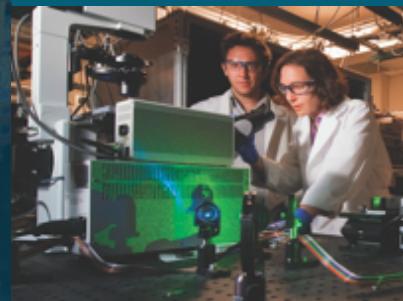


# Stanford ME469: Nalu Overview



*PRESENTED BY*

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Computational Thermal and Fluid Mechanics

Sandia National Laboratories SAND2018-4619 PE



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## 2 | Nalu Overview: Outline

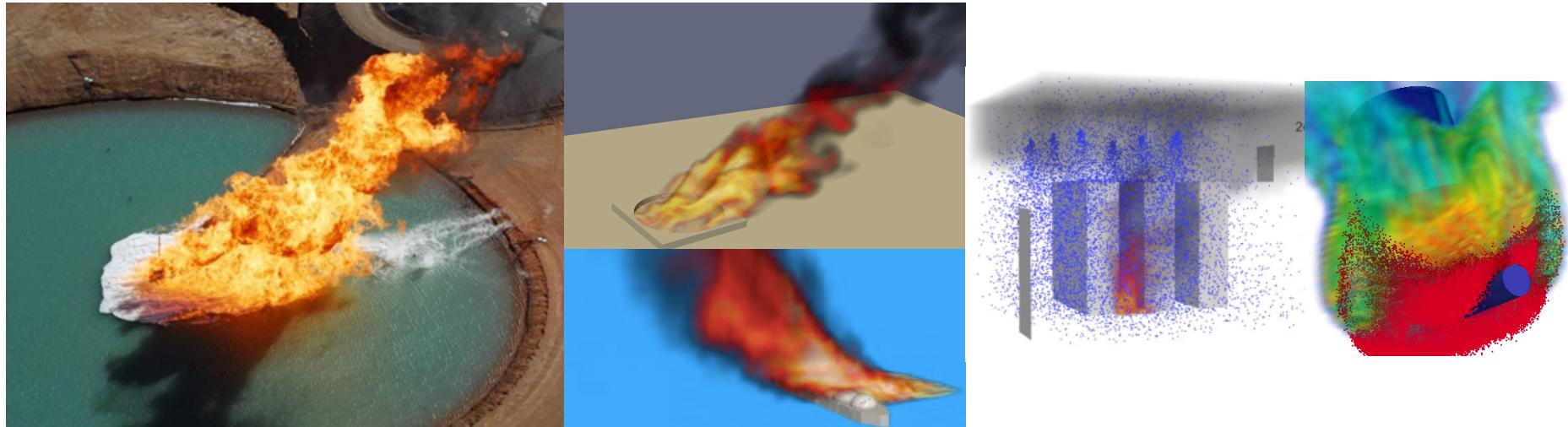


- Nalu Technology Origination: ASC
- Beyond the 32-bit Limit
- Supported Physics
- Supported Numerics
- Low- and High-order
- Moving Mesh (Sliding and Overset)
- Multiphysics:
  - Fluid Structure Interaction
  - Conjugate Heat Transfer (CHT)
  - Participating Media Radiation
- Examples
- Conclusion

## Core Technology Provided to Nalu Origination: Advanced Simulation and Computing Sierra/Fuego



- Use-case characterized by a highly sooting, turbulent, reacting flow with Participating Media Radiation (PMR), Conjugate Heat Transfer (CHT), and propellant multi-physics coupling

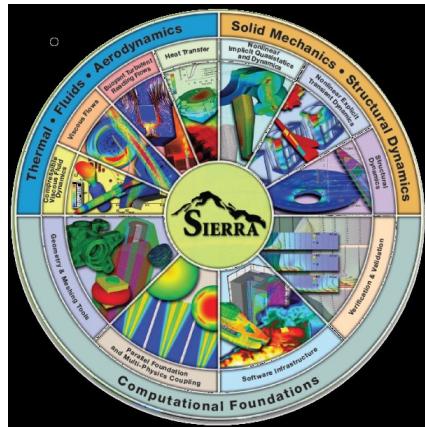


- Complex geometry has driven a generalized, hybrid unstructured discretization approach supporting Hex8, Tet4, Wedge6, and Pyramid5 elements in addition to arbitrary promotion of Hex8 to Hex27, Hex64, etc.

## 4 Goal: Beyond 32-bit Computing



- Circa 2013, many scientific production codes were limited to 32-bit
- Therefore, maximum simulation size for entities, e.g., node, edge, face, element, etc., was ~2.2 billion
- Next Generation Platforms were advocated to overcome poor MPI scaling and power needs to support Exascale computing ( $10^{18}$  floating point operations/second)
  - Platform architectures are not yet known

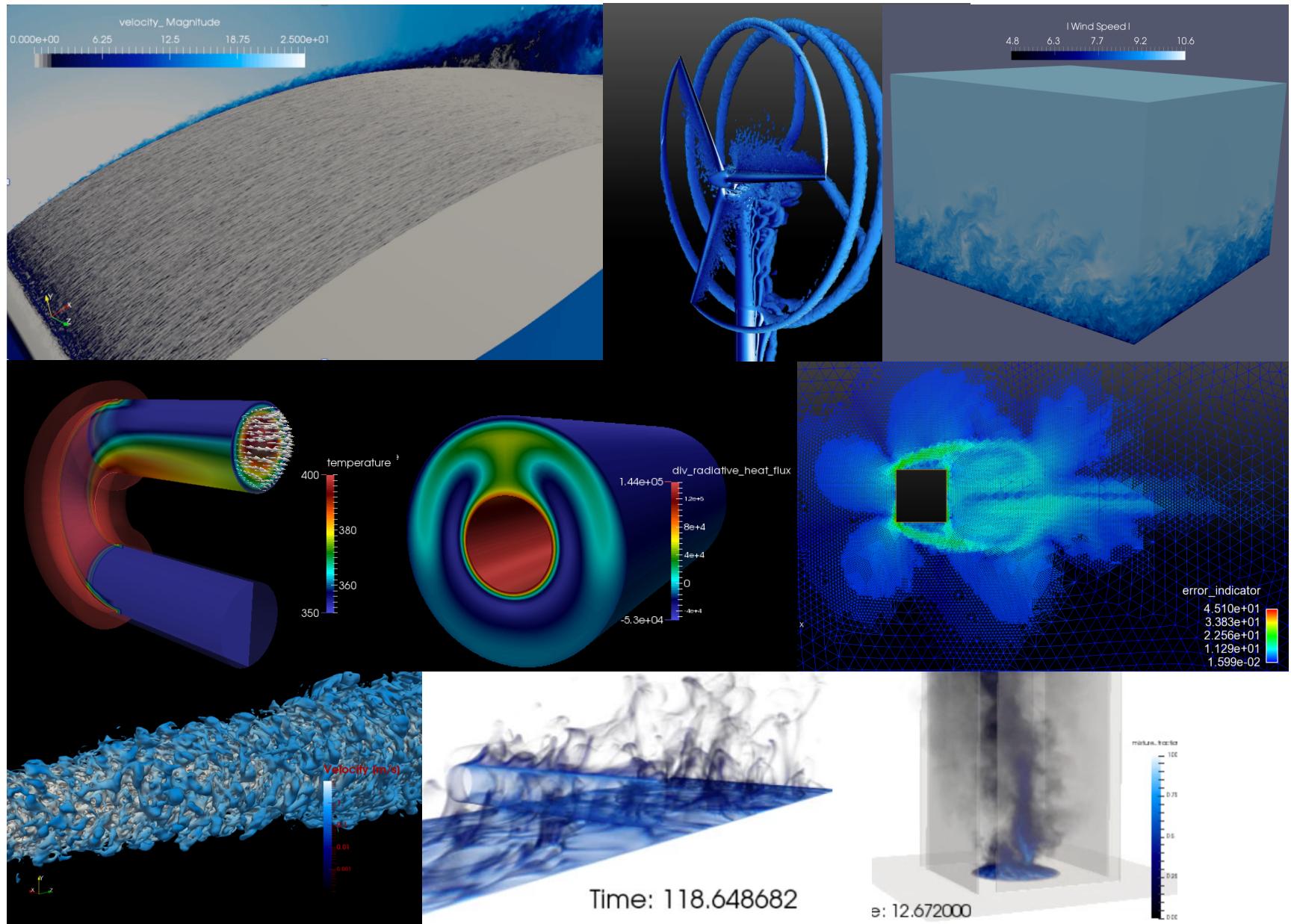


+ ASC IC  
Investments



Sierra Toolkit/Trilinos (open-source)  
MPI+X parallelism  
Support for new architectures

## Supported Physics



## 6 Developed Open-Source BSD-clause 3 Distribution Policy



- Philosophy: Open-source collaborations

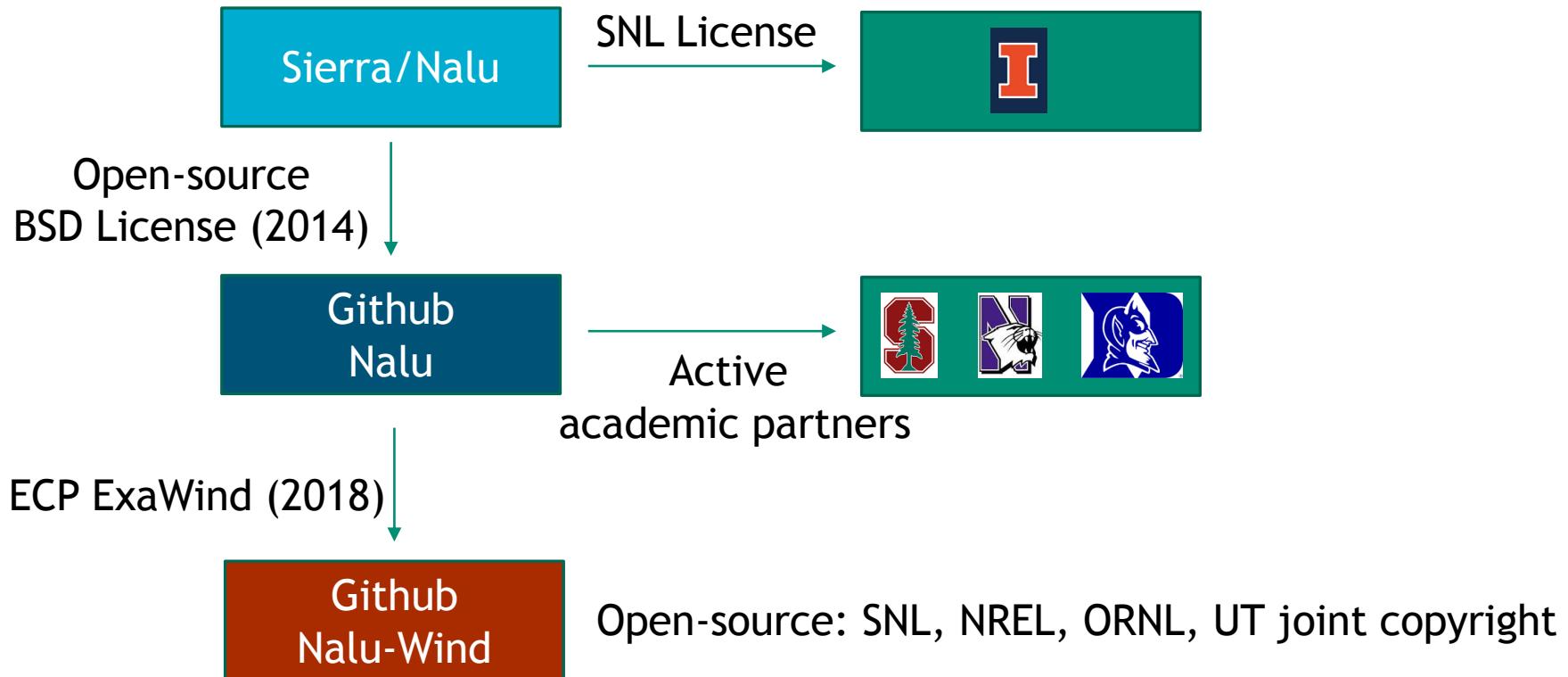


<https://github.com/NaluCFD>





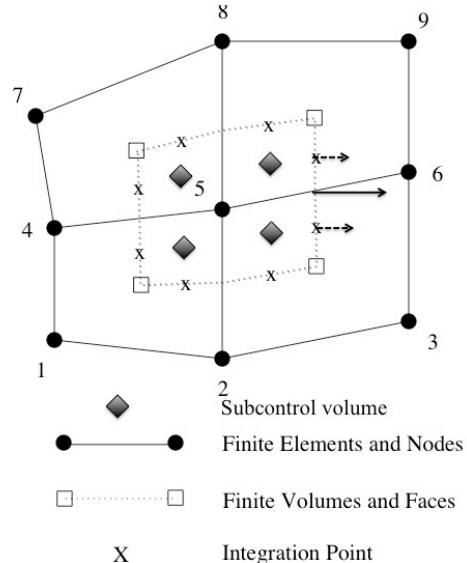
- A time-history of the Nalu code base:
- By CFD standards, this is a relatively new code base



## 8 | Supported Discretizations: CVFEM/FEM/EBVC



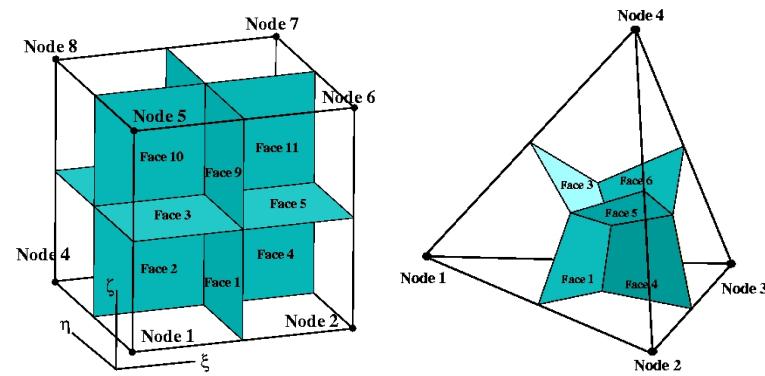
- The core discretization used in the low Mach code base has been the Control Volume Finite Element Method, CVFEM
- Finite Element Method and Edge-based Vertex-Centered, EBVC, are also supported



$$\int w \frac{\partial \bar{\rho} \tilde{u}_j \tilde{\phi}}{\partial x_j} d\Omega = - \int \bar{\rho} \tilde{u}_j \tilde{\phi} \frac{\partial w}{\partial x_j} d\Omega + \int w \bar{\rho} \tilde{u}_j \phi n_j d\Gamma$$

$$w = w_I; \frac{\partial w_I}{\partial x_j} = -\delta(x - x_{scs})$$

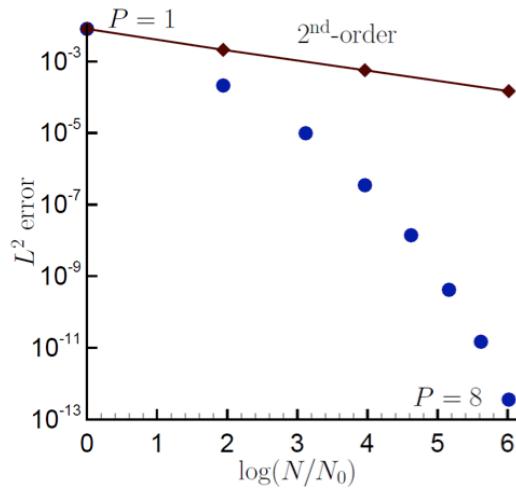
$$\int w \frac{\partial \bar{\rho} \tilde{u}_j \tilde{\phi}}{\partial x_j} d\Omega = \sum_{ip} (\bar{\rho} \tilde{u}_j)_{ip} \tilde{\phi}_{ip} n_j dS = \sum_{ip} \dot{m}_{ip} \tilde{\phi}_{ip}$$



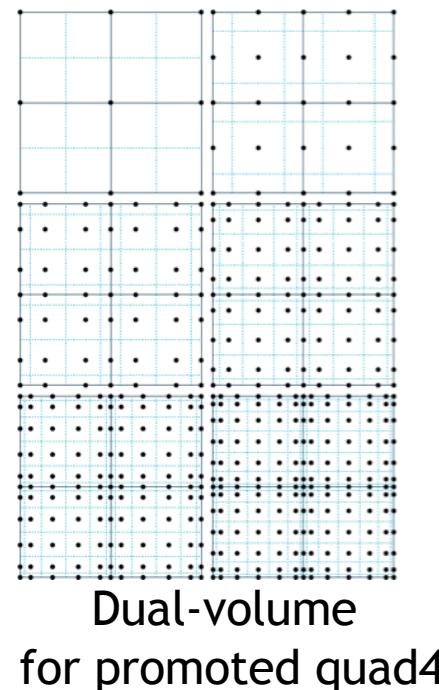
# Scientific Research Platform to Evaluate Higher-Order Methods on Next Generation Platforms



- As the cost of parallel assembly increases, should we strive to perform more local work? Higher-order achieves this design-point (at the cost of a larger memory footprint)



Spectral convergence



Time: 0.055000

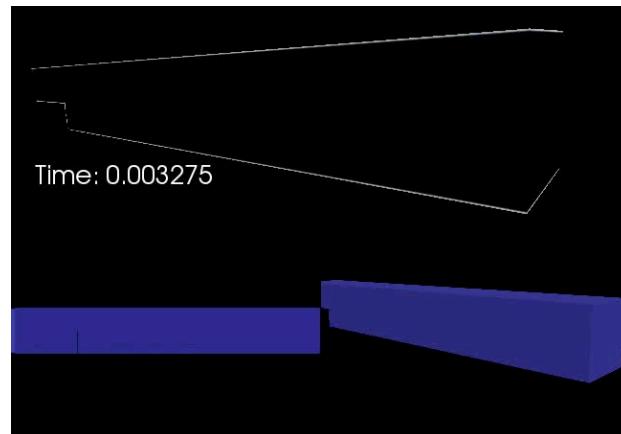
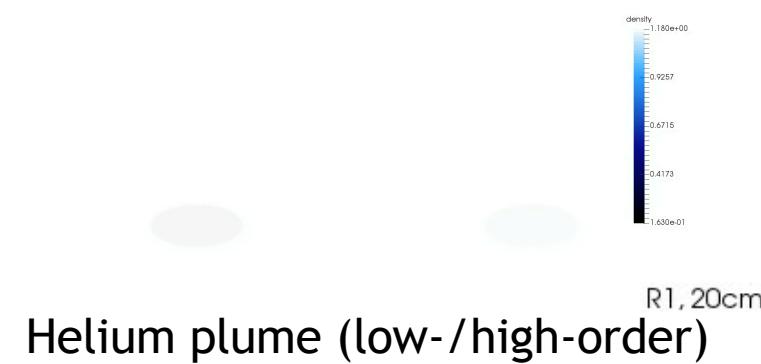


Time: 0.055000

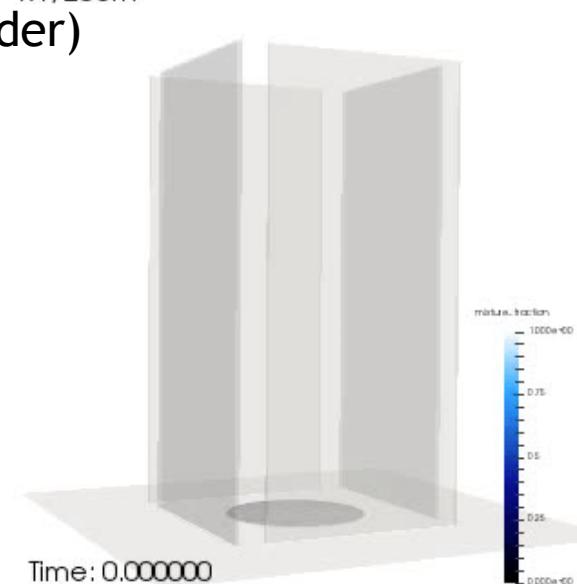


Flow-past rotating cube  
Re~4000, RPM~3200  
Same node count,  
 $P=1$  (top)  $P=2$  (bot)

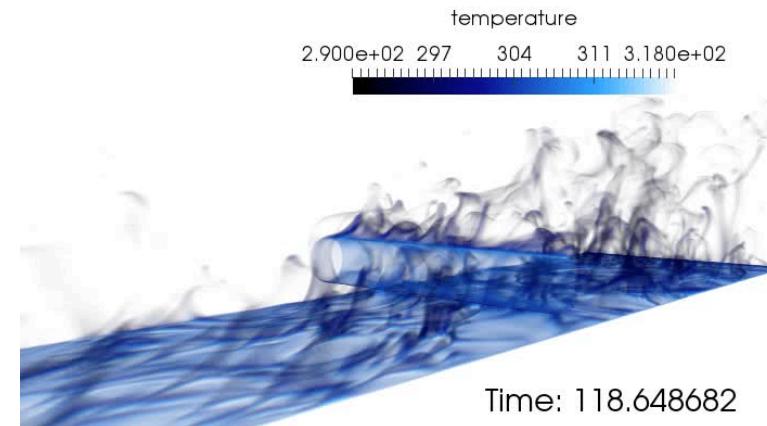
## Several Multi-physics Flow Examples



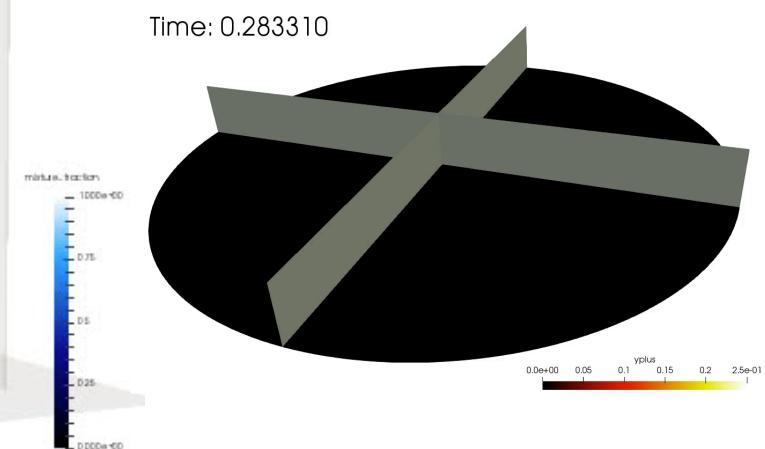
Heated backstep



Whirling behavior



Cylinder in cross flow



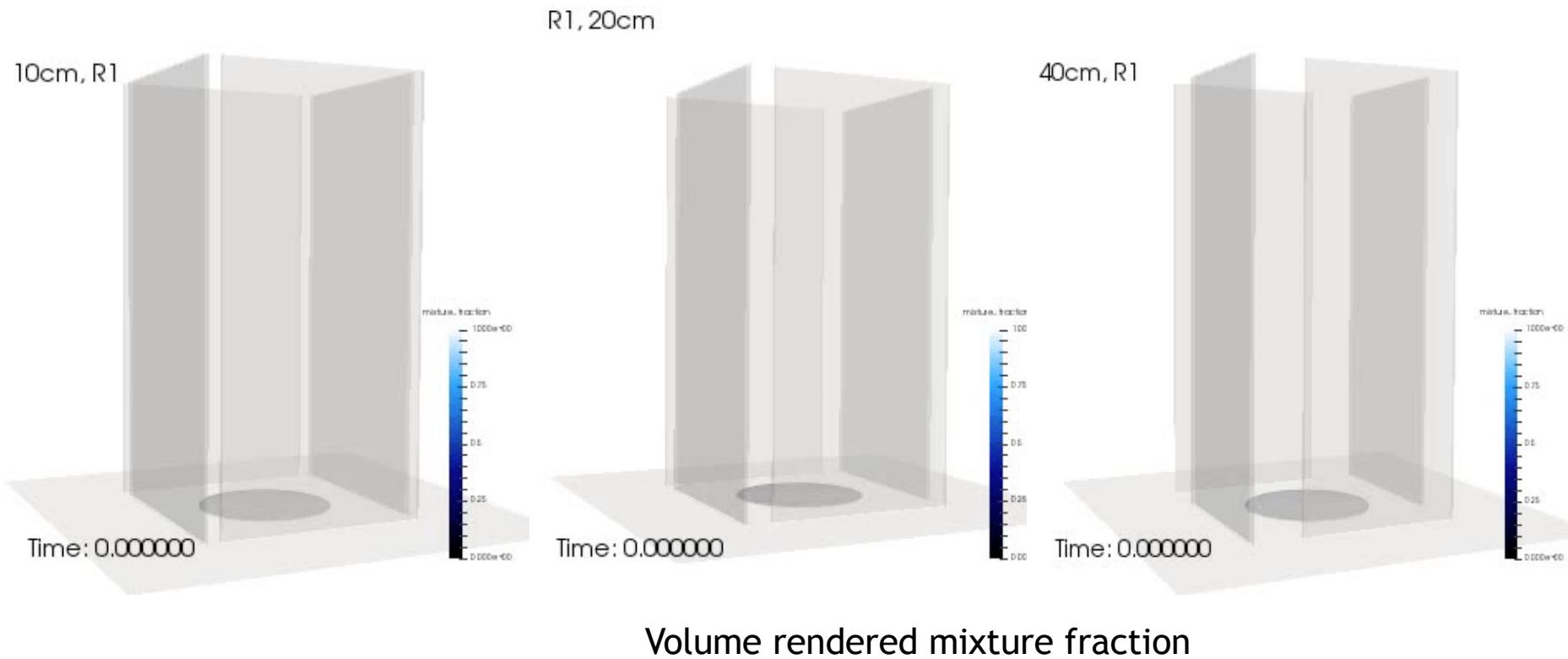
Impinging Jet DNS

## Evolution of a Mindset..... Modeling Whirling-like Flow



SAND2019-7052 C

- Idealized chamber in which swirl is provided by selective wall placement in the experimental design
- Gap varied between 10, 20, and 40 cm
- Objective: Can the onset of swirl be predicted? What is the strength?

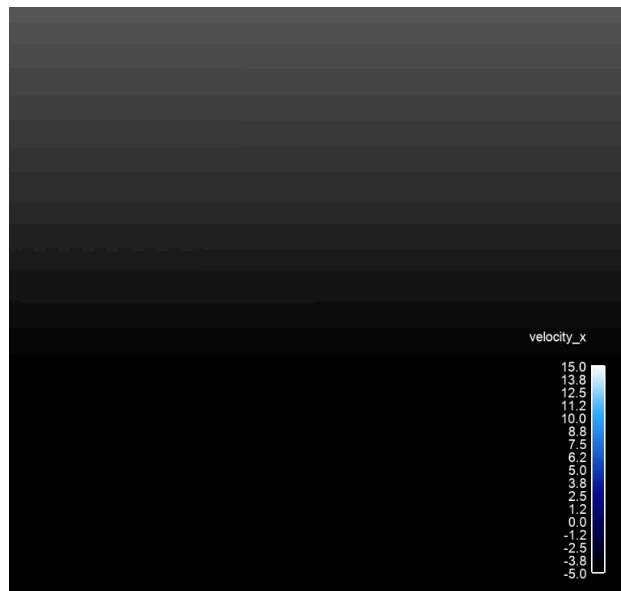


## Unique Wind Energy Needs

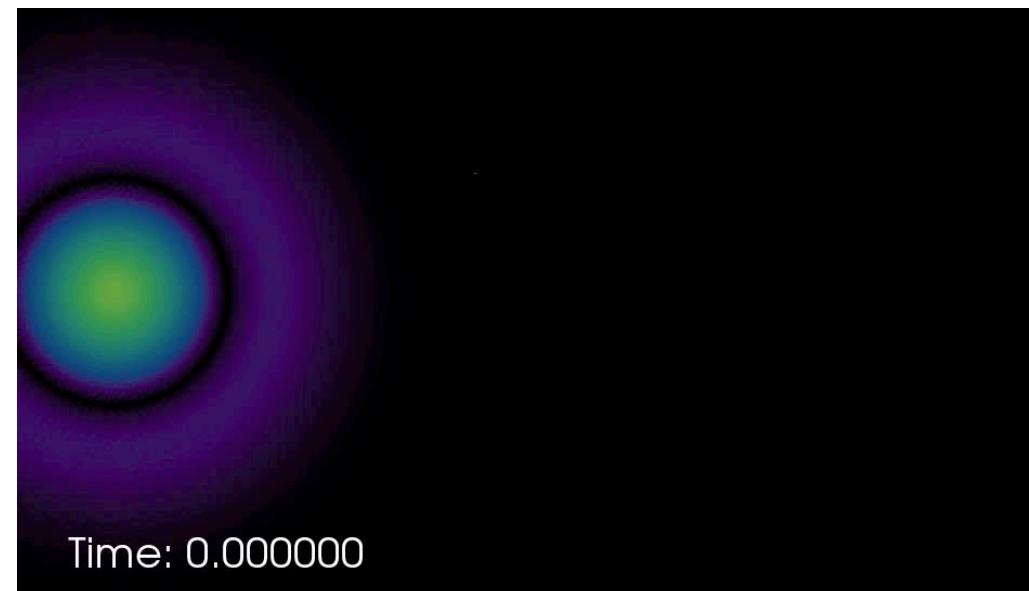


- Low-dissipation methods with suitable nonlinear stabilization operators to perform blade-resolved physics
- Complex rotating blades, pitching blades, with possible yaw
- Transition from low-order (near the blade) to higher-order (in the wake)

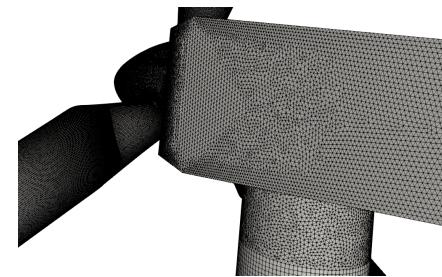
Generalized, unstructured, hybrid low-order simulations shown

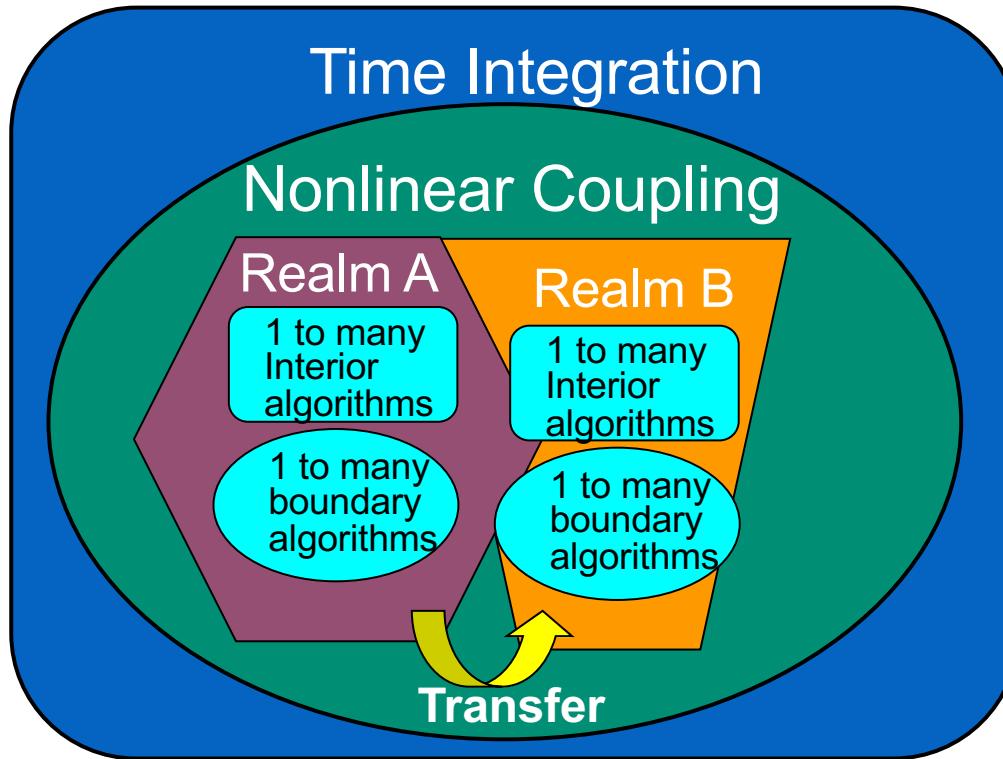


Horizontal Axis Wind Turbine  
(HAWT)

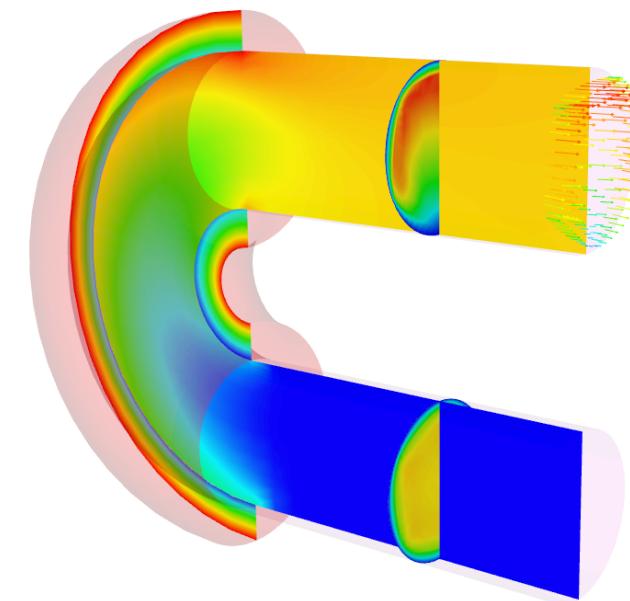


Vertical Axis Wind Turbine  
(VAWT)





- *Realm* specifications define the physics and desired boundary conditions
- Pre-defined *EquationSystems* (segregated or monolithic)



- Operator-split multi-physics  
Conjugate heat transfer coupling
- Fluids Realm
  - Heat Conduction Realm

## 30K View: Anatomy of a Nalu Input File: YAML-based



Simulation:

linear\_solvers: ← Specification of sparse Trilinos-based precond/solver

transfers: ← Data transfer for multi-physics coupling

realms:

YAML enforces strict spacing and ordering

- name: realm\_heatCond

- boundary\_conditions:

- wall\_boundary\_condition: bc\_exposed

- solution\_options:

- initial\_conditions:

- material\_properties:

- equation\_systems:

- systems:

- HeatConduction:

- output:

- restart:

- name: realm\_fluids

TimeIntegrators:

Physics definitions



<https://www.democraticunderground.com/10021540110>

← Time integration, e.g., BE, BDF2

## High-Level Elements of an Input File



systems:

- LowMachEOM:  
name: myLowMach
- MixtureFraction:  
name: myZ

initial\_conditions:

- constant: ic\_1  
target\_name: [block\_1, ...]  
value:  
pressure: 0  
velocity: [0.5,0.0]  
mixture\_fraction: 0.0

boundary\_conditions:

- inflow\_boundary\_condition: bc\_left\_inflow
- wall\_boundary\_condition: bc\_front\_wall
- open\_boundary\_condition: bc\_right\_open
- symmetry\_boundary\_condition: bc\_top
- nonconformal\_boundary\_condition: bc\_nc

material\_properties:

target\_name: block\_1

specifications:

- name: density  
type: constant  
value: 1.0

- name: viscosity  
type: constant  
value: 1.8e-5

material\_properties:

target\_name: block\_1

specifications:

- name: density  
type: ideal\_gas

- name: viscosity  
type: polynomial  
coefficient\_declaration:

- inflow\_boundary\_condition: bc\_left  
target\_name: surface\_1  
inflow\_user\_data:  
velocity: [0.5,0.0,0.0]  
mixture\_fraction: 0.0

- wall\_boundary\_condition: bc\_back  
target\_name: surface\_7  
wall\_user\_data:  
user\_function\_name:  
velocity: wind\_energy  
user\_function\_string\_parameters:  
velocity: [mmTop\_ss7]  
mixture\_fraction: 1.0



- All input files are part of the Nalu regression test suite: Nalu/reg\_test/test\_files
- Mesh files are found under: Nalu/reg\_test/mesh
  - Formally, /mesh is a git submodule

Test Cases Highlighted:

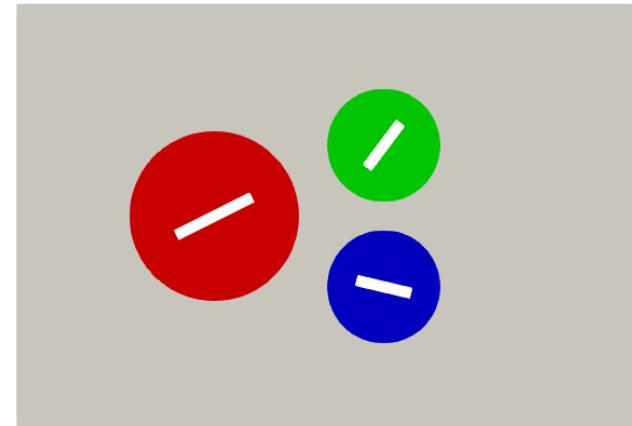
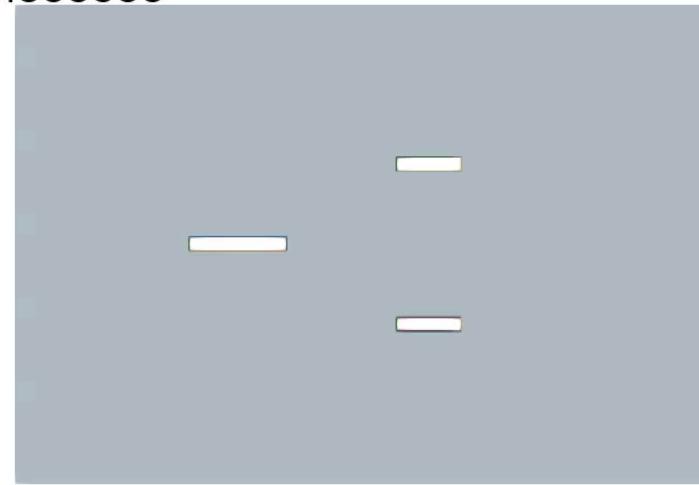
1. Nalu/reg\_tests/test\_files/dgNonConformalThreeBlade
2. Nalu/reg\_tests/test\_files/fluidsPmrChtPeriodic
3. Homework #1:
  1. <https://github.com/spdomin/Present/tree/master/standformMe469/hwOne>
    - Feel free to run any case that you feel looks interesting to you!
    - Note that the regression test suite is (mostly) focused on providing code coverage and may not represent “sane” physics-based choices

Resource: <https://nalu.readthedocs.io/en/latest/source/theory/index.html>

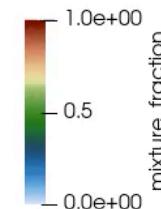


- Physics
  - Flow past rotating square blades ( $Re = 10,000$ )
- Models
  - Newtonian fluid (air) with constant properties
- Boundary Conditions
  - Inflow, open, symmetry, DG/CVFEM interface

Time: 0.000000



Domino, JCP, 2018



```
>mpirun --np 4 /naluPath/naluX -i dgNonConformalThreeBlade.i &
```

## Nalu/reg\_tests/test\_files/dgNonConformalThreeBlade



$U\Delta t / \Delta x$

Time Step Count: 7 Current Time: 0.0127268  
 $dtN: 0.00266002 dtNm1: 0.00231306$  gammas: 1.53488 -2.15 0.615116

Max Courant: 1.54421 Max Reynolds: 236.792 (realm\_1)  
 Realm Nonlinear Iteration: 1/1

$\rho U L / \mu$

realm_1::advance_time_step()		Linear Iter	Linear Res	NLinear Res	Scaled NLR
NLI	Name	-----	-----	-----	-----
1/2	Equation System Iteration	equations	4 9 19 20 5 5	1.27653e-07 5.17721e-06 4.2818e-09 9.70201e-09 1.31346e-09 6.33586e-09	1 1 1 1 1 1
	myLowMach				
	MomentumEQS				
	ContinuityEQS				
	PNGradPEQS				
	PNGradUEQS				
	myZ				
2/2	MixtureFractionEQS	5	8.33682e-10	2.23818e-06	0.0128842
	PNGradZEQS				
	Equation System Iteration				
1/1	myLowMach				
	MomentumEQS				

nonlinear iterations

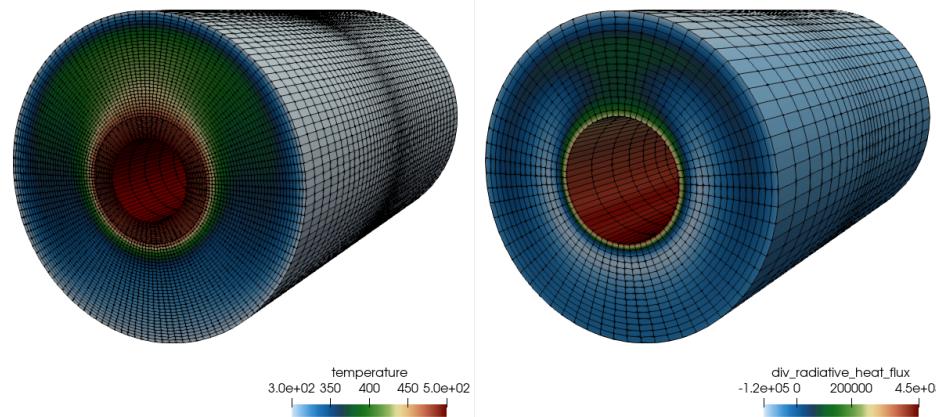
Mass Balance Review:  
 Density accumulation: 0  
 Integrated inflow: -0.375  
 Integrated open: 0.3749998354138842  
 Total mass closure: -1.64586e-07  
 Mean System Norm: 0.0002458198407611864 7 0.0127268

Review

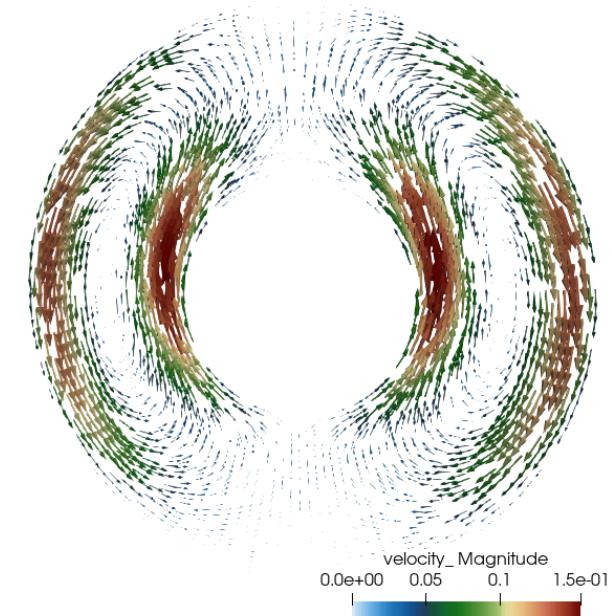
## Nalu/reg\_tests/test\_files/fluidsPmrChtPeriodic



- Physics
  - Uniformly emitting/absorbing participating media radiation (PMR) conjugate heat transfer (CHT) with buoyancy
- Models
  - Newtonian fluid (air): ideal gas
- Boundary Conditions
  - Wall, periodic



```
>mpirun --np 8 /naluPath/naluX -i fluidsPmrChtPeriodic.i &
```

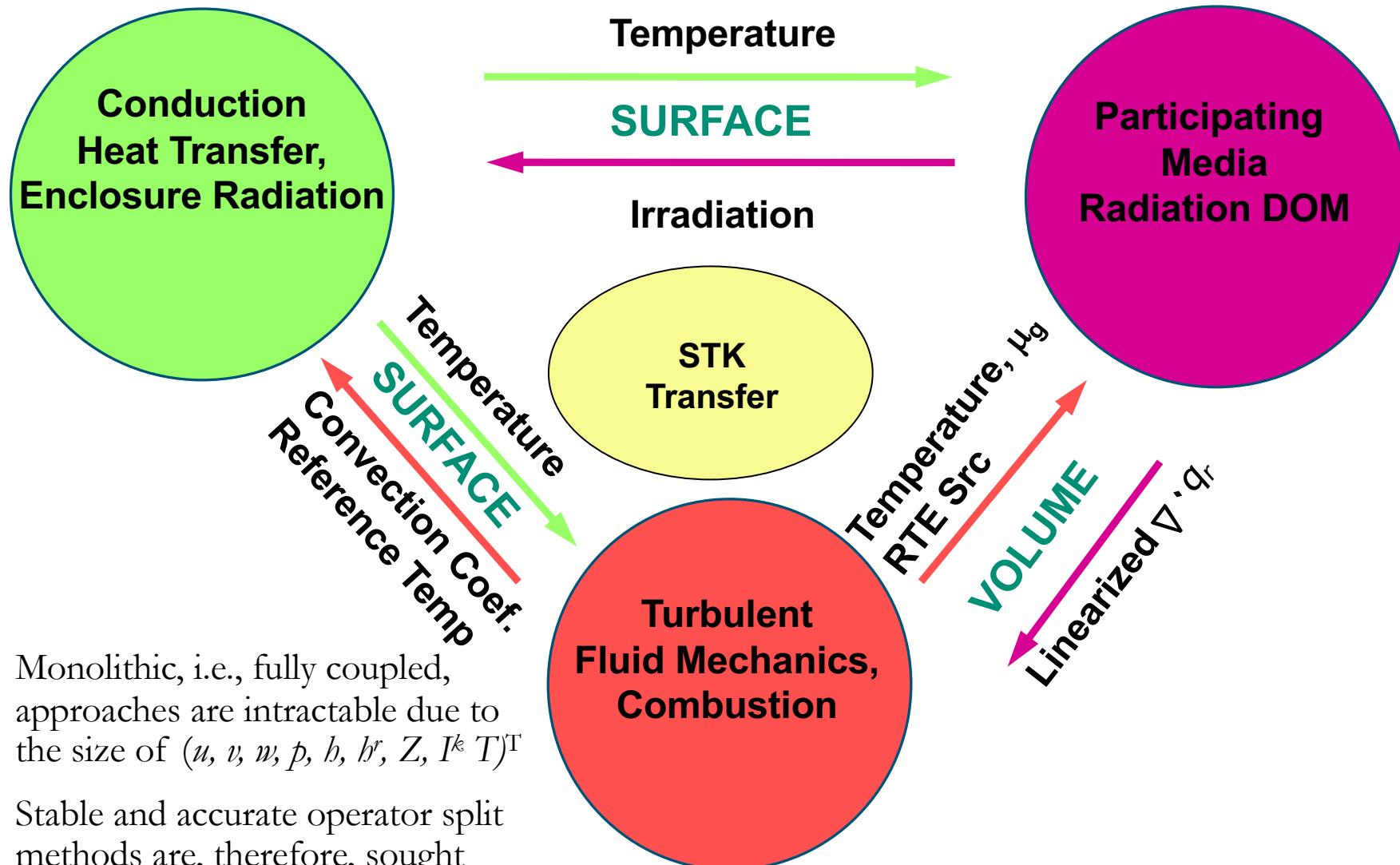


$$\text{Stark\#}, \text{cond/rad}$$

$$Sk = \lambda \mu / \sigma T_i^3 \sim 0.4$$

$$\text{Rayleigh\#}, \tau^{\text{ThermalDiff}} / \tau^{\text{Conv}}$$

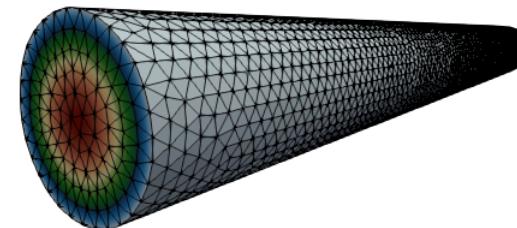
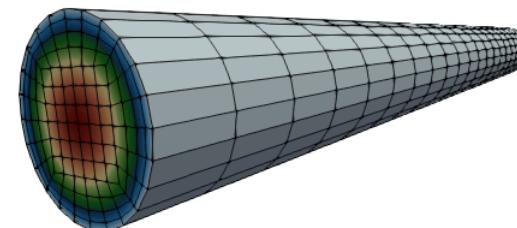
$$Ra = g \beta (T_i - T_o) L / Pr \alpha^2 \sim 2e6$$



## Laminar Pipe Flow: Specified Pressure Drop for $Re^\tau = 10$



- Physics
  - Laminar pipe flow (specified pressure drop)
- Models
  - Newtonian fluid (air): ideal gas
- Boundary Conditions
  - Wall, open (pressure specified)
- Location:  
<https://github.com/spdomin/Present/tree/master/stanfordMe469/hw/one>
- Specifications:
  - $Re^\tau = 10$
  - Pipe diameter,  $D = 0.01 \text{ m}$
  - Pipe Length,  $L = 0.2 \text{ m}$
  - $\rho = \text{TBD}$
  - $\mu = \text{TBD}$
  - $dp/dz = \text{TBD}$
  - $U_c = \text{TBD}$





- Nalu's technology has its roots in the ASC Sierra/Fuego effort
- Multi-physics capabilities are in development
- Research platform for high-order low-Mach methods
- Open-source collaboration model
- Funded through ASC, ECP, A2e, ASCR, and LDRD