INL/CON-22-70059-Revision-0

ANS MultiApps tutorial

Guillaume Louis Giudicelli, Cody J Permann, Derek R Gaston, E. Shemon, Y. Miao, A. Abdelhameed, F. Kong

November 2022

Idaho National Laboratory
Idaho Falls, Idaho 83415

http://www.inl.gov

Prepared for the
U.S. Department of Energy
Under DOE Idaho Operations Office
Contract DE-AC07-05ID14517

NRIC National Reactor Innovation Center

INL/CON-22-XXXXX
ANS Winter 2022

Assembling Multiphysics Nuclear Reactor Simulations Using the MOOSE Framework

E. Shemon, Y. Miao, A. Abdelhameed
Argonne National Laboratory
C. Permann, A. Lindsay, **G. Giudicelli**, F. Kong, D. Gaston
Idaho National Laboratory

NEAMS
Nuclear Energy Advanced Modeling and Simulation

INL
Idaho National Laboratory

Argonne
NATIONAL LABORATORY

Mission Statement

NRIC: Deliver successful demonstration and deployment of advanced nuclear energy

- **EBRII Test Bed (DOME)**
- **ZPPR Test Bed (LOTUS)**
- **Virtual Test Bed (VTB)**: Accelerate deployment of advanced reactors by leveraging state-of-the-art Modeling and Simulation (ModSim) tools developed by the NEAMS program

Ok, but what is it?

Reactor Demonstrations

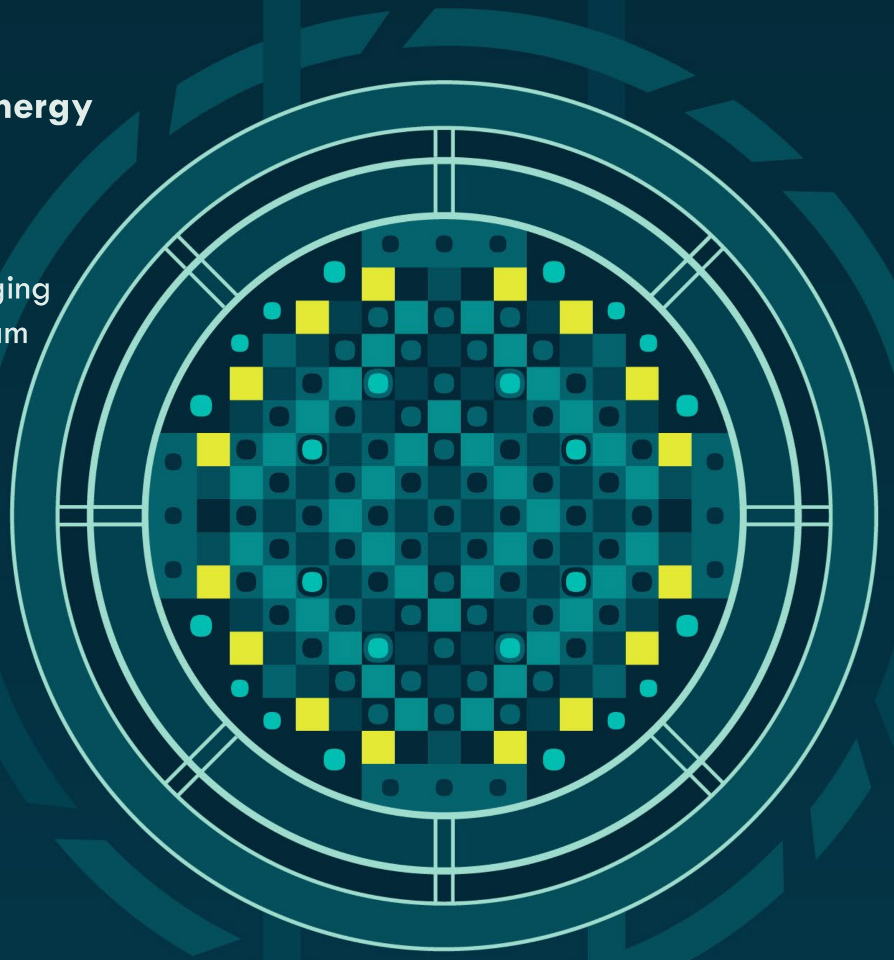
1) Model Development

Leverage codes supported by NEAMS to provide powerful, highly-adaptable simulations:

- Analysis Tools
- Problem benchmarks
- Testing capabilities
- Safety review

2) Model Repository

- Storing and showcasing open use-cases
- Stewardship of industry-relevant models
- Integration with code development framework to avoid legacy issues



NRIC

The VTB Repository

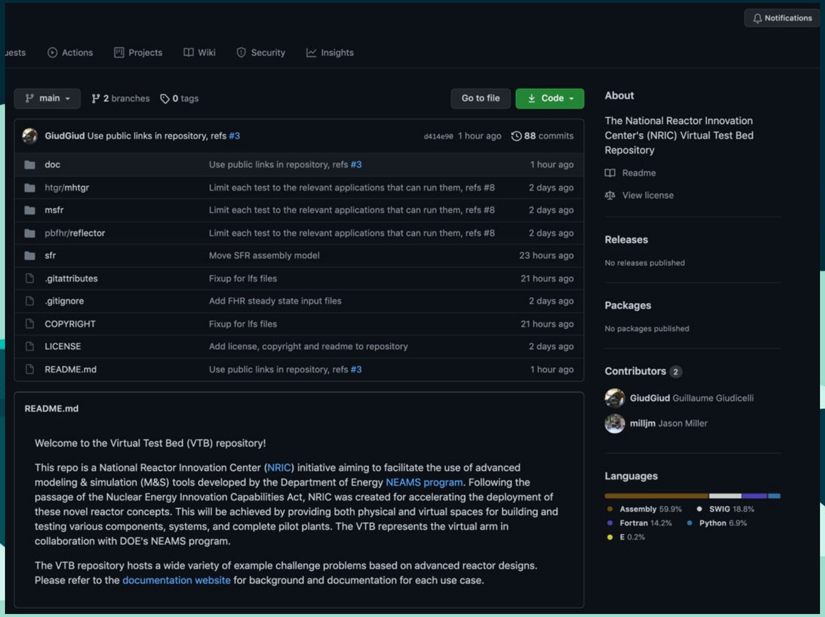
https://mooseframework.inl.gov/virtual_test_bed

1. Documentation

Detailed explanation of models

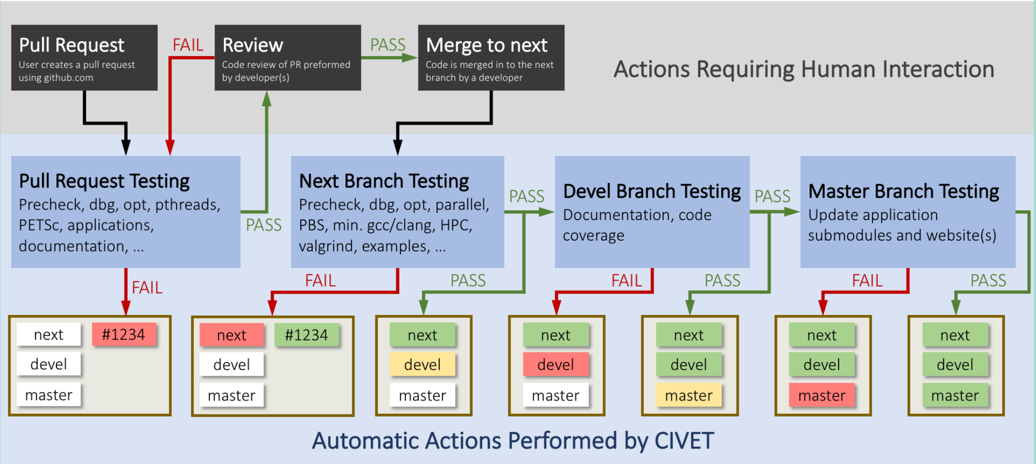
2. GitHub Repo

Ability to clone and contribute to models

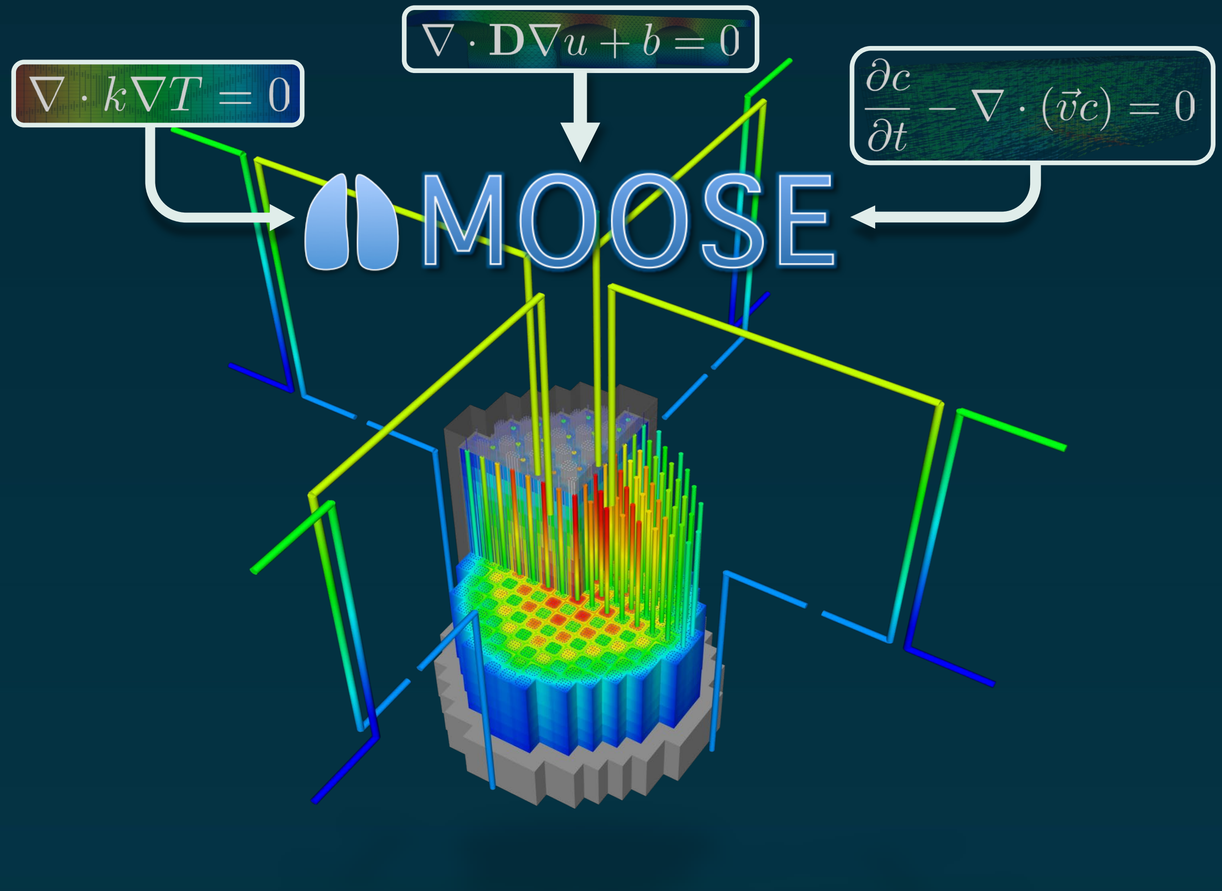


3. Integration with Code Development

Continuous testing of models against codes using CIVET



MOOSE Framework



What is MOOSE?

- Multiphysics framework to capture various reactor physical phenomena (neutronics, hydraulics, heat conduction, fuel performance etc.)
- Finite element based (with new finite volume capability) and massively parallelizable
- Standardized input structure
- Nuclear Software Quality Assurance (SQA) compliant

Why Multiphysics?

- Reactors are inherently Multiphysics
- Upcoming reactor designs rely on non-traditional Multiphysics effects (e.g. core expansion, heat pipes, molten fuel, fluidized beds, porous flow, etc.)
- Predictive Multiphysics enables the study of:
  - Power uprates, material changes, design/safety basis, accident scenarios, design feasibility, moderator choice, fuel loading optimization, material degradation, etc.

Tutorial

NRIC

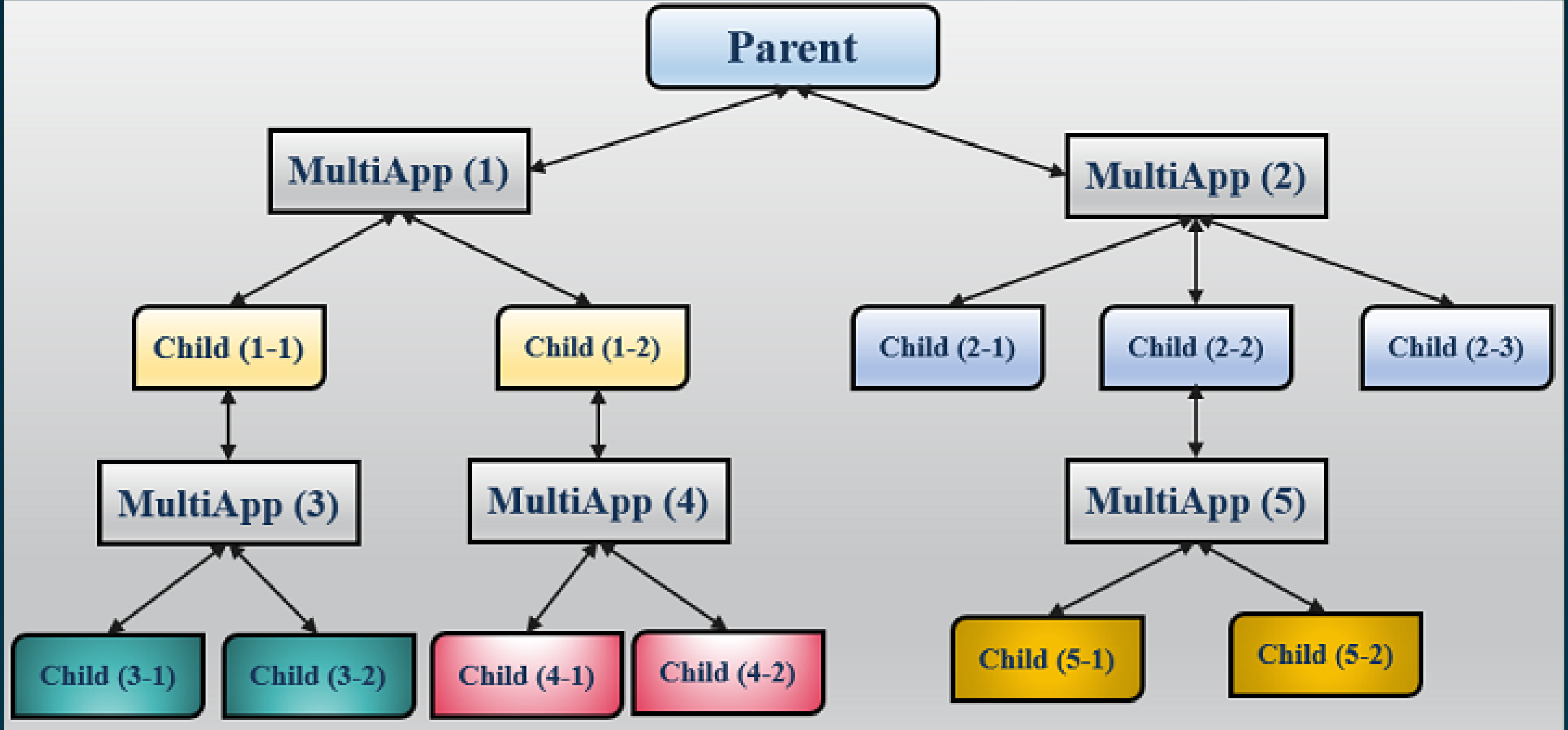
1) MultiApps Introduction

- System to numerically separate a physics solve
- Why separate?
  - Dissimilar time scales
  - Dissimilar spatial scales or dimensions
  - Weakly coupled physics
  - Numerical reasons
  - UQ/Optimization studies

NRIC

2) MultiApps Terminology

- Application
- Parent app
- MultiApp
- Child or subapp
- Transfers
- Fixed point



NRIC

3) Applications for MultiApps

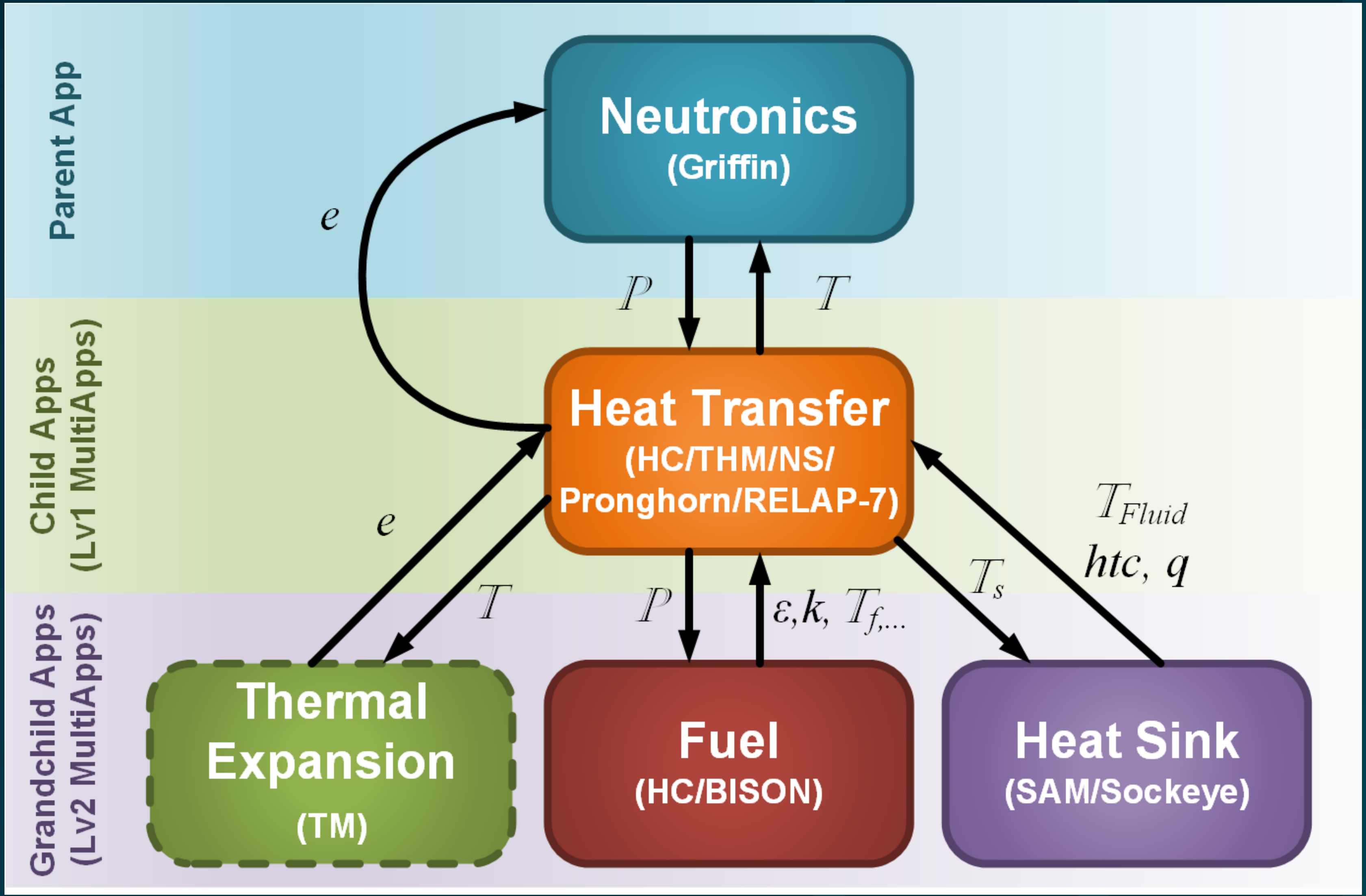
- Coupling physics applications from the NEAMS program
- Full list on NEAMS website

Physics	MOOSE Application	Features
Fuel Performance	BISON	A finite element-based nuclear fuel performance code applicable to a variety of fuel forms including light water reactor fuel rods, TRISO particle fuel, and metallic rod and plate fuel. It is a multiphysics fuel analysis tool that solves fully-coupled thermomechanical problems.
Neutronics	Griffin	A reactor physics application for advanced reactor multiphysics modeling and simulation.
Structure Analysis	Grizzly	A code for modeling degradation of nuclear power plant systems, structures, and components due to exposure to normal operating conditions.
Thermal Hydraulics	nekRS	An open-source Navier Stokes solver based on the spectral element method targeting classical processors and hardware accelerators like GPUs. Use of **nekRS** in the MOOSE ecosystem is through **Cardinal**, a wrapping of the spectral element code CFD NekRS and the Monte Carlo radiation transport code OpenMC as a MOOSE application.
Thermal Hydraulics	Pronghorn	A multiscale thermal-hydraulic (T/H) application developed by the Idaho National Laboratory
System analysis	RELAP-7	A next generation nuclear systems safety analysis code being developed at the Idaho National Laboratory (INL).
System Analysis	System Analysis Module (SAM)	A modern system analysis tool being developed at Argonne National Laboratory for advanced non-LWR safety analysis. It aims to provide fast-running, whole-plant transient analyses capability with improved-fidelity for SFR, LFR, and MSR/FHR.
Heat Pipe	Sockeye	A heat pipe analysis application based on the MOOSE framework.
Chemistry	MOSCATO	The **MO**lten **S**alt **C**hemistry **A**nd **T**ranspOrt (MOSCATO) code is a code being developed at Argonne that focuses on simulating chemical and electrochemical reactions in molten salts. **(MOOSE wrapping development is on-going?)**
Chemistry	Mole	An engineering scale MOOSE-based molten salt species transport code developed at Oak Ridge National Laboratory.

NRIC

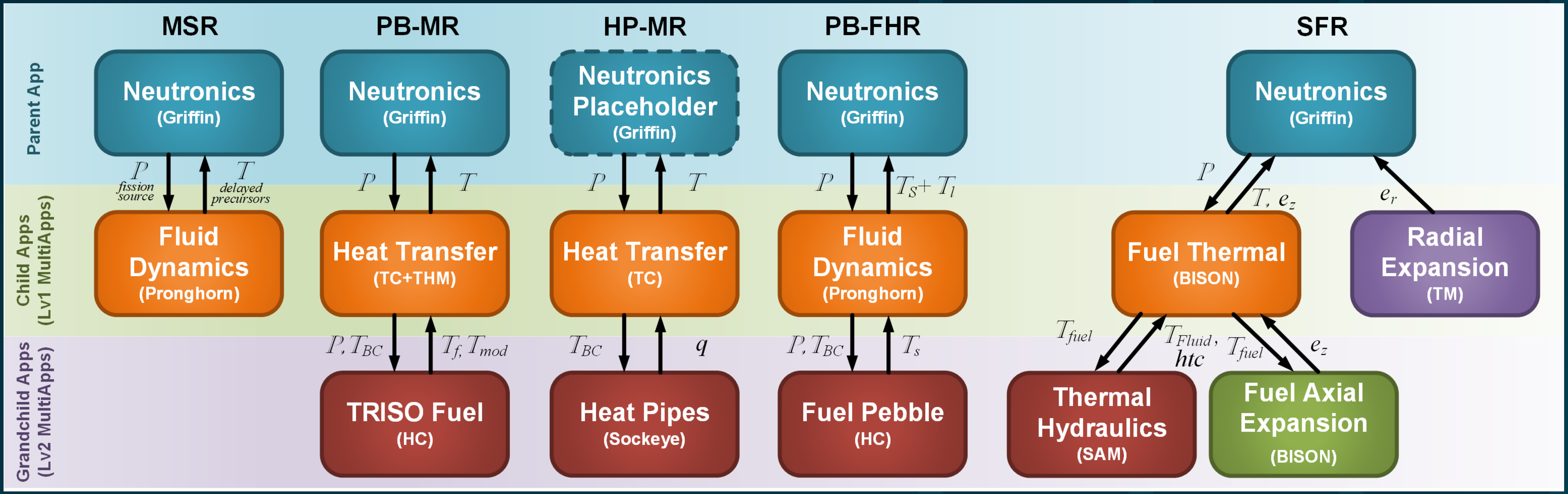
3) Applications for MultiApps

- Typical core multiphysics model



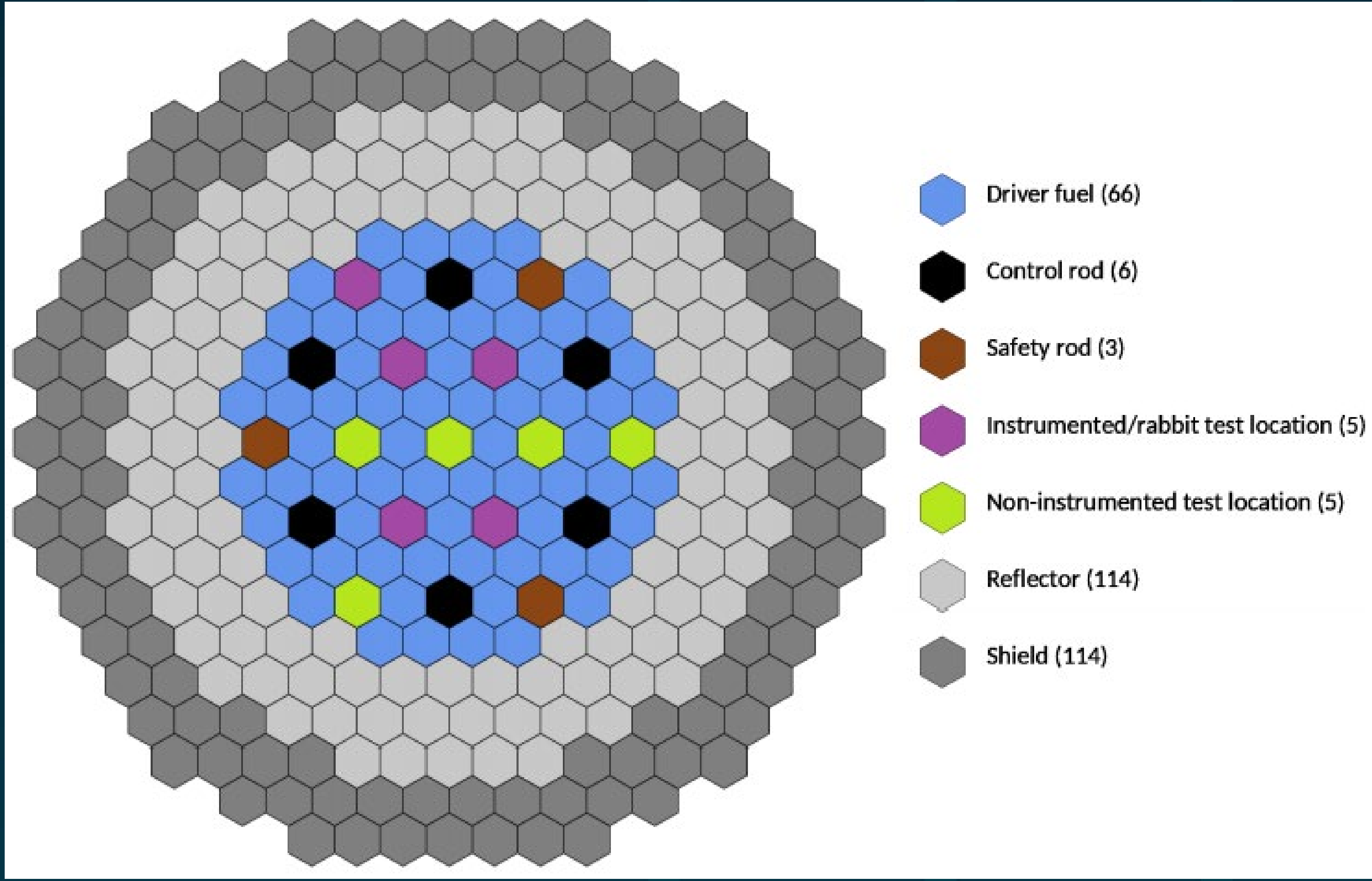
NRIC

3) Multiphysics Models Leveraging MultiApps



4) Workflow for Building Multiphysics Application

- Sodium Fast Reactor (SFR) example
- Declined in an assembly and a core model, both on VTB
- Contributed to the VTB by N. Martin, T. Folk and VTR team

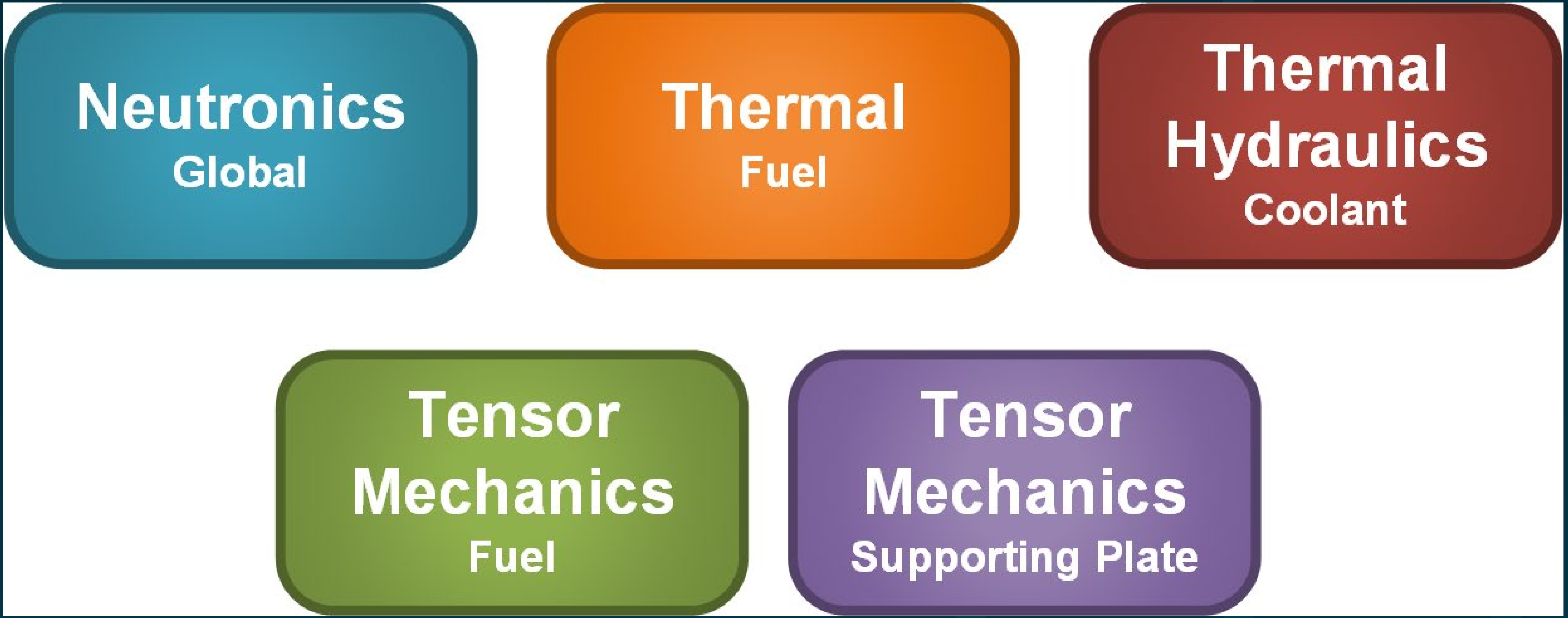


Radial configuration of the VTR core layout, taken from (Heidet, F. and Roglans-Ribas, J., 2021).

NRIC

4) Workflow for Building Multiphysics Application

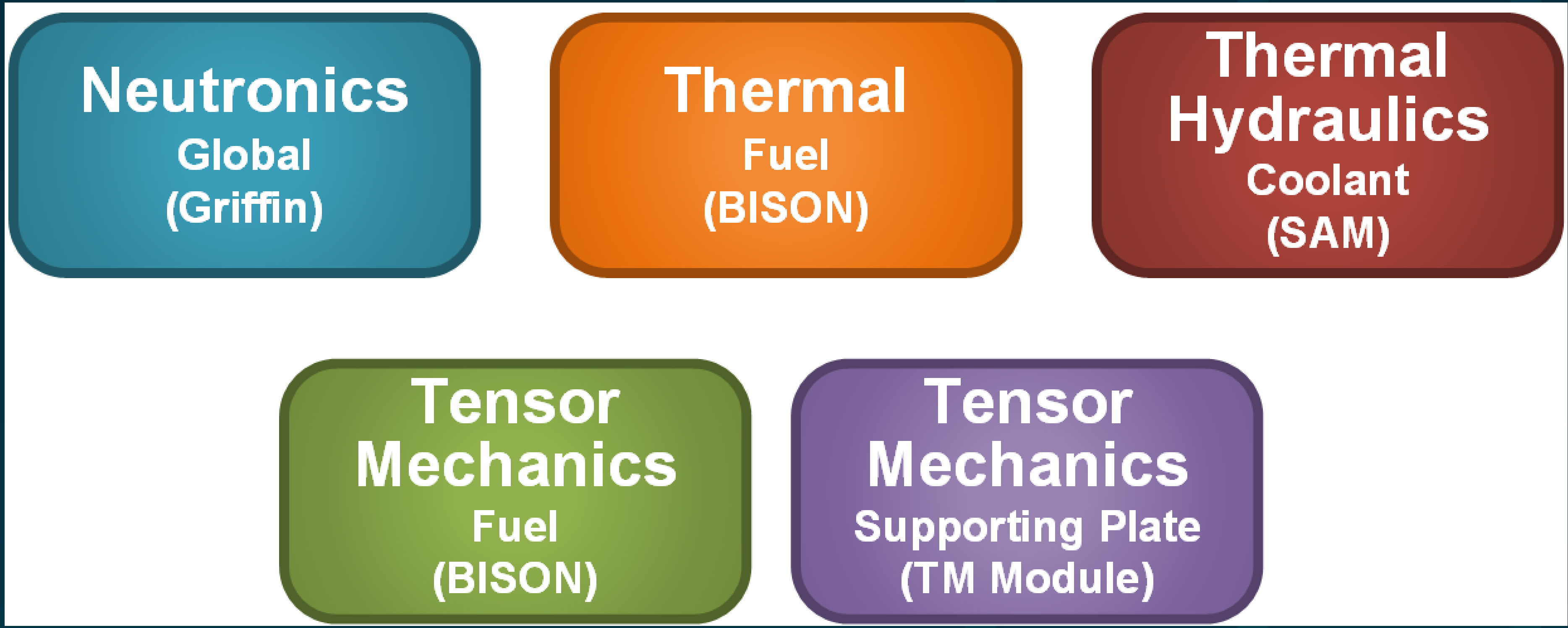
- Identify each physics involved



NRIC

4) Workflow for Building Multiphysics Application

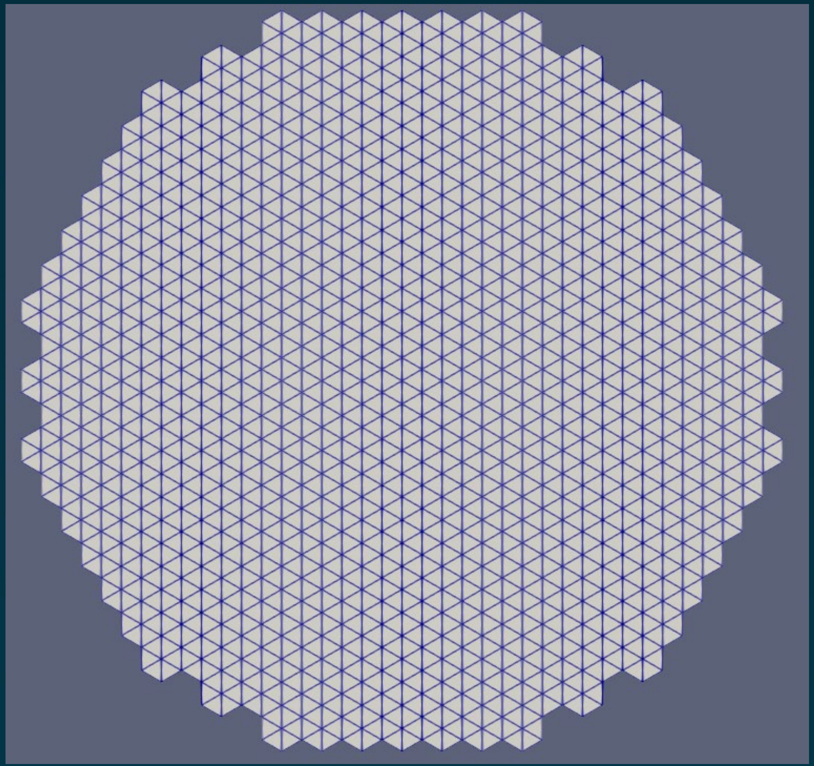
- Identify tool and build relevant single physics model
- Needs to run well standalone



NRIC

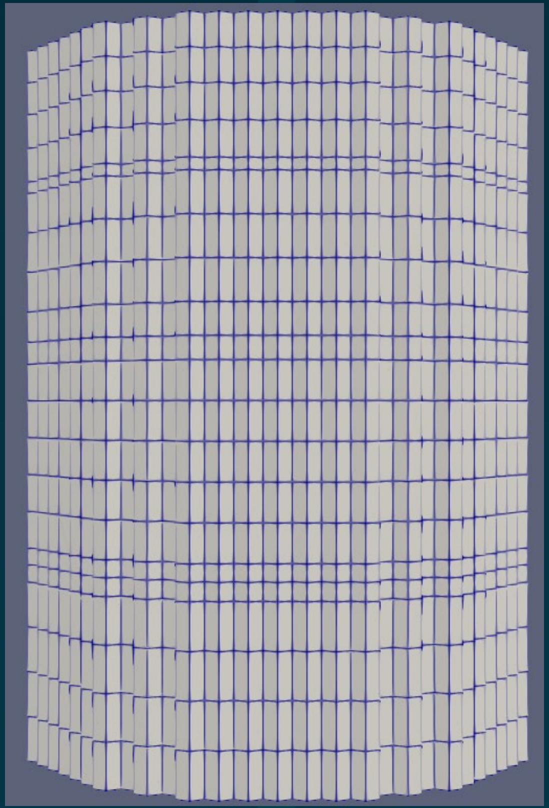
SFR Example Single-physics Models

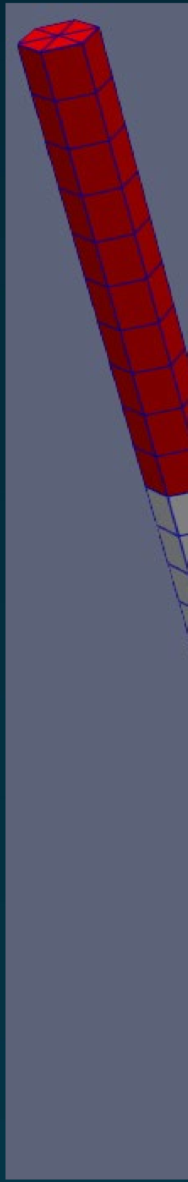
- Single assembly model: homogenized assembly
- Core model: homogenized Continuous Finite Element Method (CFEM) core



Radial mesh (left)

Axial mesh (right)

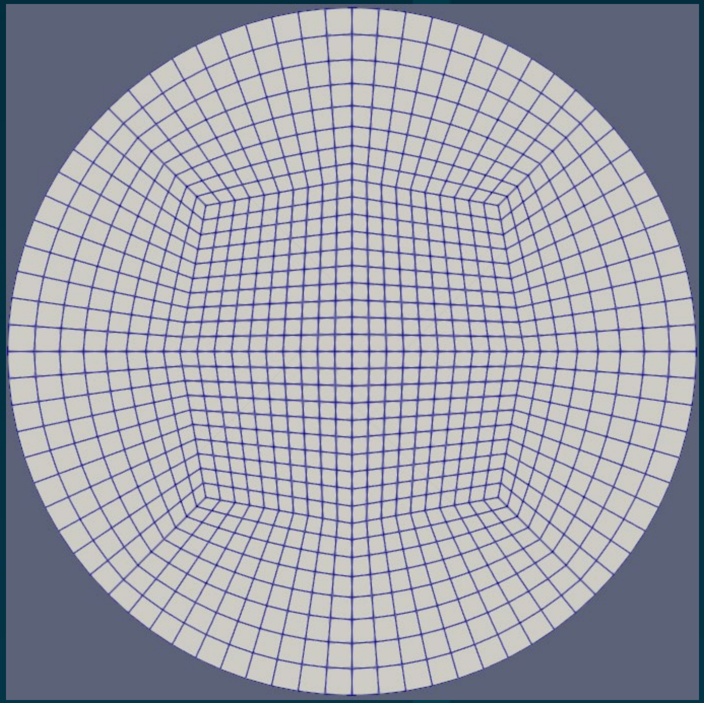




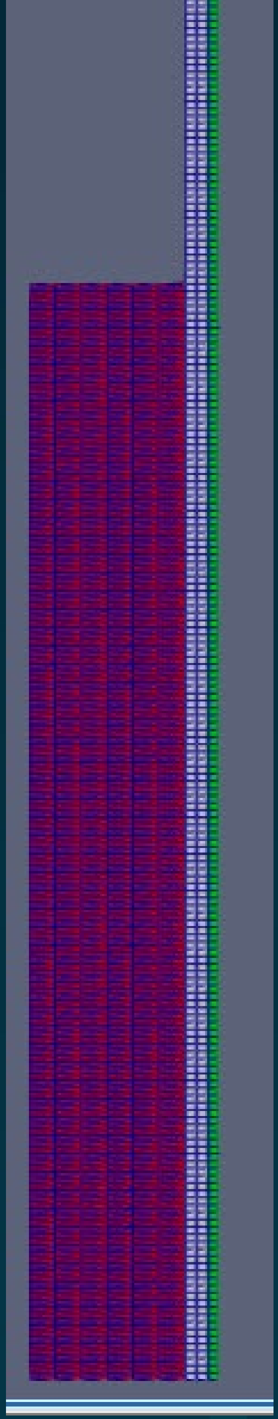
Assembly mesh (fueled region in grey)

SFR Example Single-physics Models

- Axial expansion on 2D RZ fuel + clad model
- Radial expansion on 2D support plate



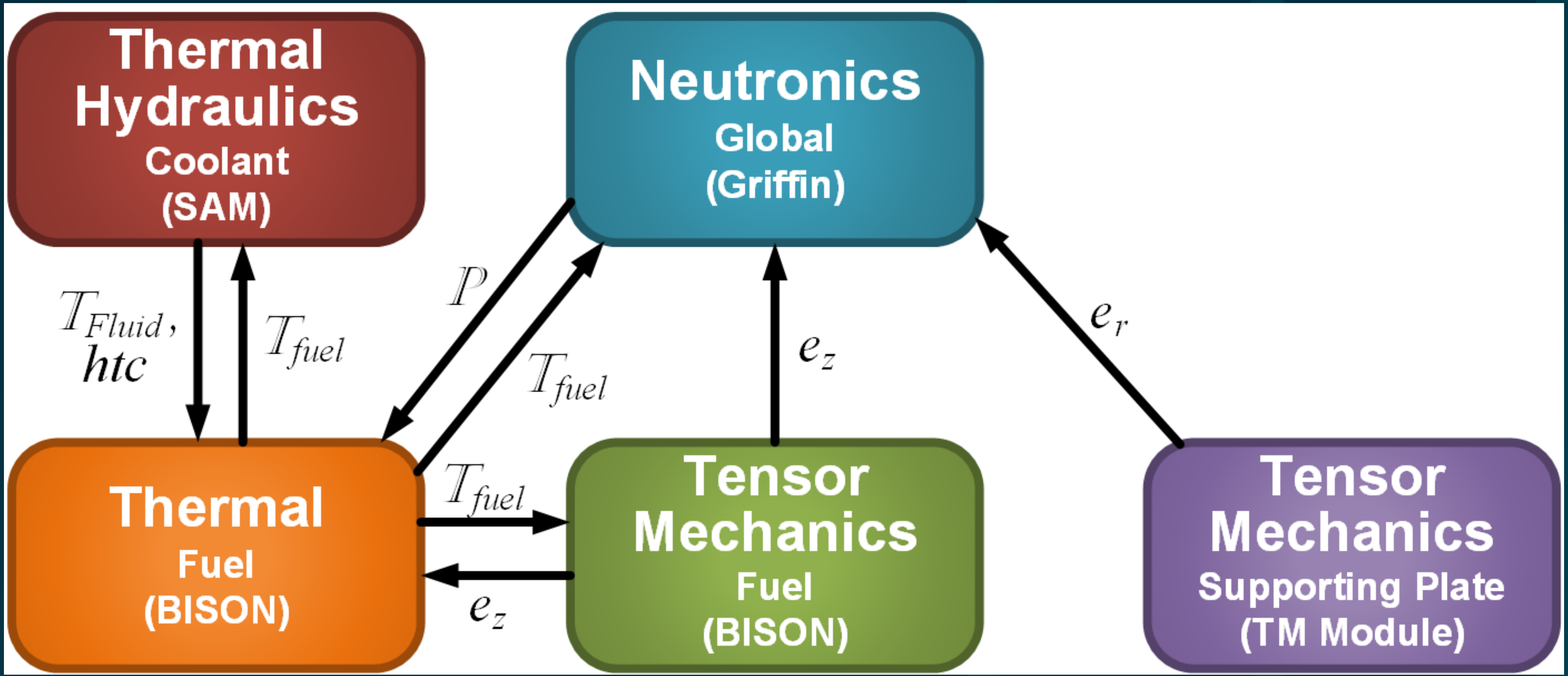
2D support plate



Axial pin Model
red: fuel
white & green: cladding

4) Workflow for Building Multiphysics Application

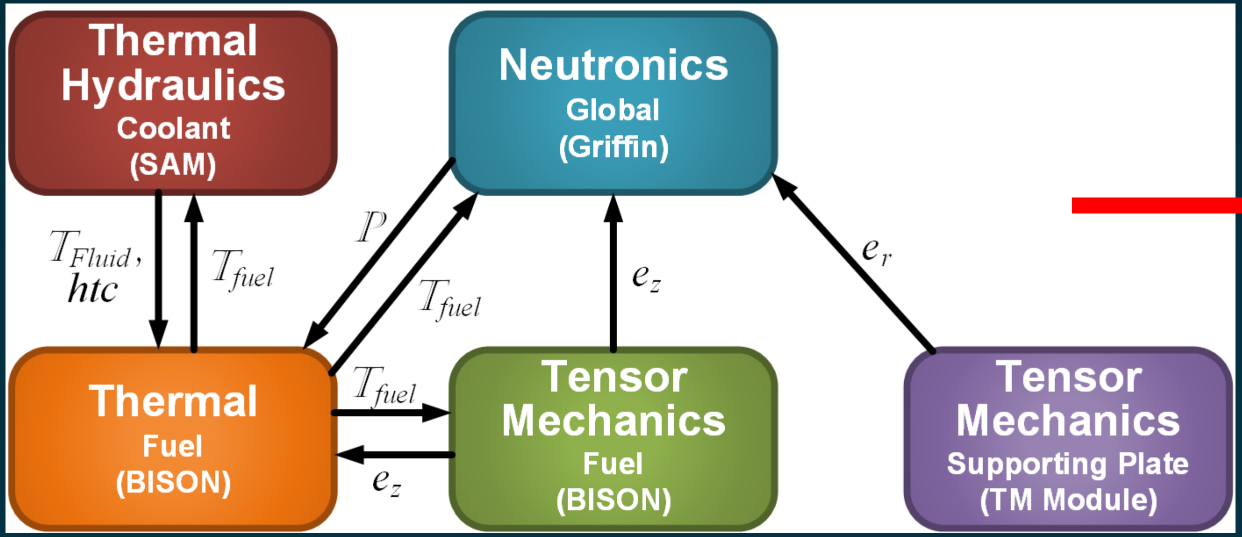
- Identify quantities involved in coupling physics

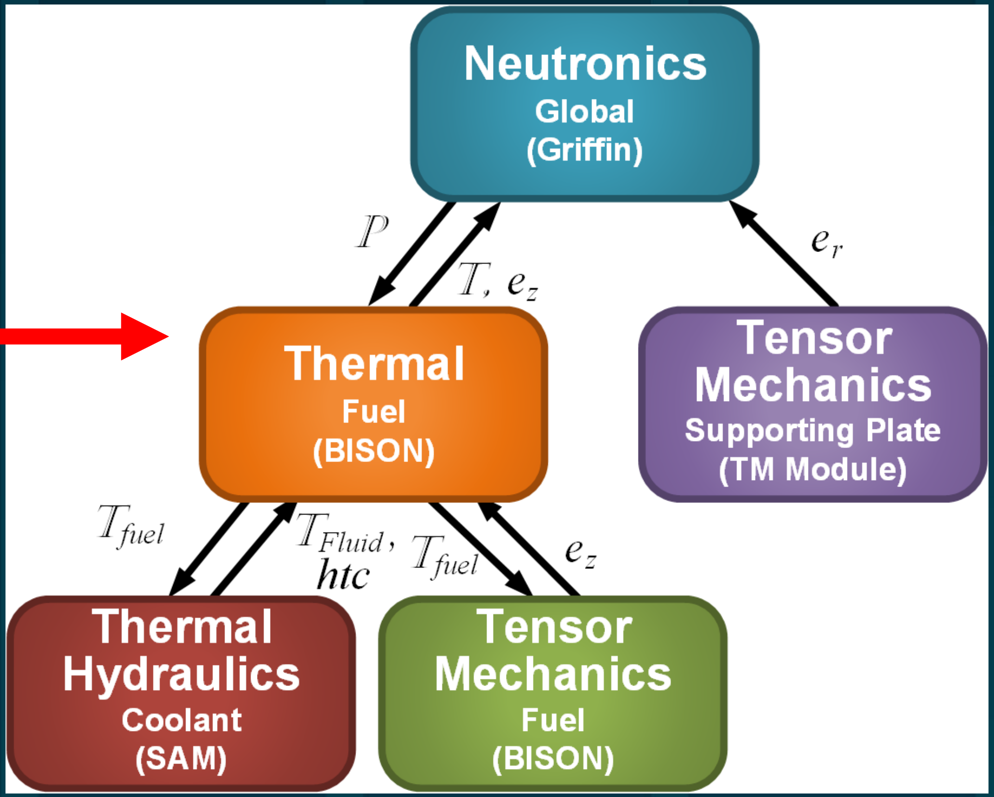


NRIC

4) Workflow for Building Multiphysics Application

- Determine MultiApps hierarchy





NRIC

5) MultiApps Timestepping

- Default behavior:

minimum timestep across apps forces synchronization

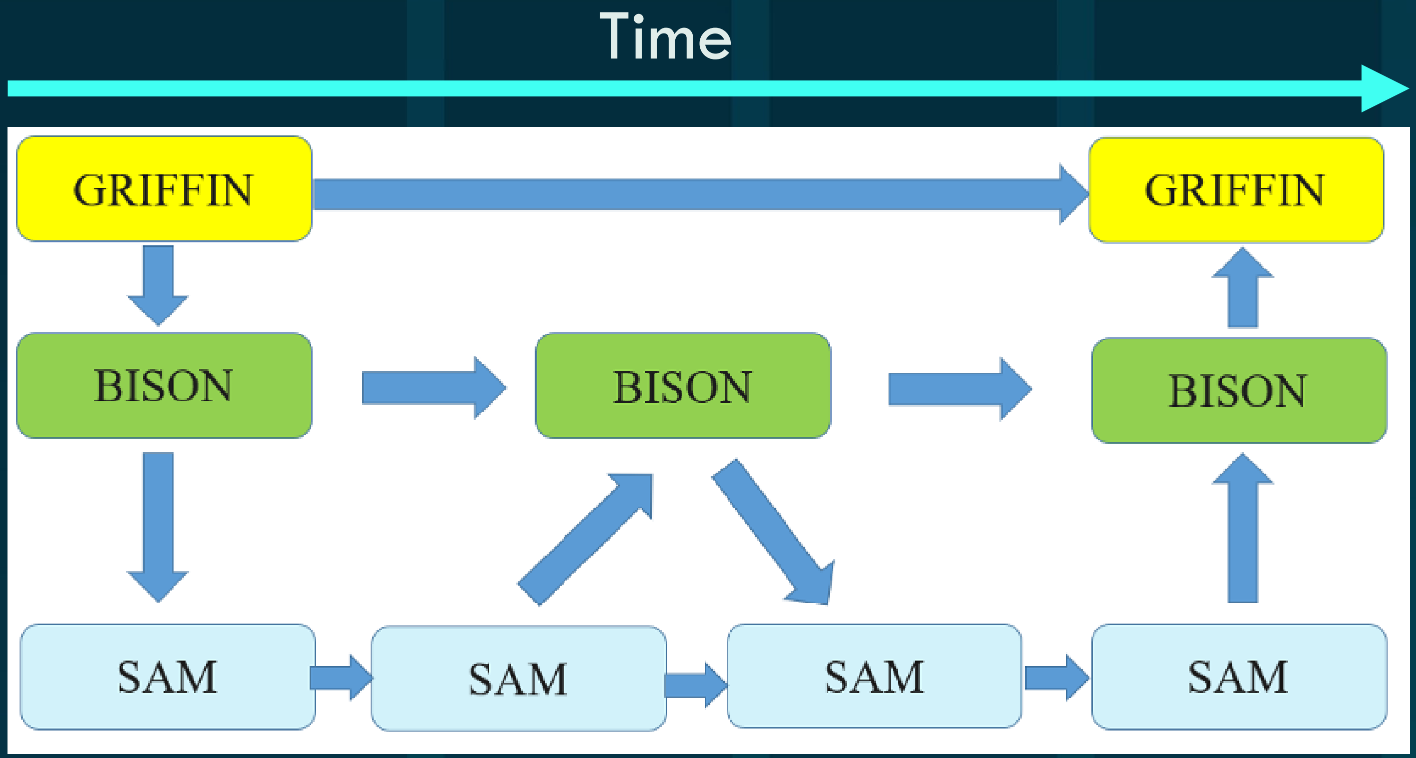
- Sub-cycles

Allows subapps to take smaller timesteps

→ **often main criteria for which app is the main app**

- Catch-up

Default + some crash-specific behavior



NRIC

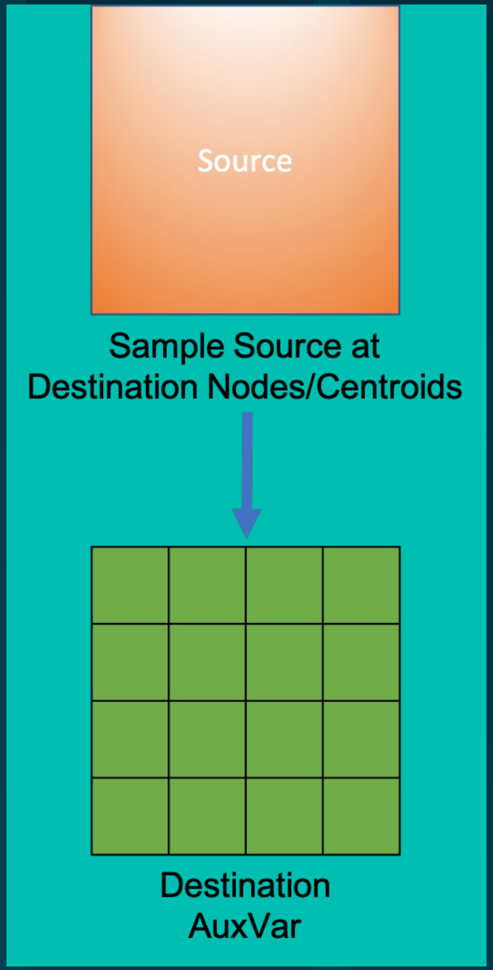
5) Other Features & Examples in the Tutorial

- Parallel capabilities and scheduling
- Nesting steady state solves
- Execution order
- Restart and recovery of simulations

NRIC

6) Transferring Information Between MultiApps

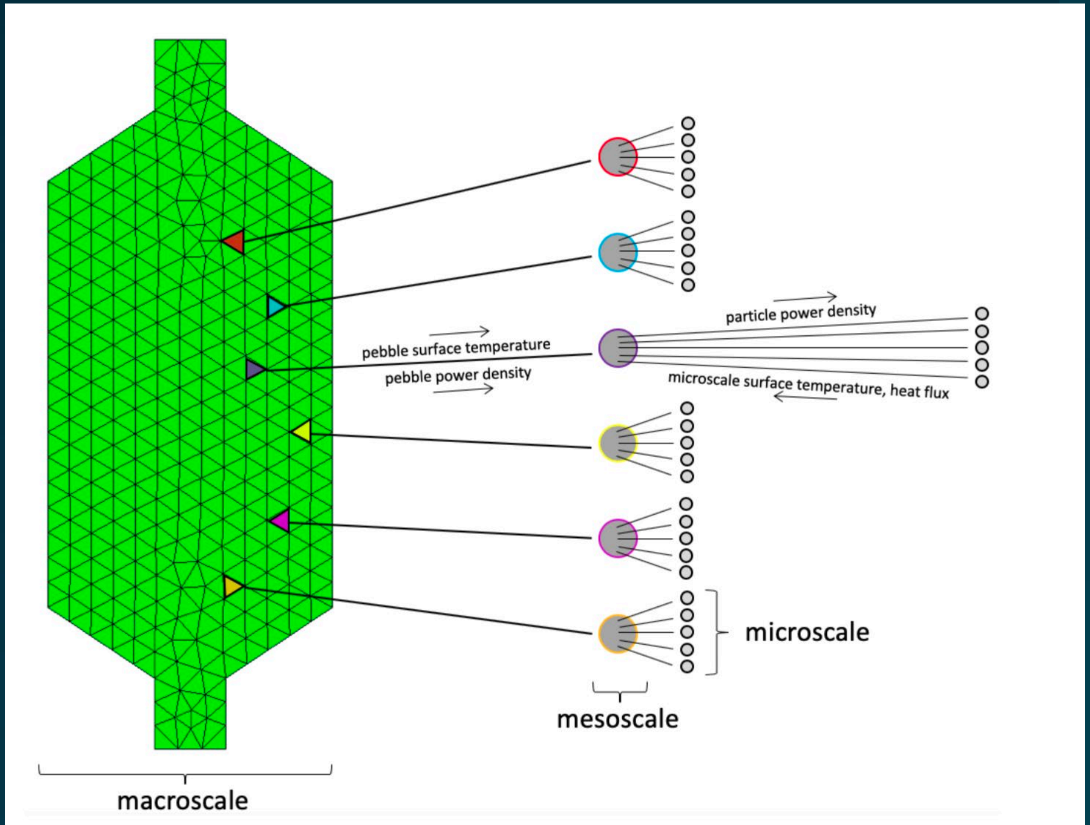
- Fields (spatially dependent)
  - Geometric interpolation
  - Shape function evaluation
  - Projection
  - Straight copy
- Scalar (one or few global numbers)
  - Postprocessors : MultiAppPostprocessorTransfer
  - Scalar variables: MultiAppScalarToAuxScalarTransfer
  - Reporters: MultiAppReporterTransfer

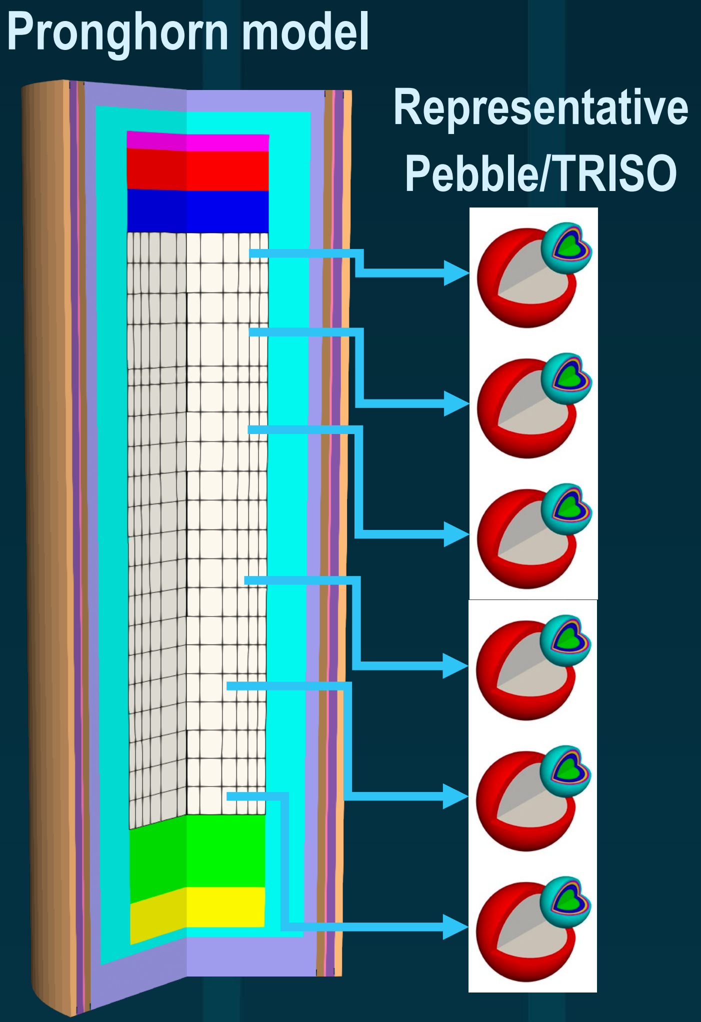


NRIC

6) Transferring Information Between MultiApps

- Conversion between types for multiple child apps and single main app





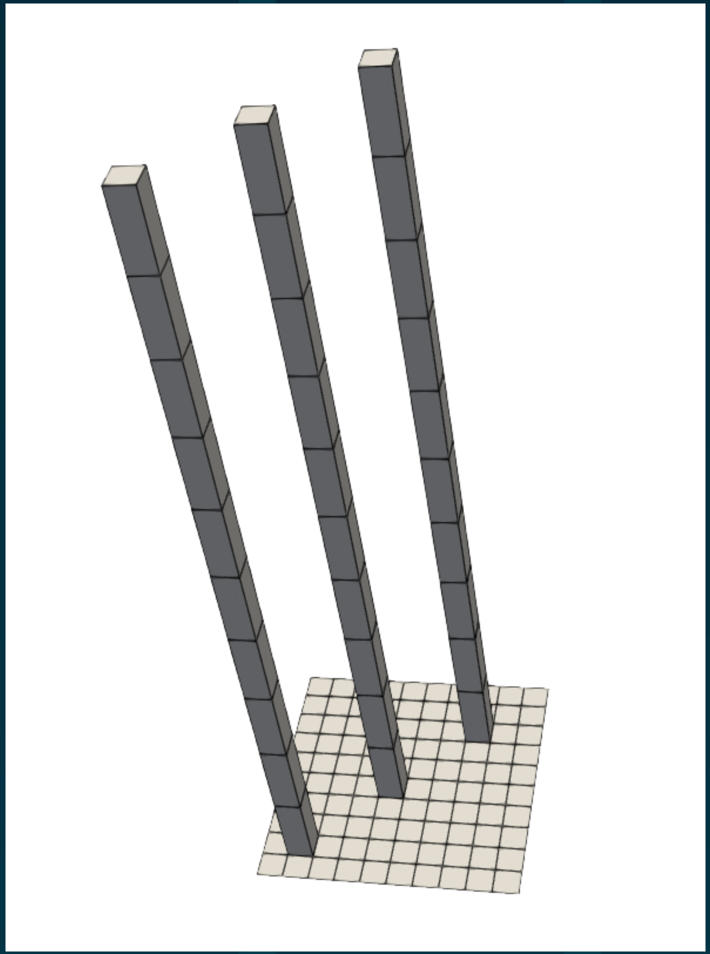
Credit: P. Balestra, Pronghorn (top)
A. Novak Ph.D. (left)

NRIC

6) Transferring Information Between MultiApps

- SFR example
- Fields:

Displacement: geometric interpolation & copy



6) Transferring Information Between MultiApps

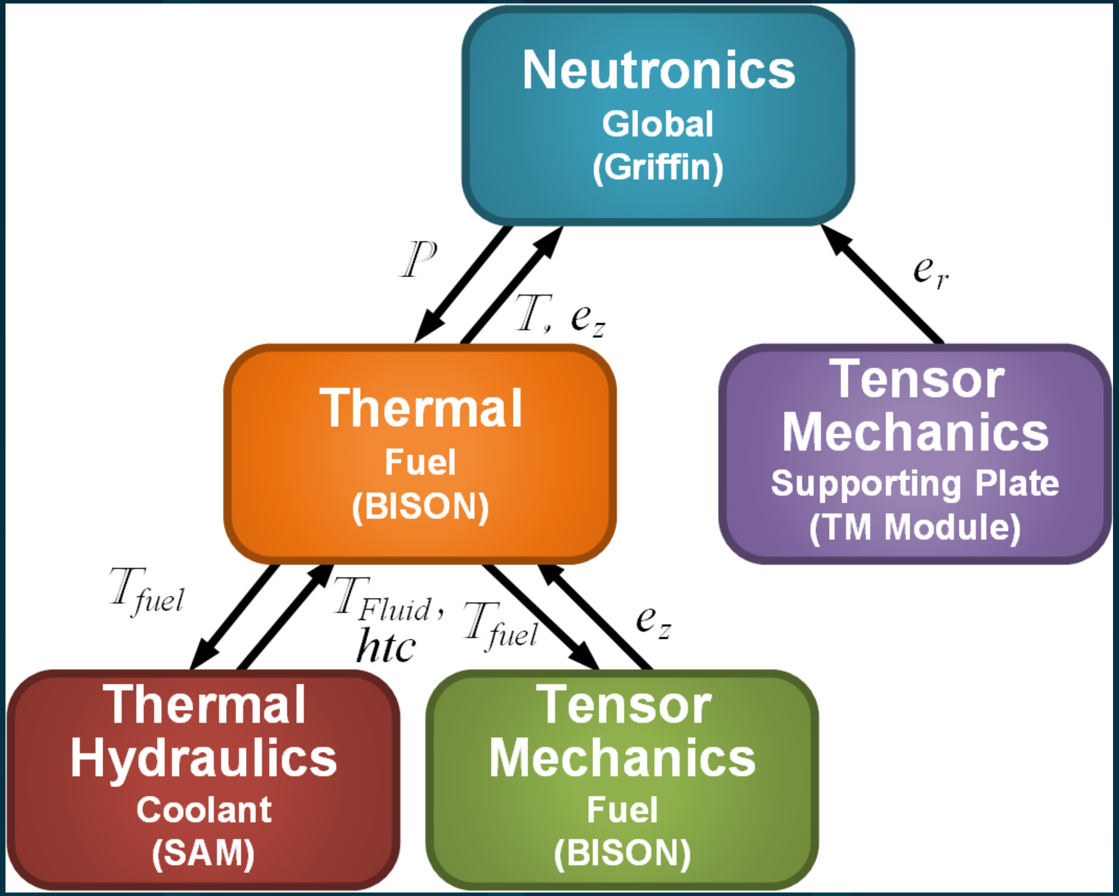
- SFR example
- Fields:

power_density: projection + conservation

displacement: geometric interpolation & copy

temperature: geometric interpolation
should it be conservative?

Optimizations: block restriction + fixed mesh



NRIC

6) Transferring Information Between MultiApps

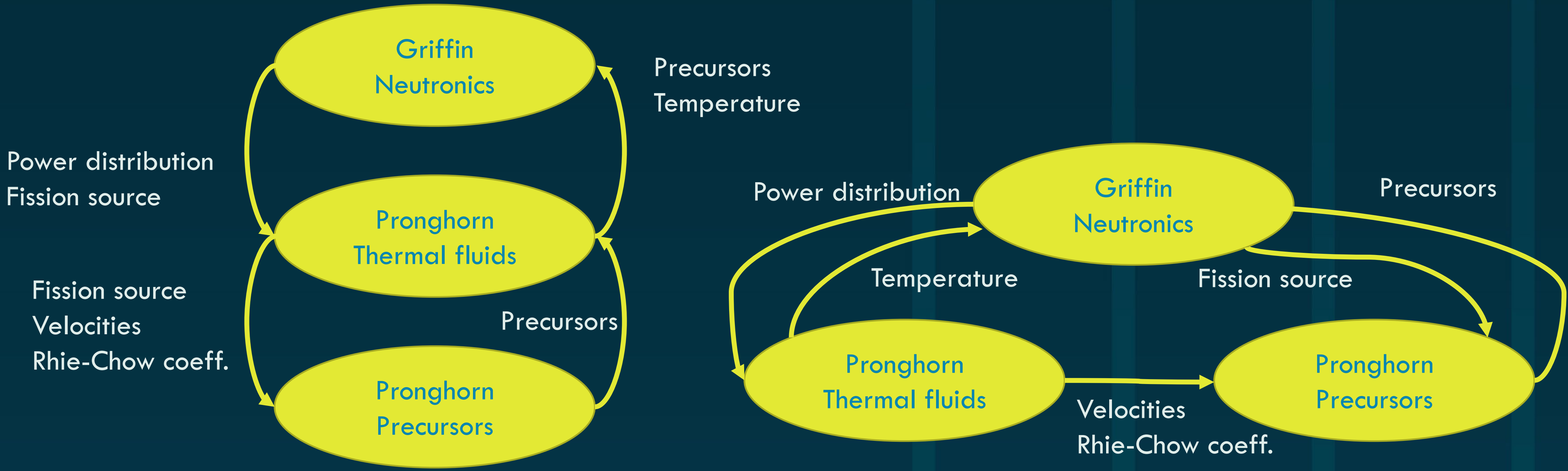
Numerous features:

- Block and boundary restriction
- Fixed mesh mapping caching
- Displaced source/target meshes
- Higher order variables
- Distributed meshes
- Multiple subapps, various parallel configurations
- Conservation of quantities
- Interpolation of transfers during sub-cycling
- Reduction operations (min/max/mean)
- Siblings transfer
- Coordinate transformation

NRIC

6) Transferring Information Between MultiApps

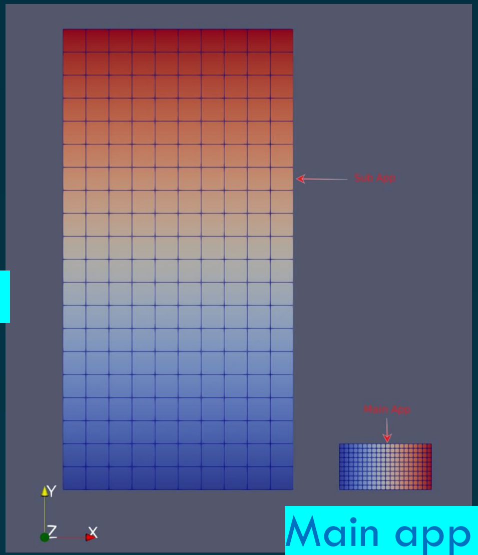
- Siblings transfer implemented in mid-FY22



NRIC

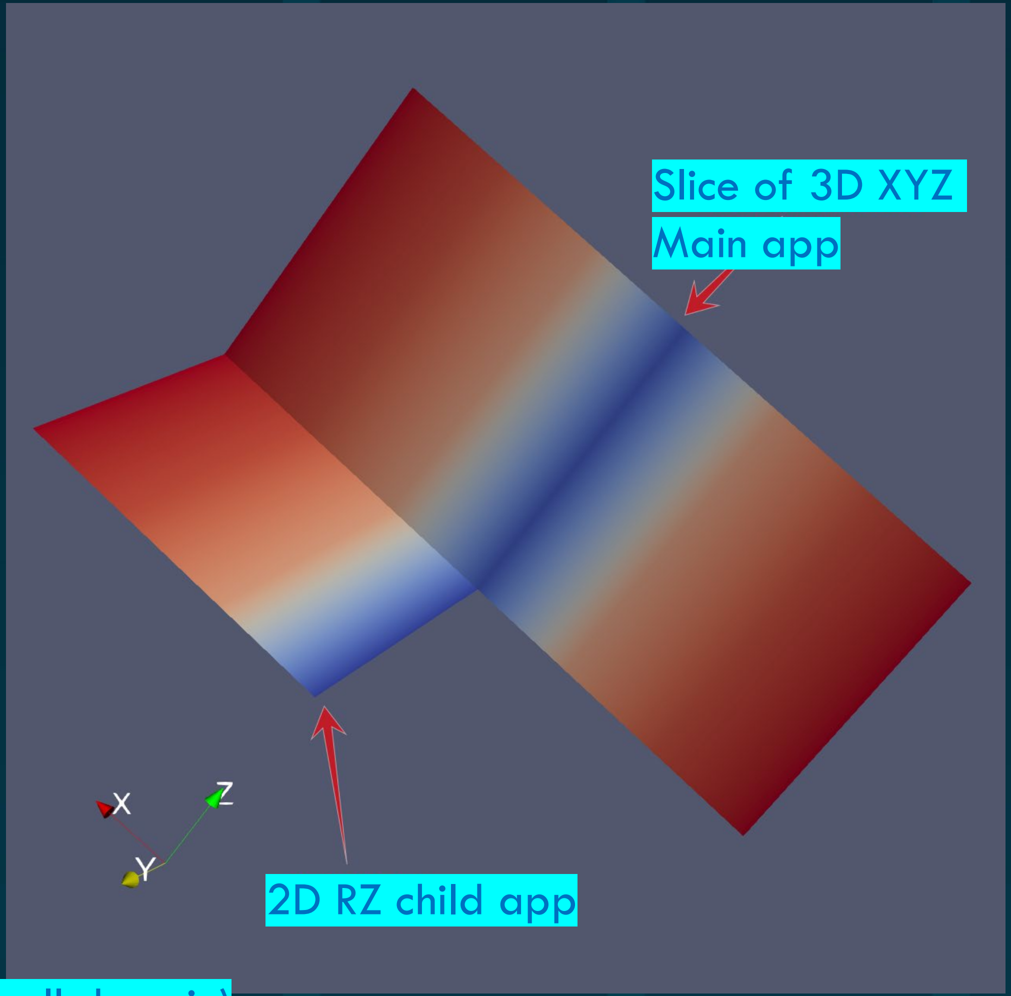
6) Transferring Information Between MultiApps

- Coordinate transforms
  - Rotation
  - Scaling
  - Translation (previously supported)
  - Collapsing between coordinates (XYZ, RZ, R-spherical)



Sub app (larger extent, scaled using transform)

Main app (small domain)



NRIC

7) Additional Resources (under construction)

- Debugging tips
- Known issues about transfers
  - Floating point comparisons with nearest nodes for example
- Dealing with coupling convergence issues
- Miscellaneous items - will be expanded

- Chapter 8 is FAQ

NRIC

Summary

- MultiApps are a very powerful and popular system in MOOSE
  - Splits each physics in a different input
  - Automatically handles parallelism, time stepping, and coupling iterations
  - Numerous native ways to transfer data between apps
- Tutorial on MOOSE website on general MultiApps
- Hosts a tutorial on using MultiApps for building nuclear reactor models
  - Uses the SFR (VTR) coupled multiphysics model
  - Necessitates Griffin, BISON & SAM, requestable at ncrc.inl.gov
- Several additional models on the VTB leverage MultiApps
  - Indexed under “Model Features”
- Virtual Test Bed (VTB) repository at: https://mooseframework.inl.gov/virtual_test_bed

- Credit to: A. Abdelhameed, A. Novak, A. Lindsay, D. Gaston, N. Martin for figures