Geometric Multi-Scale Coupling

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Seminar: Partitioned Fluid Structure Interaction and Multiphysics Simulations

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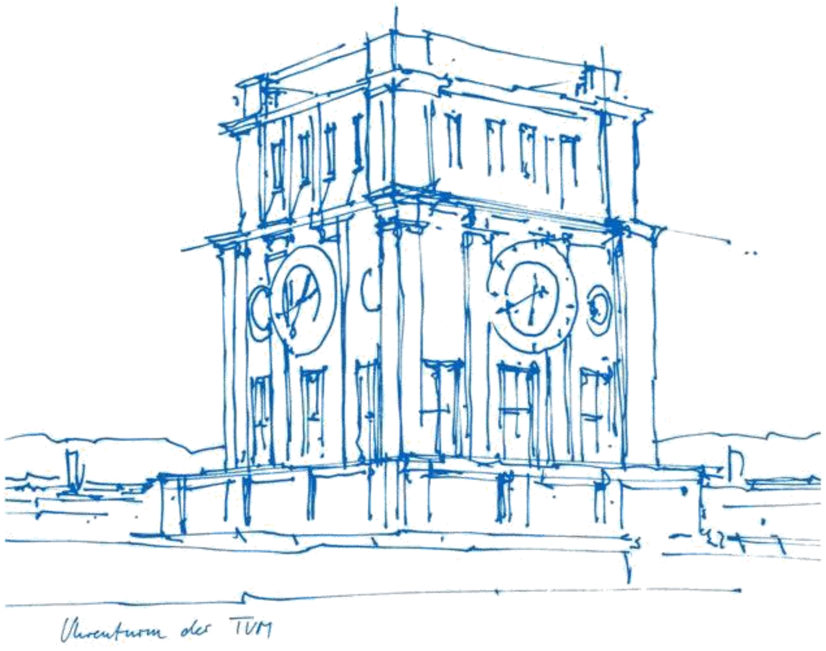


Overview

What is Geometric Multi-Scale Coupling?

How are Geometric Multi-Scale Models used?

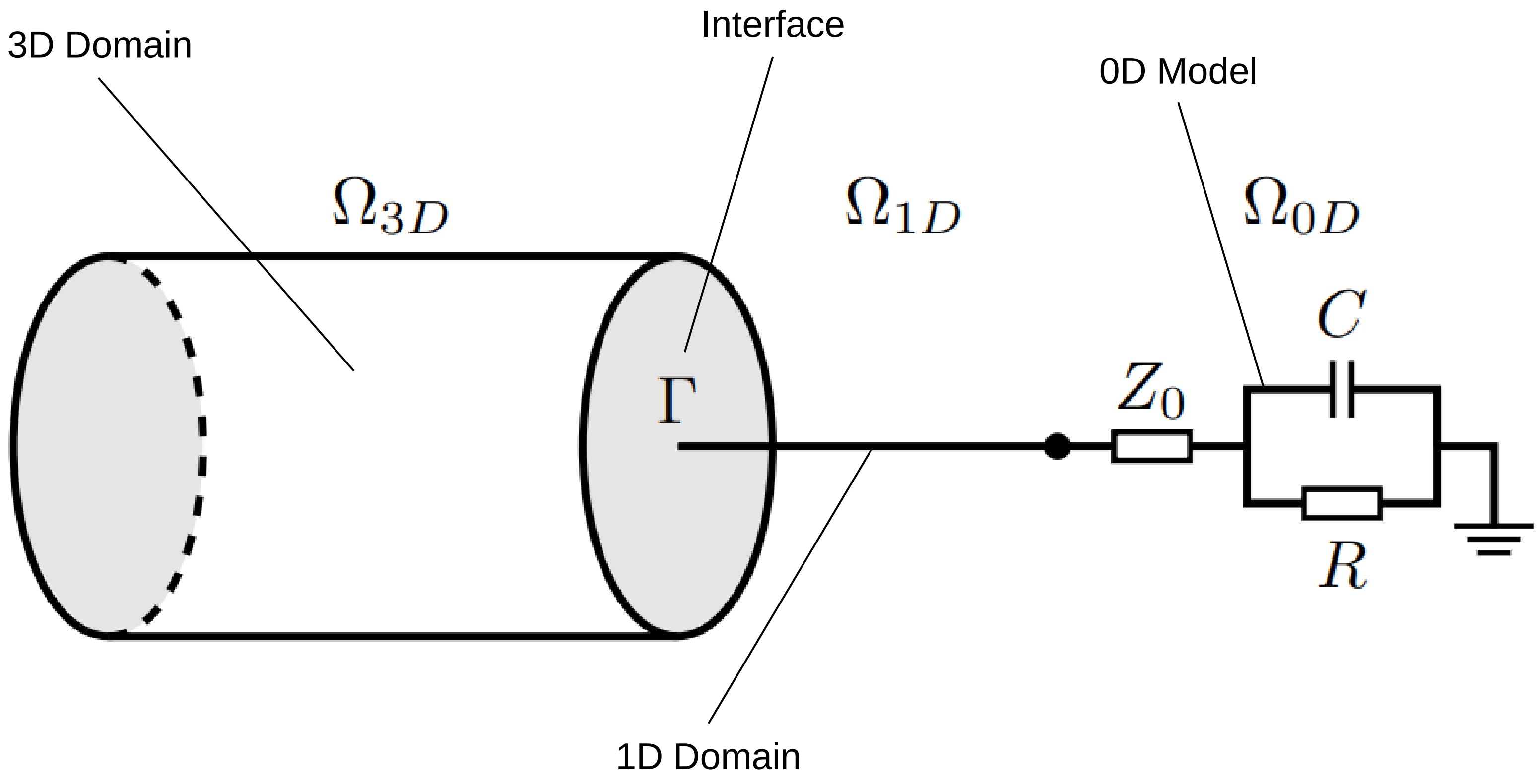
What numerical aspects need to be considered?

Simulation results: 1D-3D partitioned pipe

Conclusion

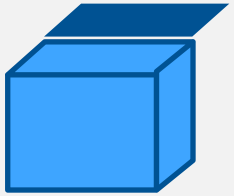
What is Geometric Multi-Scale Coupling?

Geometric Multi-Scale Coupling



Geometric Multi-Scale Models

3D-2D



For example:

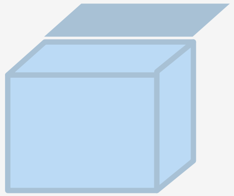
3D NSE
2D SWE

3D-1D

3D-0D

Geometric Multi-Scale Models

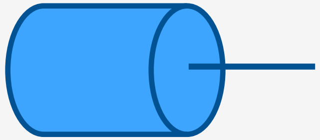
3D-2D



For example:

3D NSE
2D SWE

3D-1D



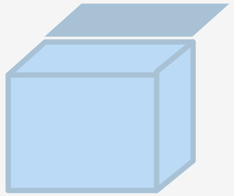
For example:

3D NSE
1D Euler

3D-0D

Geometric Multi-Scale Models

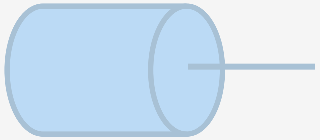
3D-2D



For example:

3D NSE
2D SWE

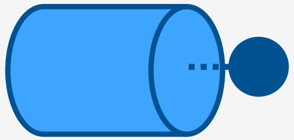
3D-1D



For example:

3D NSE
1D Euler

3D-0D

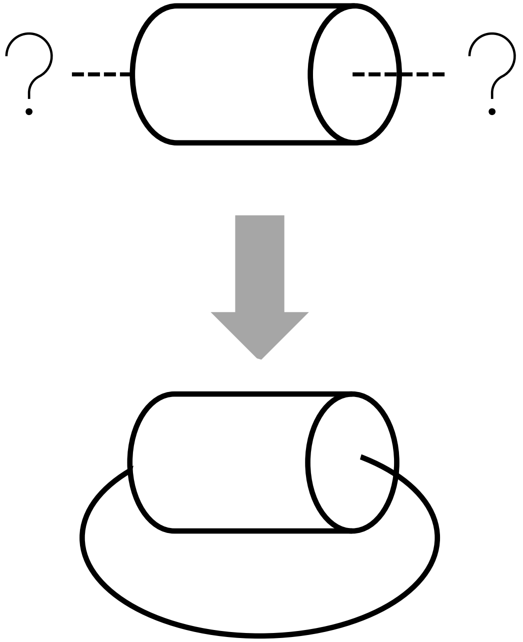


For example:

3D NSE
0D Windkessel

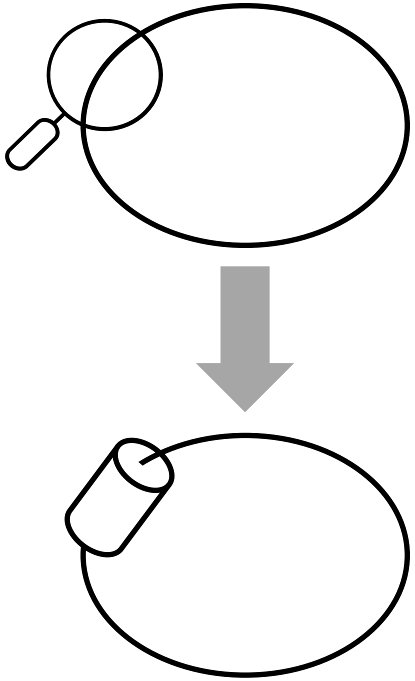
Two Different Approaches

Top-Down Approach



Computing correct boundary conditions for non-physical boundaries

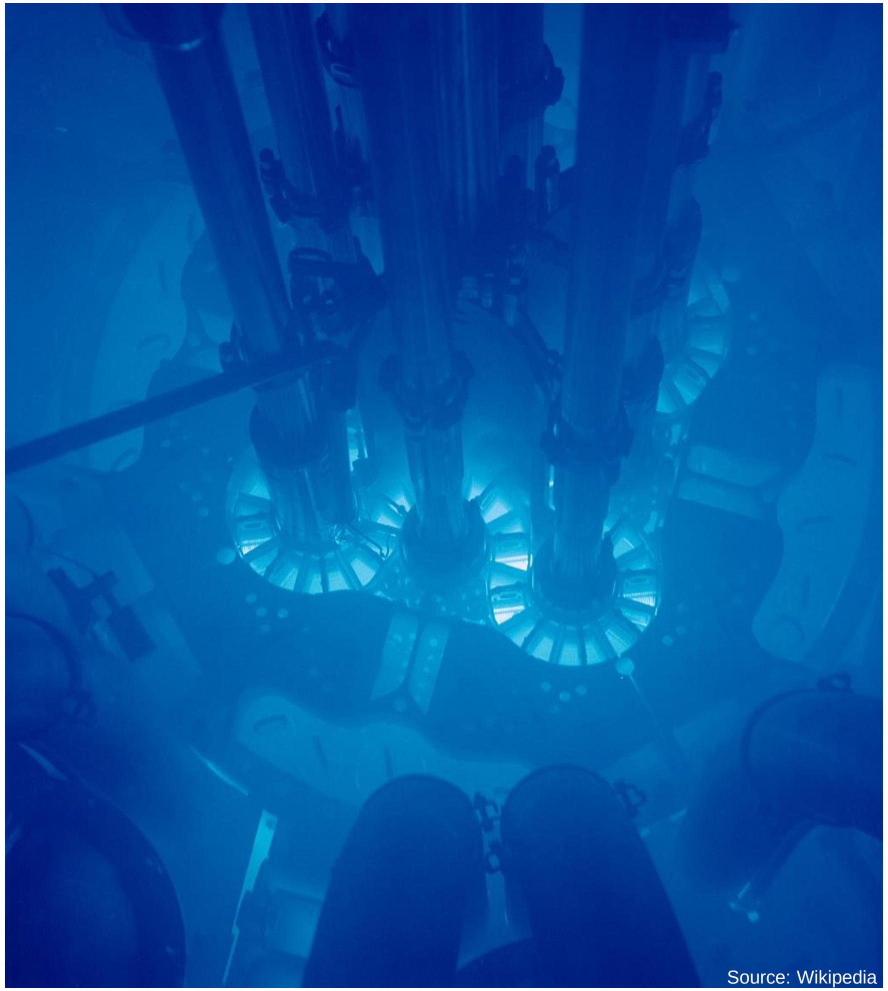
Bottom-Up Approach



Refining the model at specific regions of interest

How are Geometric Multi-Scale Models used?

Nuclear Reactor Simulations



Power plants can be simulated using system-thermal-hydraulic (STH) solvers

STH codes mostly 1D

Areas with 3D effects (e.g., circulating flow) can be modeled using CFD (“bottom-up”)

→ Increased fidelity of simulation results for safety margins

Example: Molten Salt Reactor [1]

Reactor type that circulates molten fuel

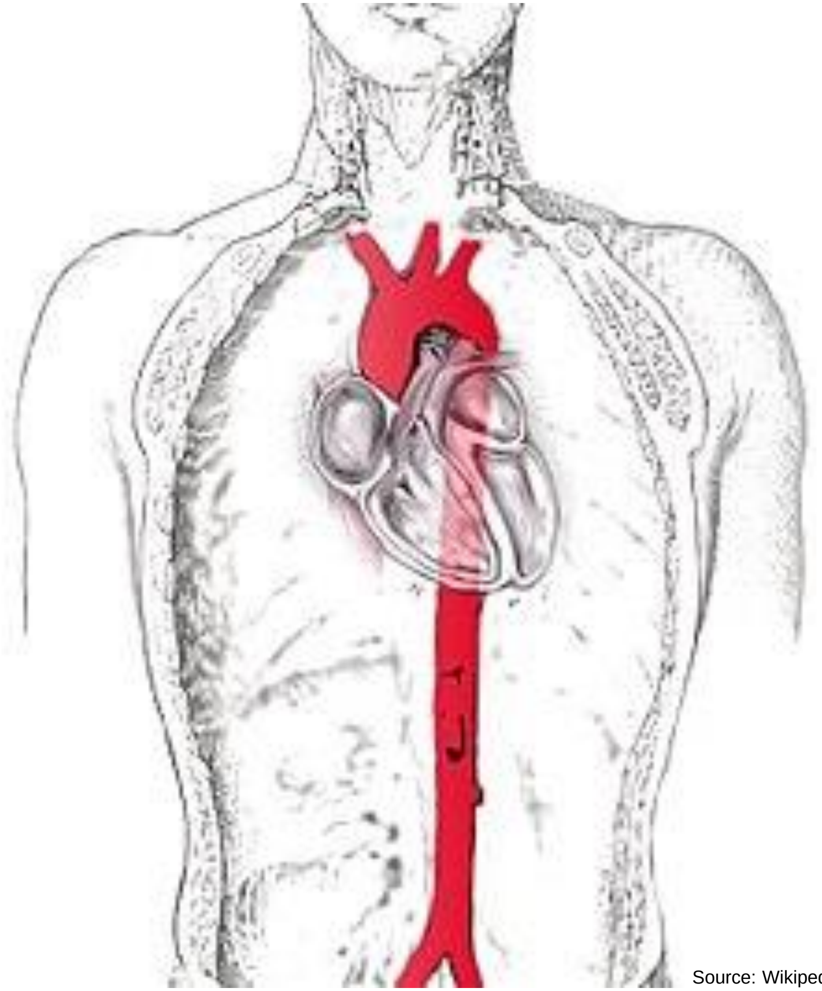
Simulation of reactor core “top-down”

Reactor core: 3D model for heat transport, fluid dynamics and delayed neutron precursor convection

Out-of-core components: 0D models that provide boundary conditions

Source: Wikipedia

Example: Patient-specific aorta model [2]



Source: Wikipedia

Simulation of patient’s aorta before and after surgical procedure — very useful, but computationally costly

Aorta: 3D finite-element model

Heart: 0D model, provides inflow boundary conditions

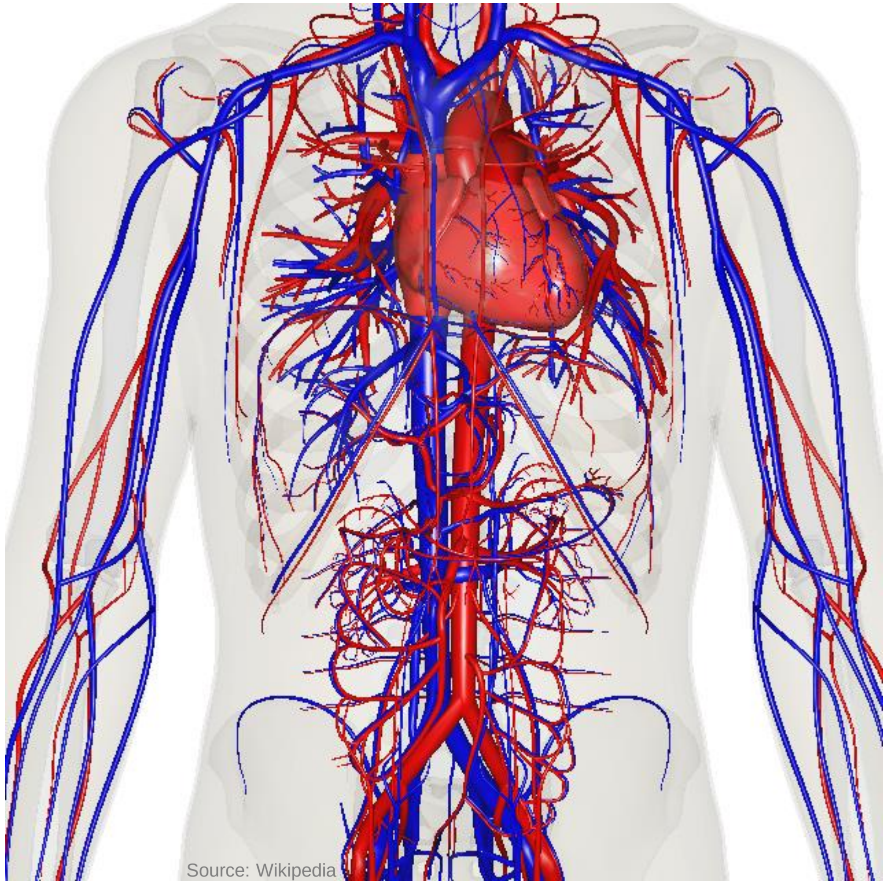
Downstream circulation: 0D Windkessel model

Example: Including the Baroreceptor Reflex [3]

Problem of simulating surgical procedures: Local changes induce global changes of the blood flow

Including a 0D model of the baroreflex mechanism (i.e., the physiological homeostatic regulation reflex) enables model to self-regulate

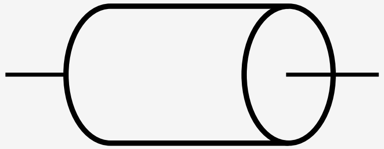
→ Complete model of the human circulatory system with high level of realism


Source: Wikipedia

What numerical aspects need to be considered?

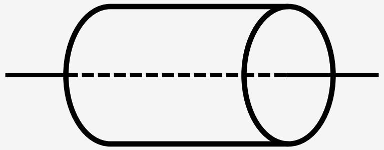
Two Paradigms

Domain-
Decomposition



Each domain is separated and simulated by its respective solver

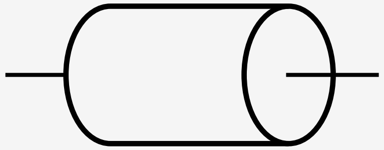
Domain-
Overlapping



The reduced model is simulated everywhere, some areas also simulated by refined solvers

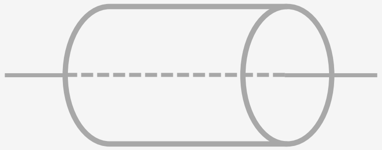
Two Paradigms

Domain-Decomposition



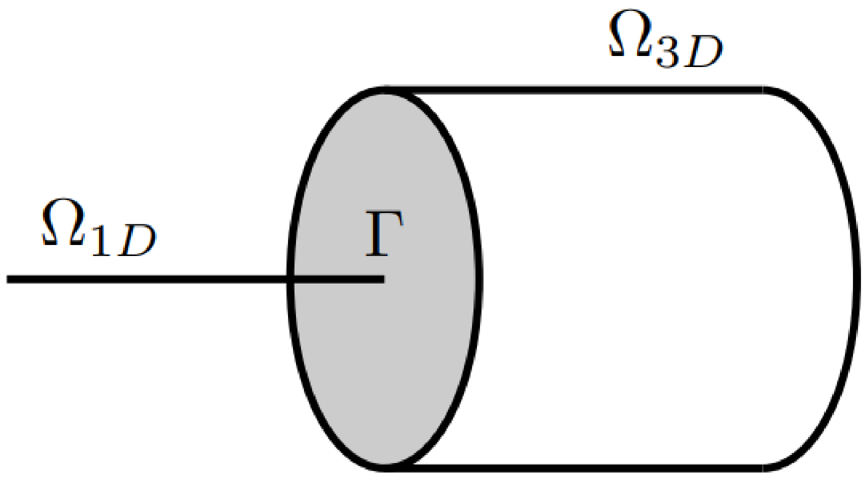
Each domain is separated and simulated by its respective solver

Domain-Overlapping



The reduced model is simulated everywhere, some areas also simulated by refined solvers

Continuity on the Interface

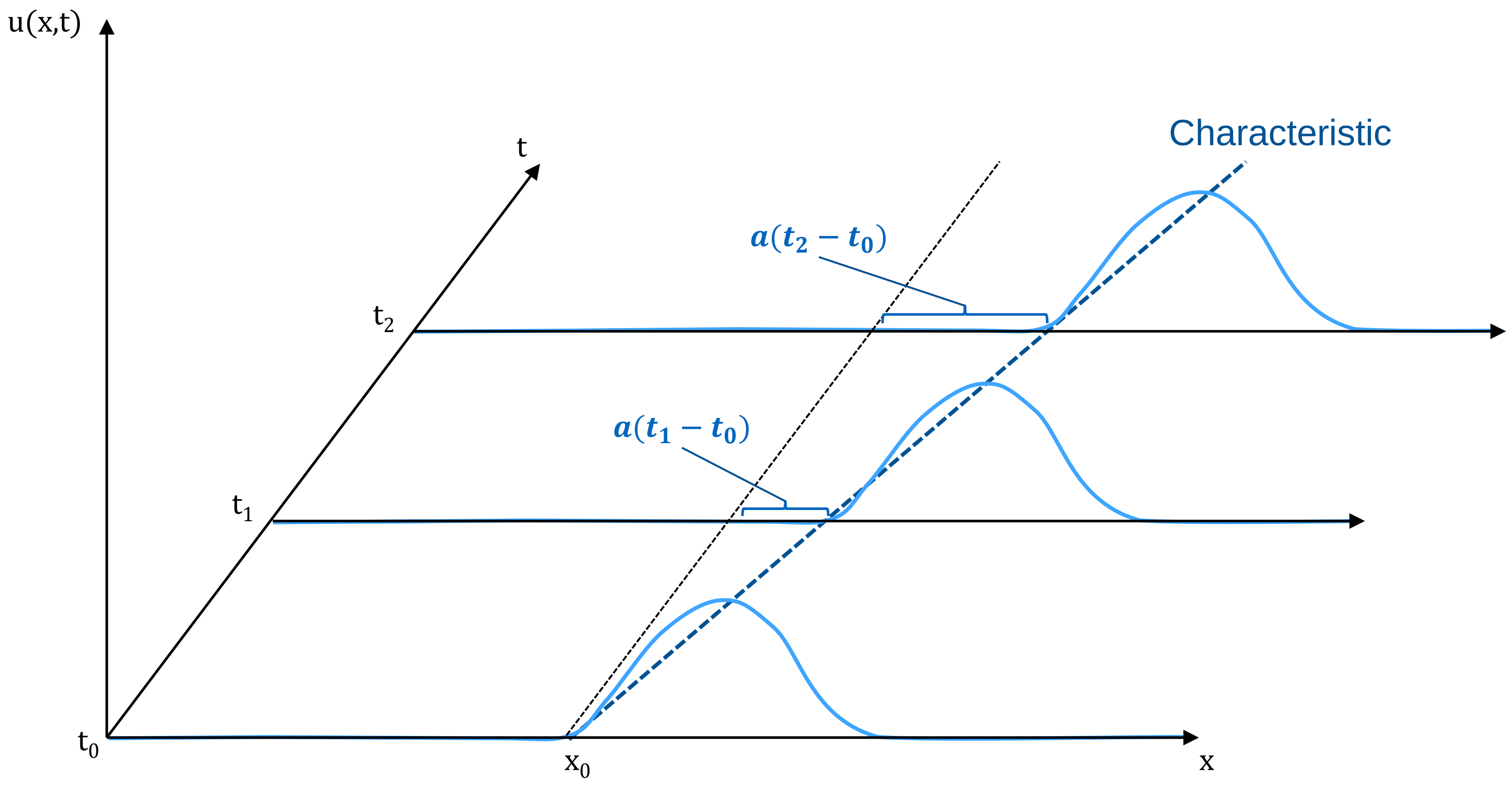


$A^\Gamma_{1D} = A^\Gamma_{3D}$	Area
$\bar{p}^\Gamma_{1D} = \bar{p}^\Gamma_{3D}$	Mean Pressure
$Q^\Gamma_{1D} = Q^\Gamma_{3D}$	Flux
$\bar{p}^\Gamma_{1D}\frac{1}{2}u^2_{1D} = \bar{p}^\Gamma_{3D} + \frac{1}{2}u^2_{3D}$	Mean Total Pressure

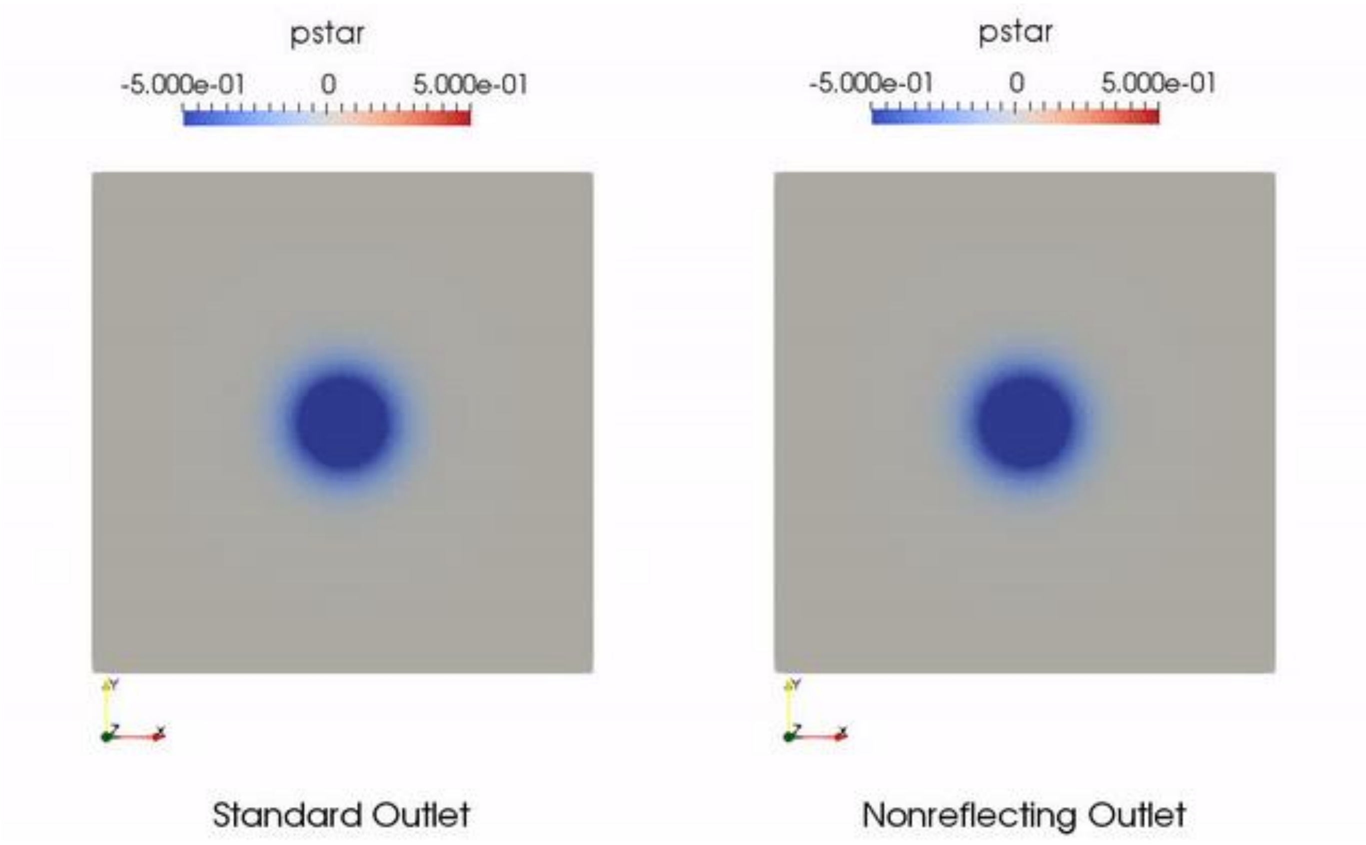
Incoming Characteristic Variable

Characteristics or Riemann Variables

Simple Example: Linear Advection



Characteristics and Spurious Effects



Source: Aither CFD

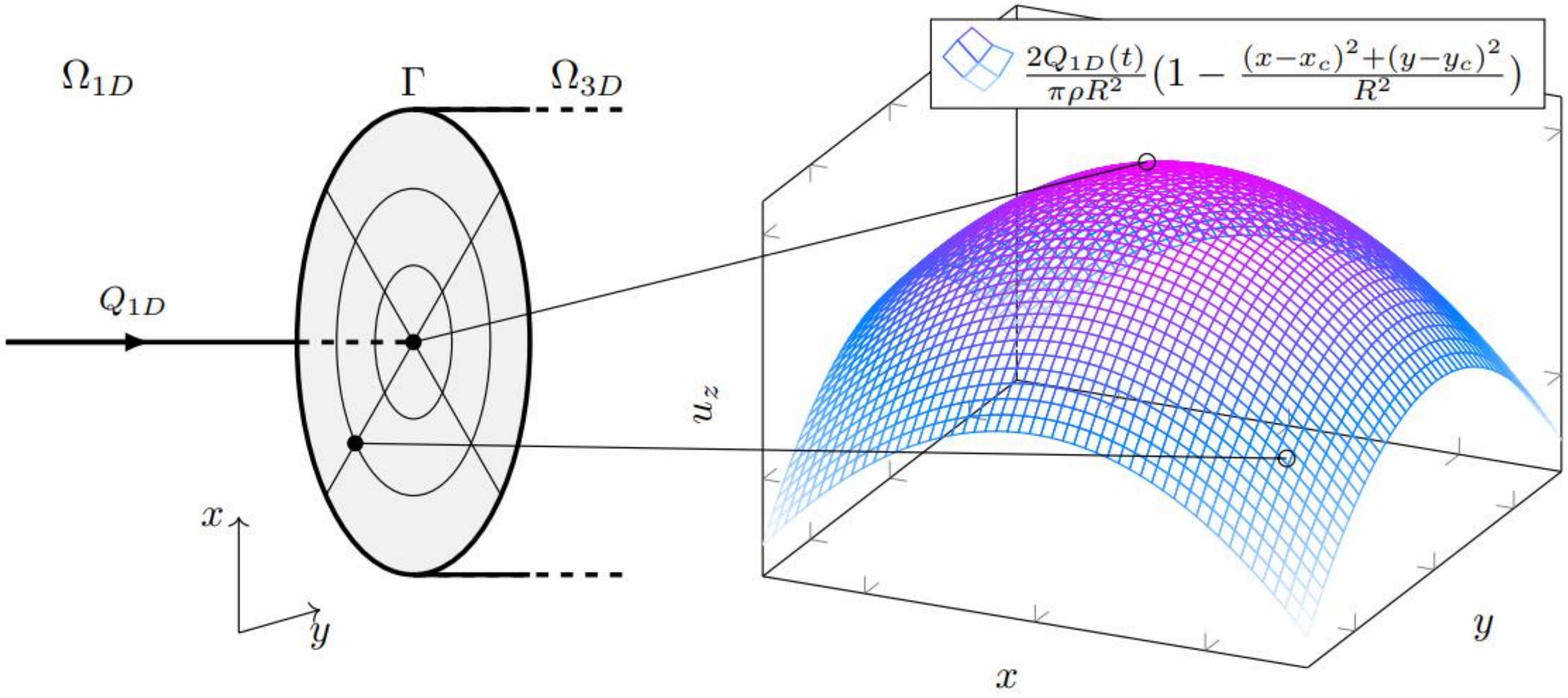
Possible Interface Boundary Conditions

Both sides of the interface need to be well-posed

Conditions are not fully independent

Boils down to ~6 combinations, also depends on the system

Velocity Profile

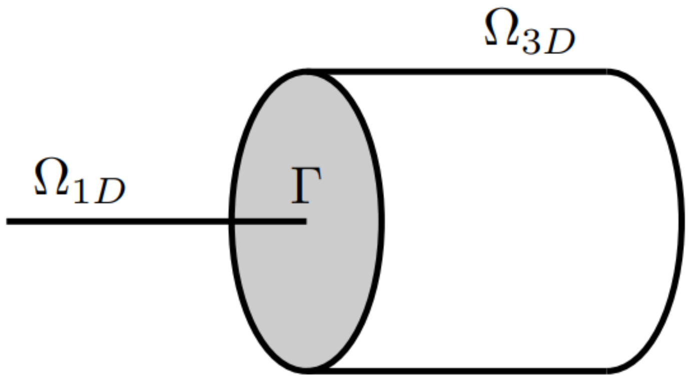


Simulation results: 1D-3D partitioned pipe

Partitioned Pipe Model

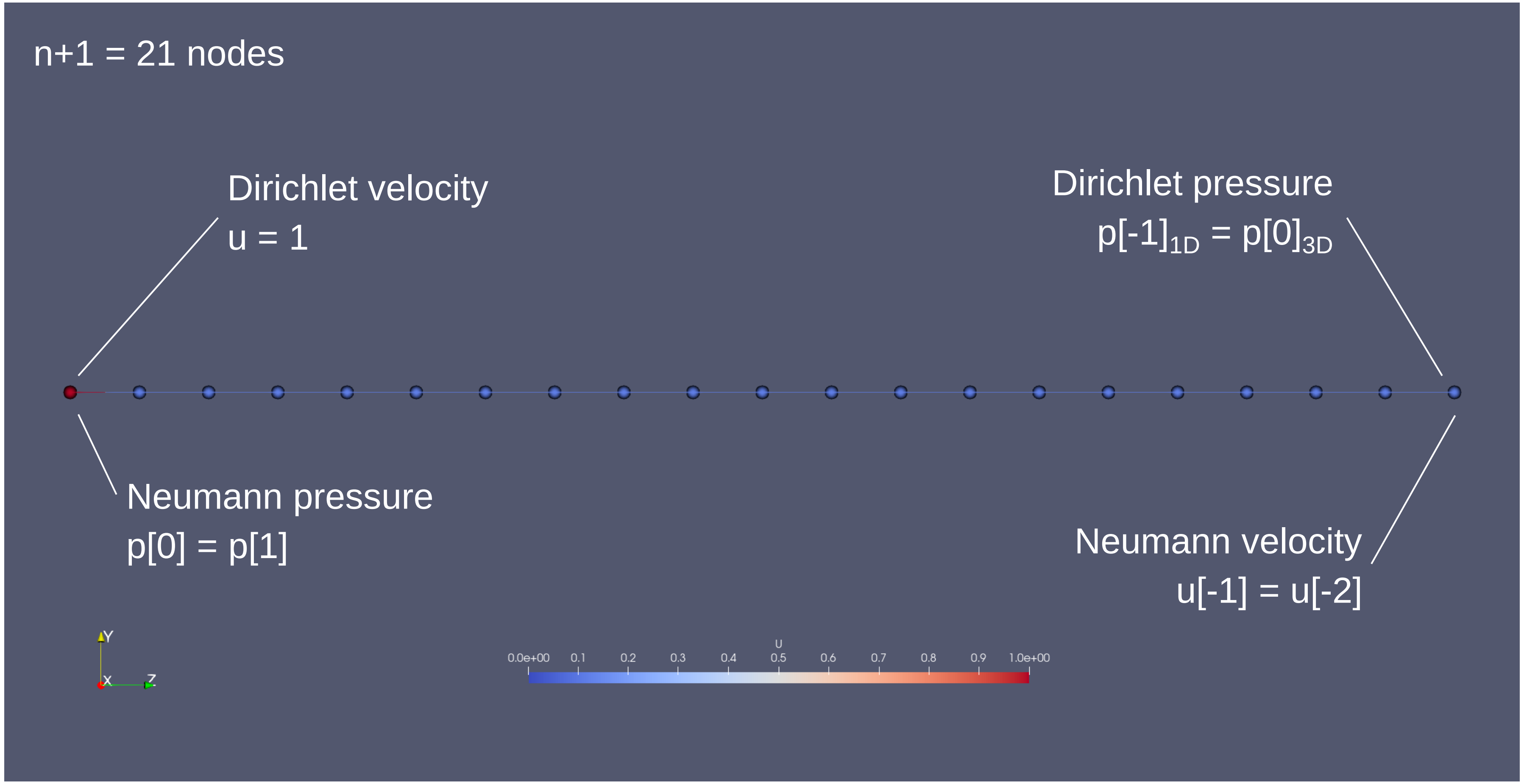
1D Model: Simplified Euler Equations
Discretized by finite differences in Python

$$\frac{\partial u}{\partial x} = 0$$
$$\frac{\partial u}{\partial t} + \frac{\partial p}{\partial x} = 0$$

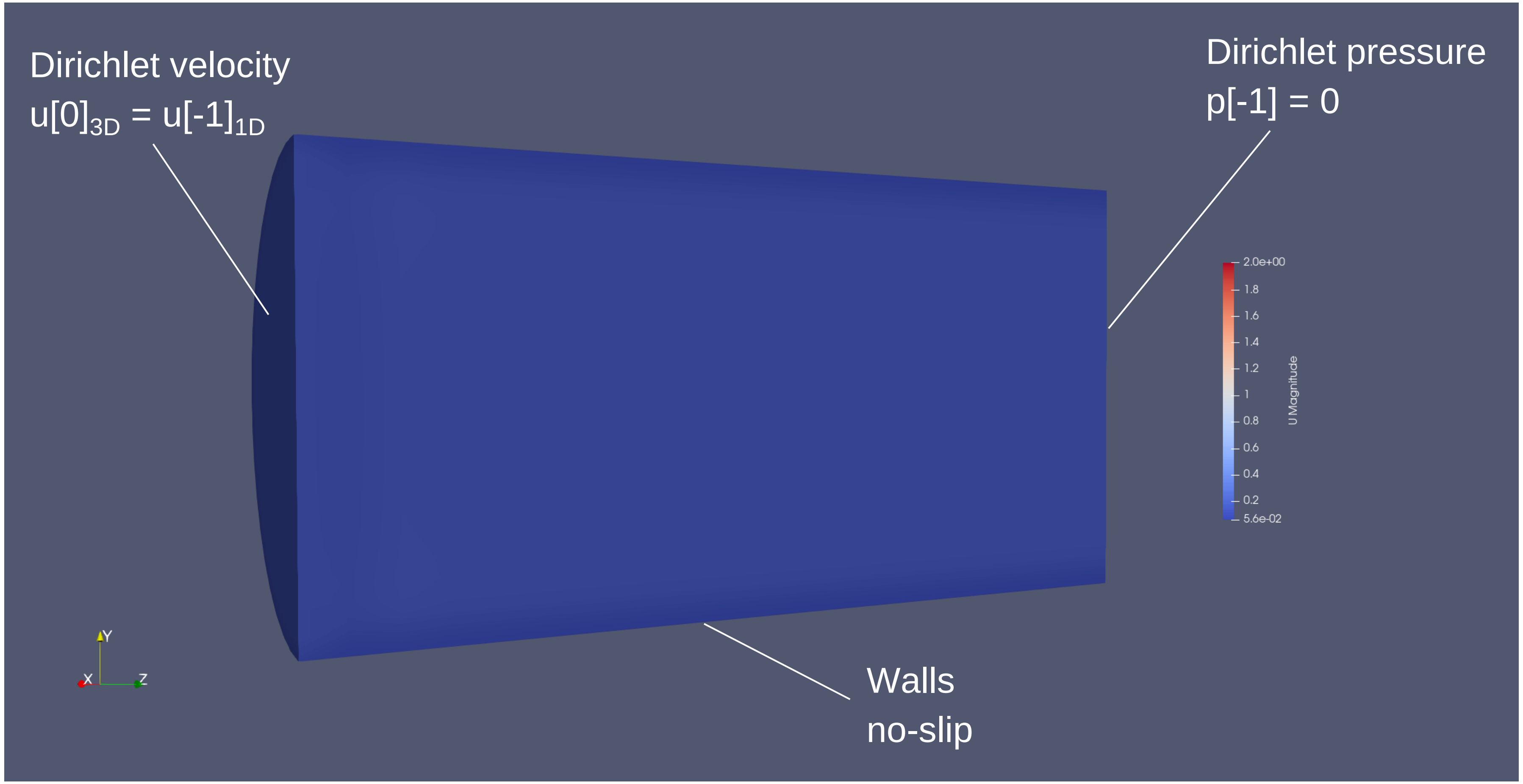


3D Model: OpenFOAM (pimpleFoam)
Transient, incompressible flow

1D Model


n+1 = 21 nodes
Dirichlet velocity
u = 1
Dirichlet pressure
p[-1]$_{1D}$ = p[0]$_{3D}$
Neumann pressure
p[0] = p[1]
Neumann velocity
u[-1] = u[-2]
U
0.0e+00
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0e+00
Y
X
Z

3D Model

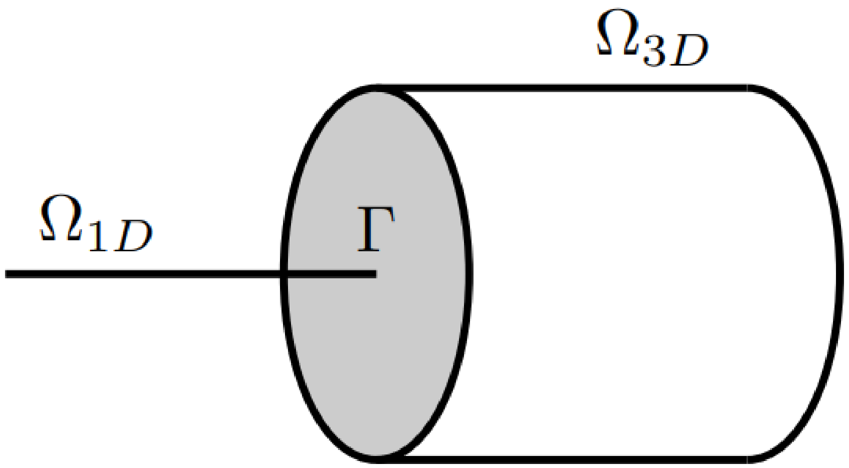

Dirichlet velocity
$u[0]_{3D} = u[-1]_{1D}$
Dirichlet pressure
p[-1] = 0
Walls
no-slip
2.0e+00
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
5.6e-02
U Magnitude
Y
X
Z

Coupling with preCICE

Serial-Implicit Coupling

Quasi-Newton Acceleration

Consistent Nearest-Neighbor Mapping



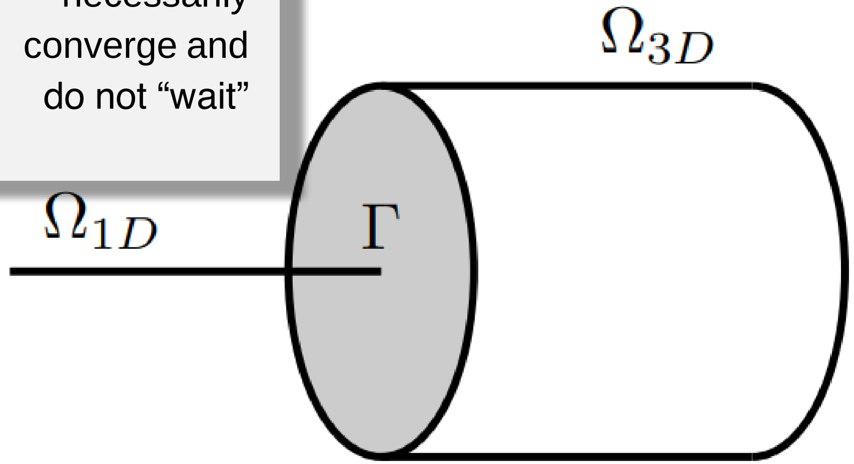
Coupling with preCICE

Implicit	Explicit
Both solvers iterate until convergence (up to tolerance)	Solvers do not necessarily converge and do not “wait”

Serial-Implicit Coupling

Quasi-Newton Acceleration

Consistent Nearest-Neighbor Mapping



Coupling with preCICE

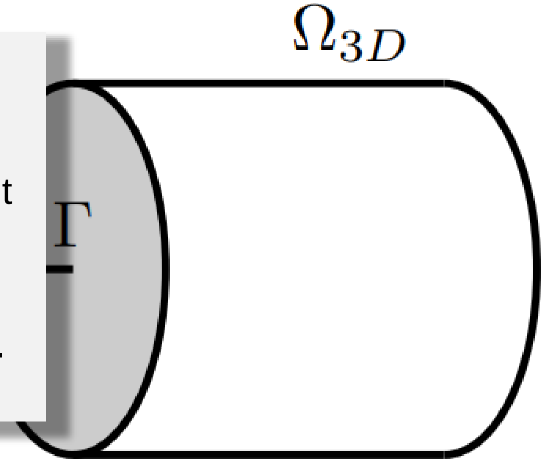
Serial-Implicit Coupling

Quasi-Newton Acceleration

Consistent Nearest-Neighbor Mapping

Acceleration

Implicit coupling leads to fixed-point equations at the interface. Acceleration techniques stabilize and speed-up the iterative process.

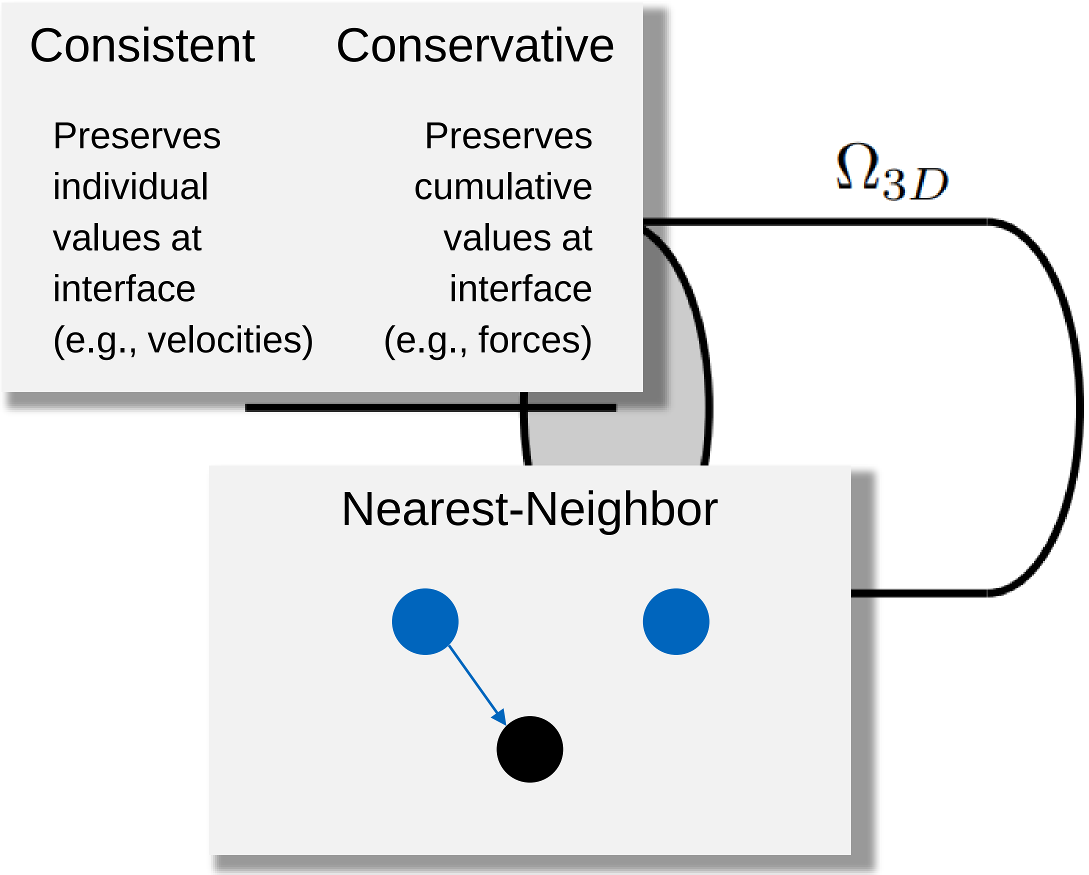


Coupling with preCICE

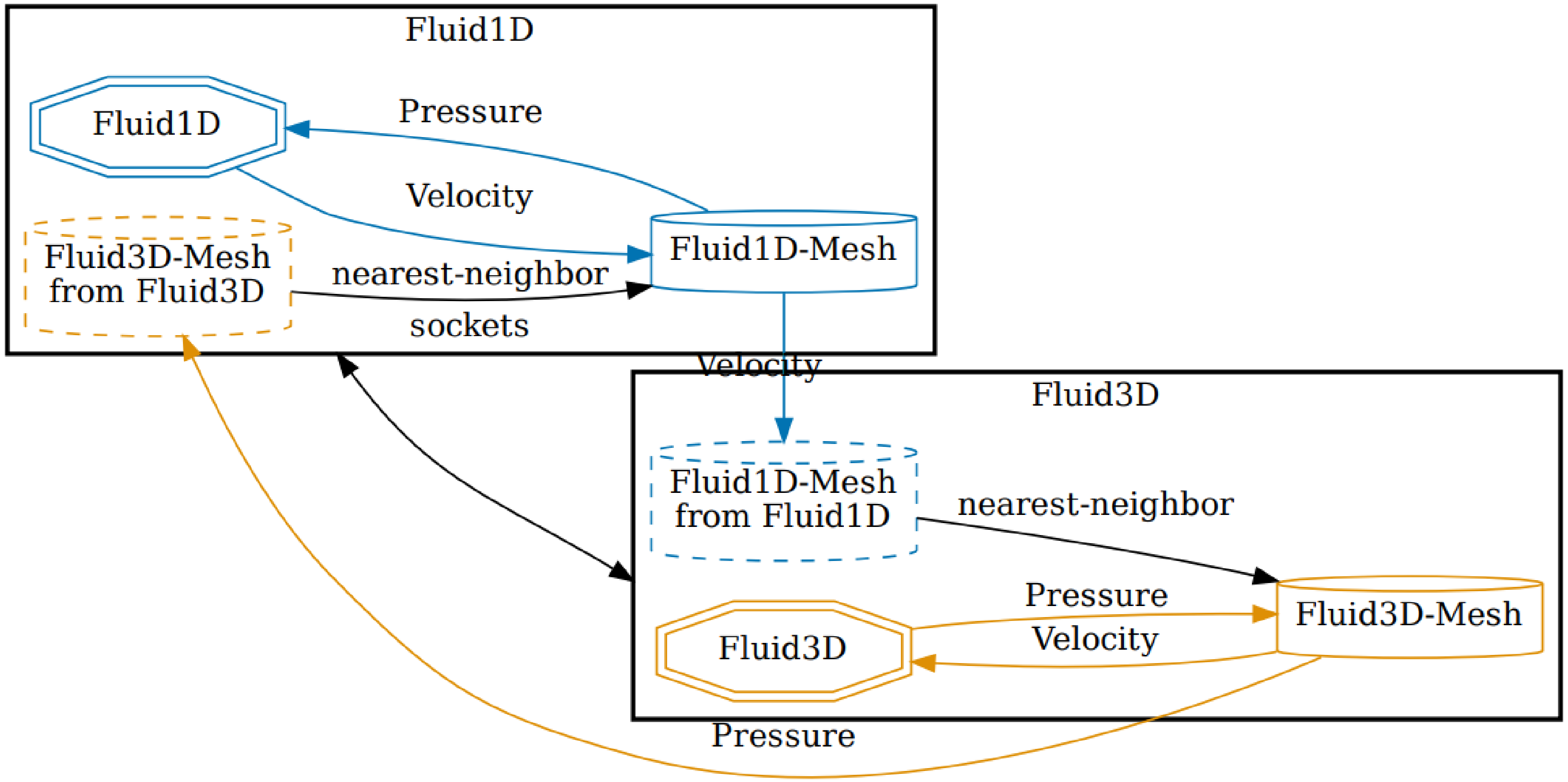
Serial-Implicit Coupling

Quasi-Newton Acceleration

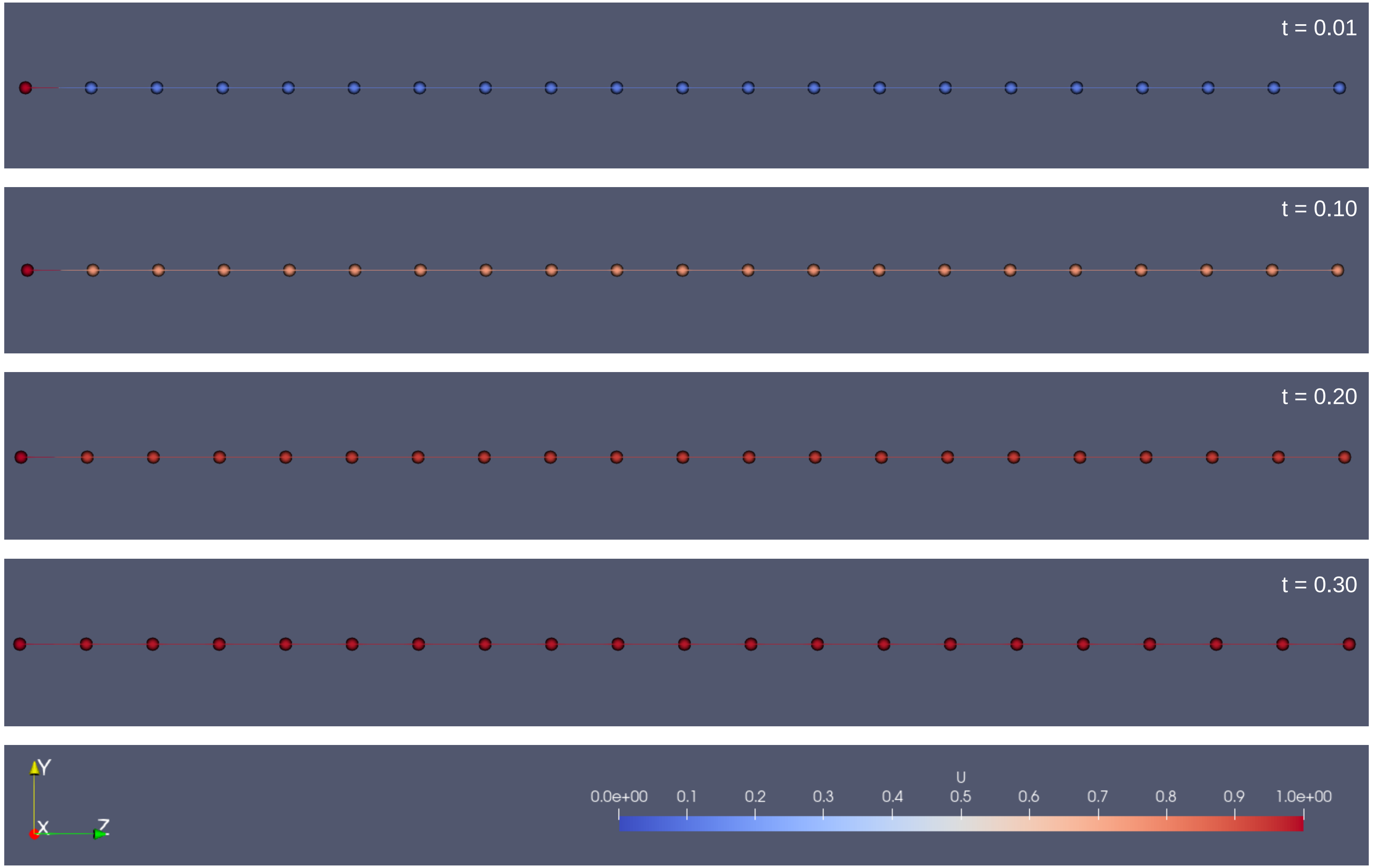
Consistent Nearest-Neighbor Mapping



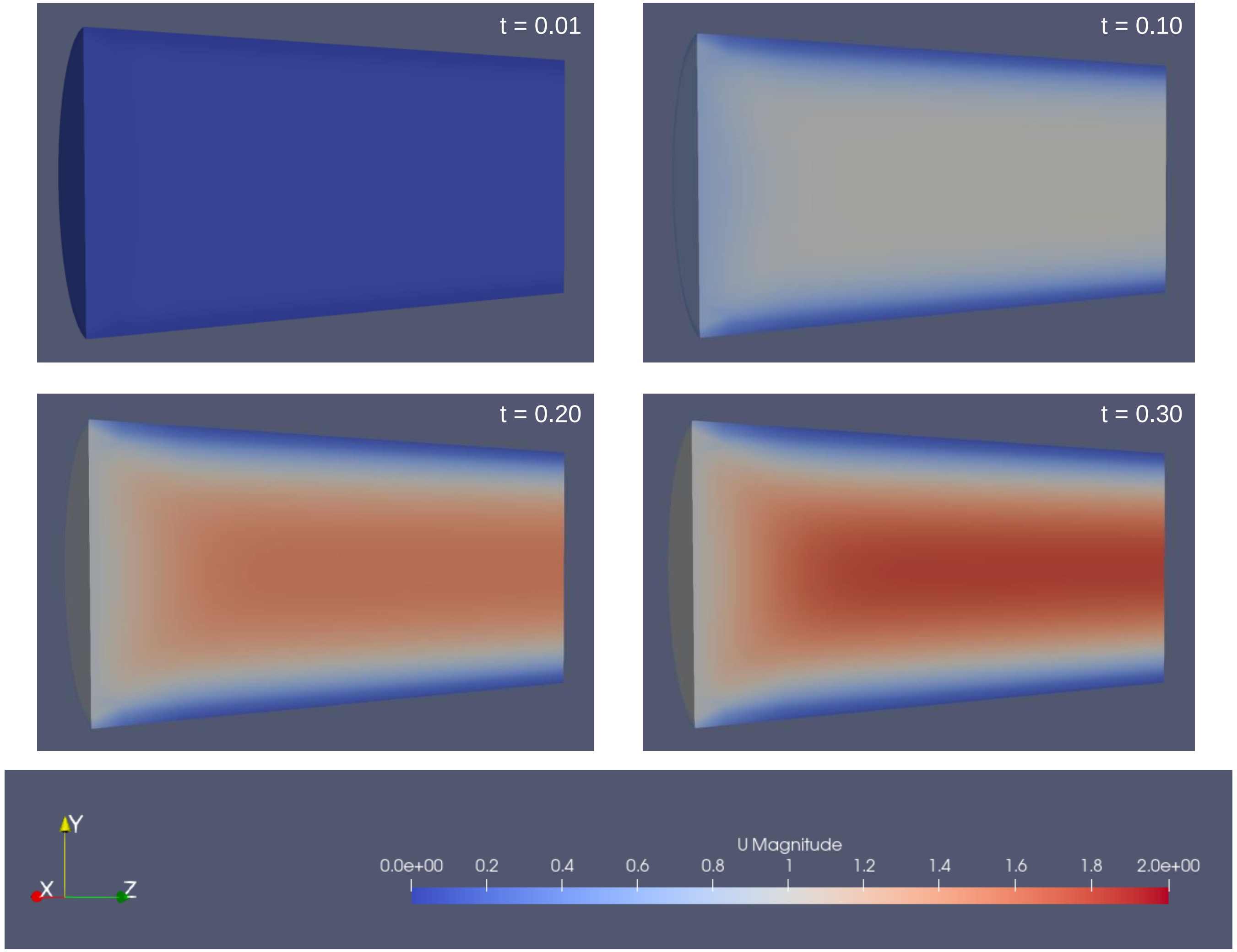
Visualization of preCICE Configuration



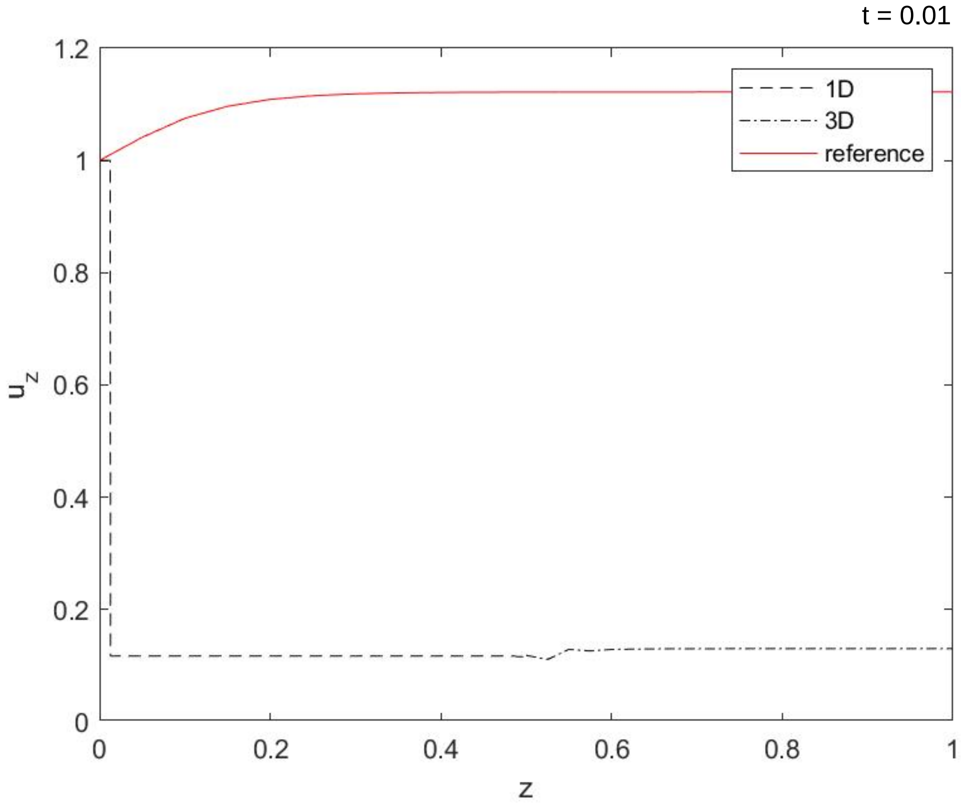
Results

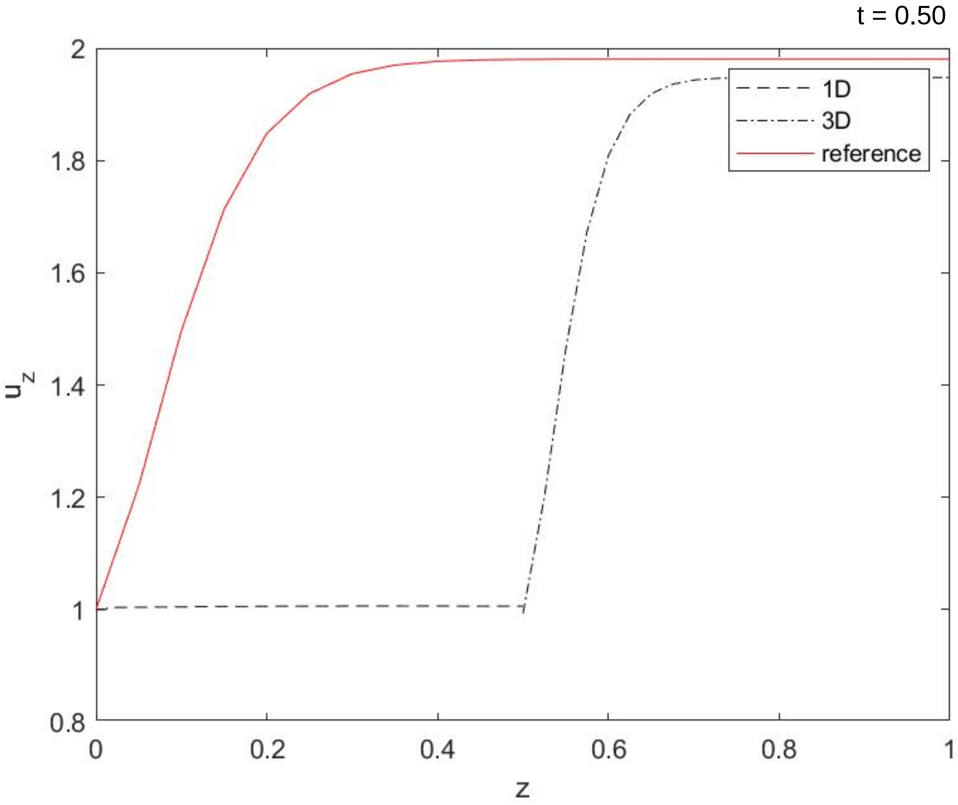


Results

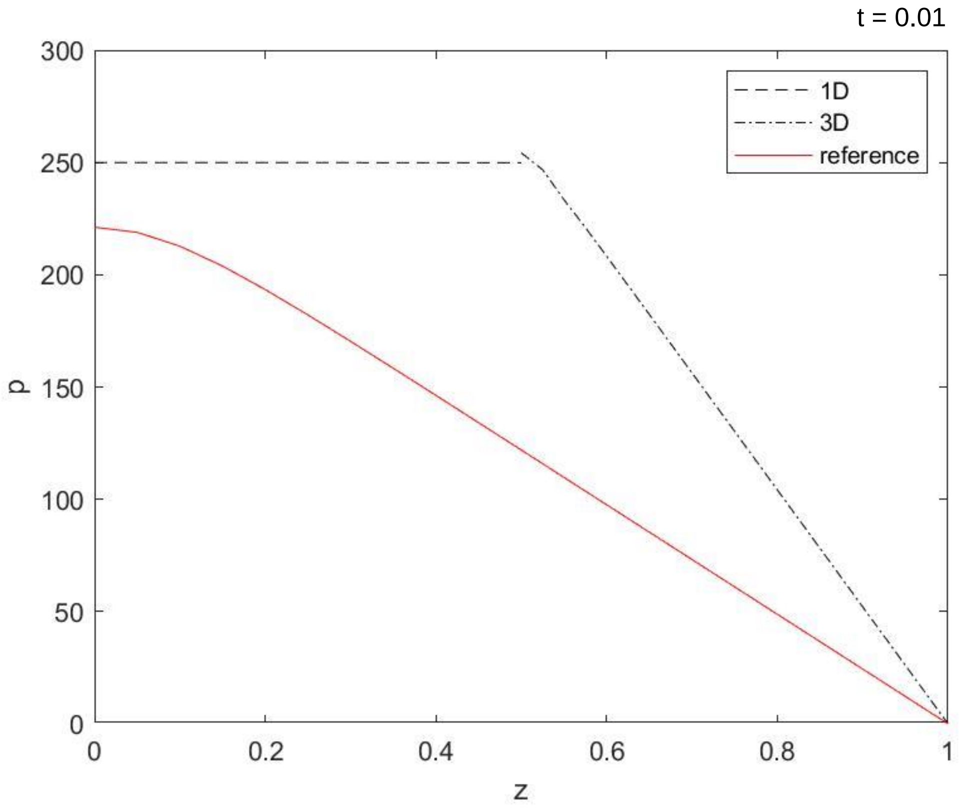

t = 0.01
t = 0.10
t = 0.20
t = 0.30
Y
X
Z
U Magnitude
0.0e+00
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2.0e+00

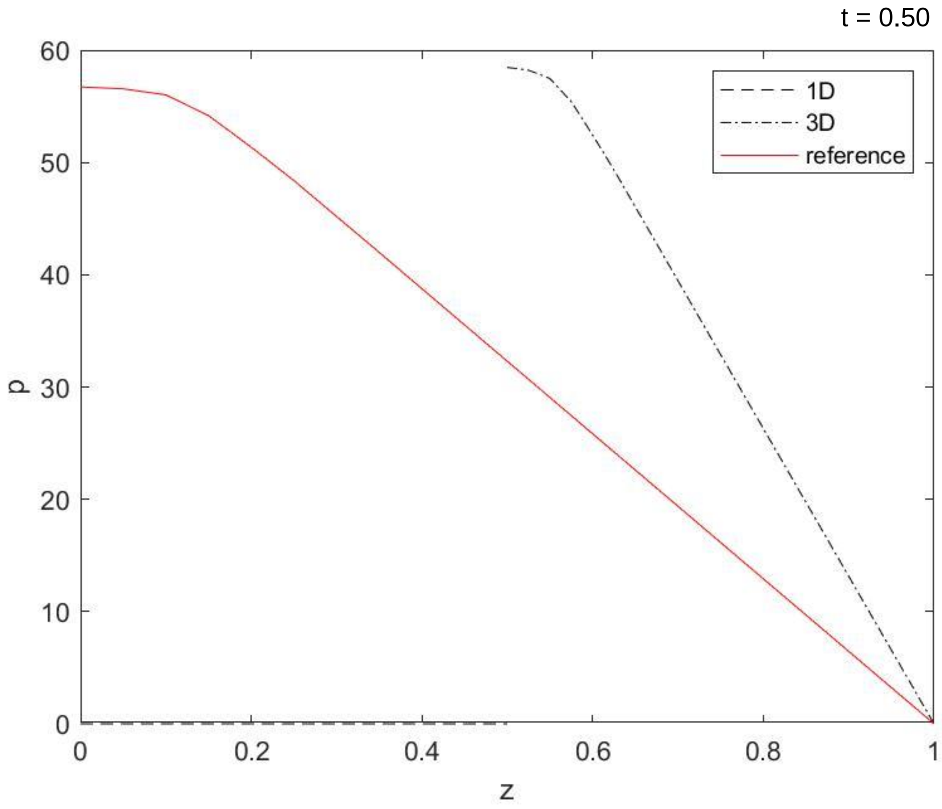
Results


t = 0.01
1.2
1
0.8
0.6
0.4
0.2
0
u_z
0
0.2
0.4
0.6
0.8
1
z
1D
3D
reference


t = 0.50
2
1.8
1.6
1.4
1.2
1
0.8
u_z
0
0.2
0.4
0.6
0.8
1
z
1D
3D
reference

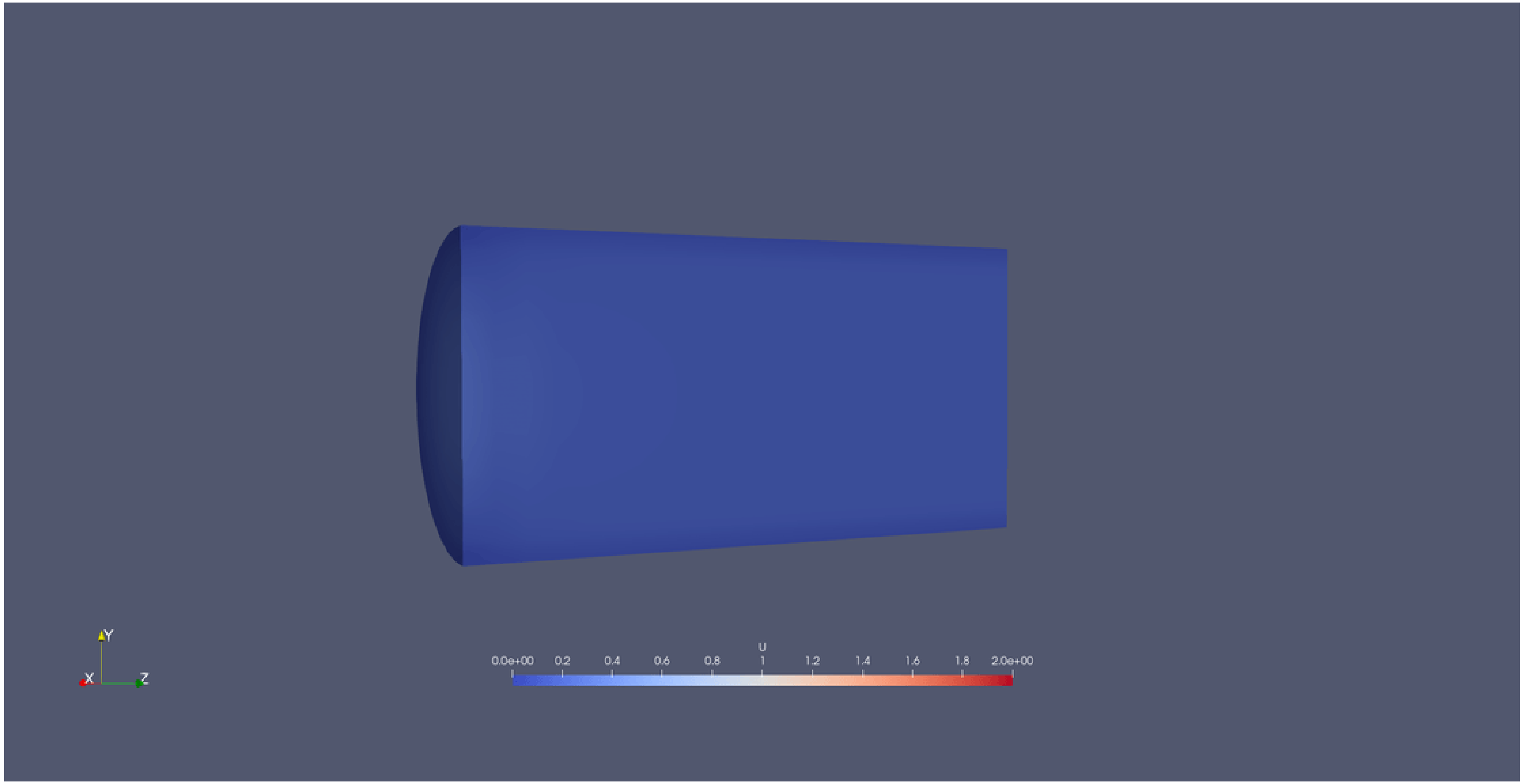
Results


t = 0.01
300
250
200
150
100
50
0
p
0
0.2
0.4
0.6
0.8
1
z
1D
3D
reference


t = 0.50
60
50
40
30
20
10
0
p
0
0.2
0.4
0.6
0.8
1
z
1D
3D
reference

Potential Improvements?

Transforming 1D Data — Velocity Profile



Conclusion

Geometric Multi-Scale Models

+ reduce computational complexity

+ very flexible

+ fairly easy black-box coupling

- reduced models are bottleneck to overall results

- which parts are regions of interest, which parts can be reduced? → expert knowledge

- introduces lots of non-physical boundaries

Thank you for your attention!

References

[1] M. Zanetti, A. Cammi, C. Fiorina, and L. Luzzi, “A geometric multiscale modelling approach to the analysis of MSR plant dynamics,” *Progress in Nuclear Energy*, vol. 83, no. 0, pp. 82–98, 2015.

[2] H. J. Kim, I. E. Vignon-Clementel, C. A. Figueroa, J. F. LaDisa, K. E. Jansen, J. A. Feinstein, and C. A. Taylor, “On coupling a lumped parameter heart model and a three-dimensional finite element aorta model,” *Annals of Biomedical Engineering*, vol. 37, no. 11, pp. 2153–2169, 2009.

[3] P. Blanco, P. Trenhago, L. Fernandes, and R. Feijoo, “On the integration of the baroreflex control mechanism in a heterogeneous model of the cardiovascular system,” *International Journal for Numerical Methods in Biomedical Engineering*, vol. 28, no. 4, pp. 412–433, 2012.