Efficiency and Stability Trade-offs in FSI Simulations of Coronary Artery Blood Flow

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NCSA Industry – Goal: 6 months ahead of competition

Industry Dedicated

- Technical Teams
- HPC Resources
- Business Leadership and Project Management

Tradition

- Industry as a part of NCSA’s mission for > 30 years

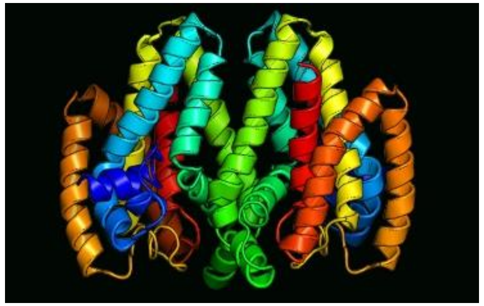
Culture

- Work at industrial pace with NDAs
- Deliver on time and under budget

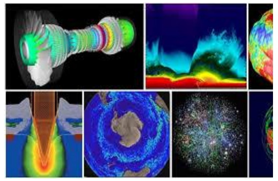
Largest Industrial HPC Program in the World

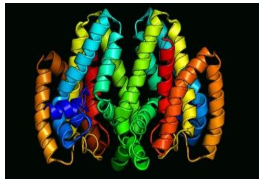
NCSA Industry – Technical Expertise

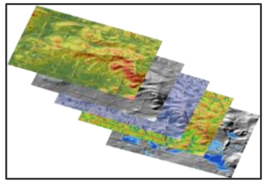
- Modeling and Simulation
- Bioinformatics and Genomics
- Big Data Analytics, GIS, and AI
- Code Profiling and Optimization
- Rapid User Support and HPC Training
- Cyber Infrastructure and Security
- Visualization
- Much more at NCSA and the University of Illinois

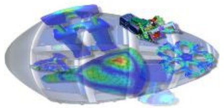


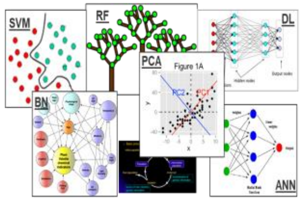
iForge – The HPC Environment for Industry





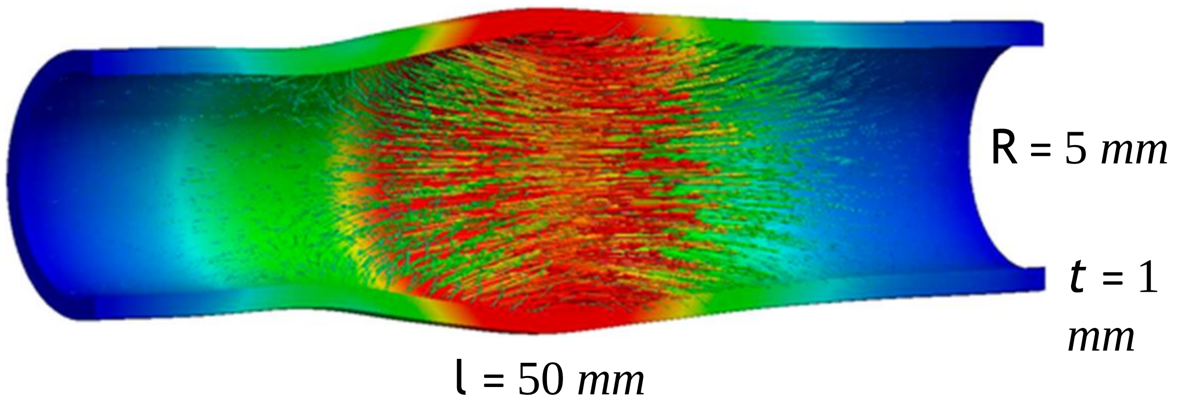






- **Latest and best**
  - Computing (Intel/Skylake 192-256 GB)
  - In-memory big data analytics (SPARK)
  - GPU driven AI technologies (V100)
- **99% uptime and live upgrades**
- **Development and production workhorse**
- **Rapid user support and advanced consulting**
- **Built exclusively for Industry’s applications and workflows**

Reduced model of blood flow – Pressure impulse traveling through flexible tube



Fluid model

- Incompressible viscous flow
- Density = 10^{-3} [g/mm^3], Kinematic viscosity = 3 [mm^2/s]
- Initially at rest
- P_{inlet} = 1333 [Pa] for t < 0.003 [s] and zero outlet pressure

Structure model

- Venant-Kirchhoff hyperelastic structure
- Young's modulus = 3x10^5 [Pa], Poisson's ratio = 0.3
- Initially undeformed
- Fixed at both ends

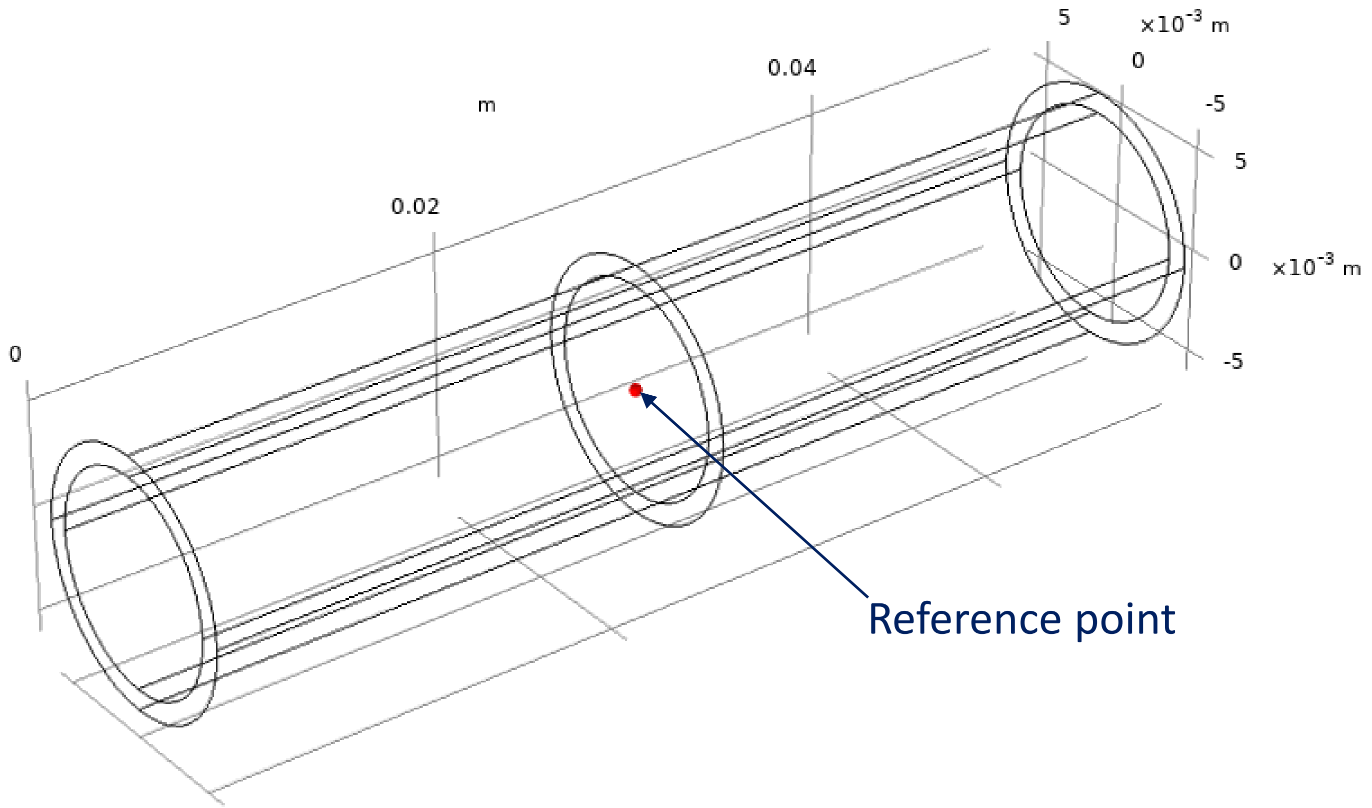
Overview of key modeling considerations

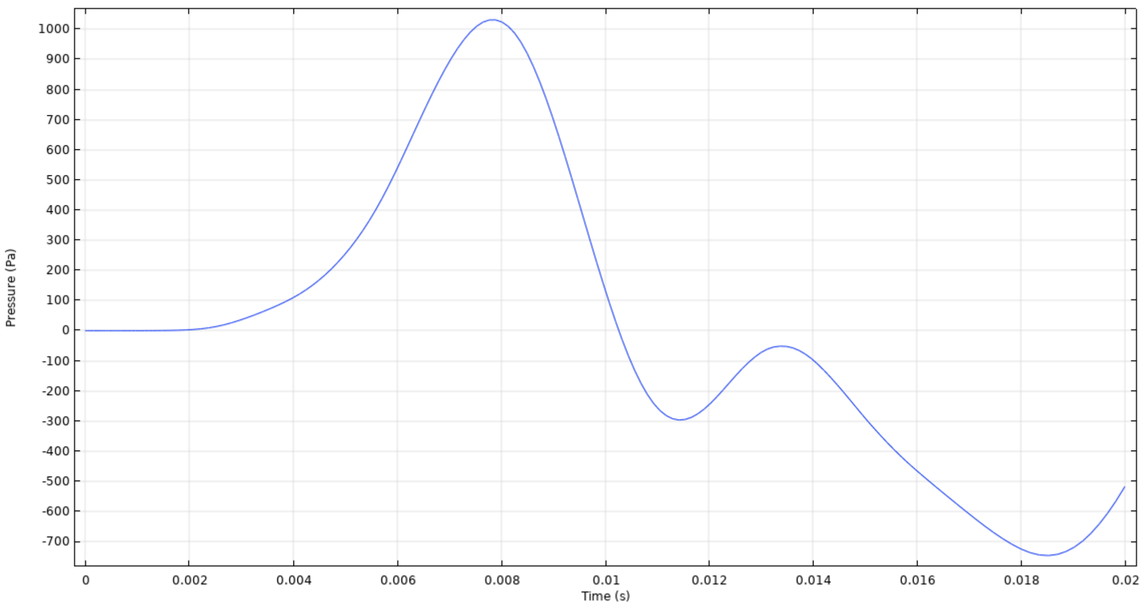
Typical modeling challenges	• Strong physics couplings • Material and geometric nonlinearities • Large model sizes
Typical computational concerns	• Solution time • Memory footprint • Numerical robustness

Two-way FSI solution options	• Multiphysics modeling approach
	  ▪ Monolithic (Fully-coupled)
	  ▪ Partitioned (Segregated)
	• Linear system solvers
	  ▪ Direct (PARDISO, MUMPS, etc.)
	  ▪ Iterative (GMG, AMG, etc.)

Goal: Quantify computational tradeoffs in FSI simulations

Effect of FSI solution options on convergence and accuracy

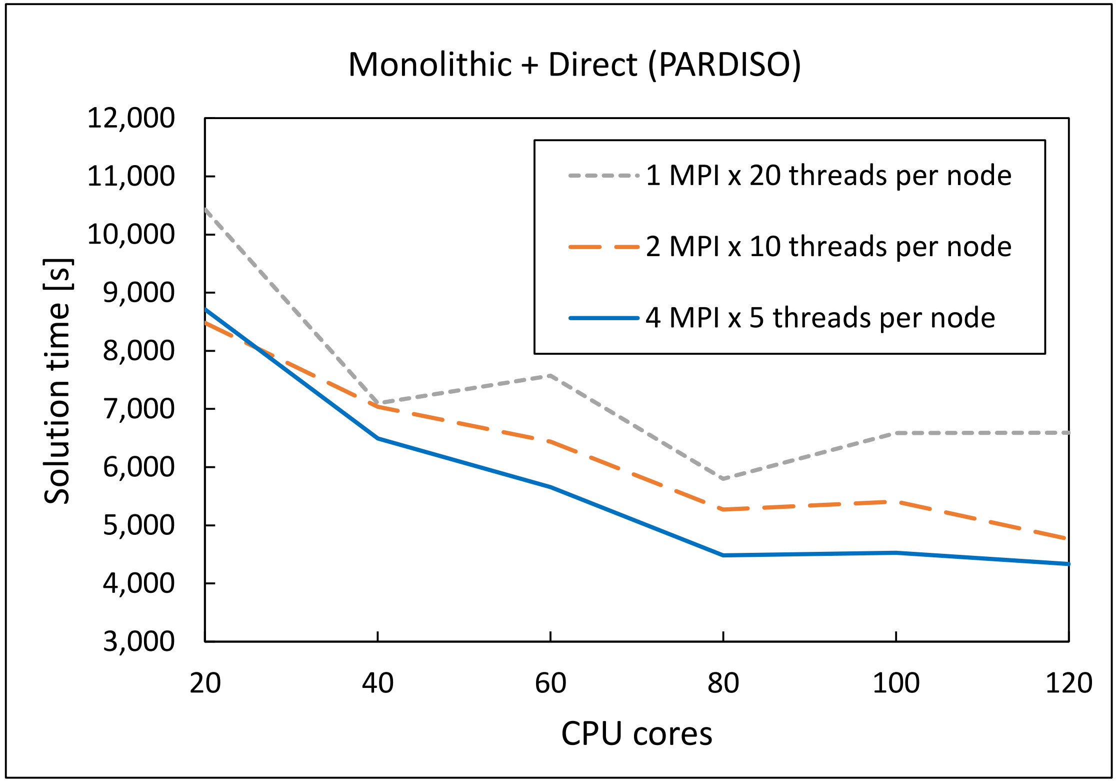


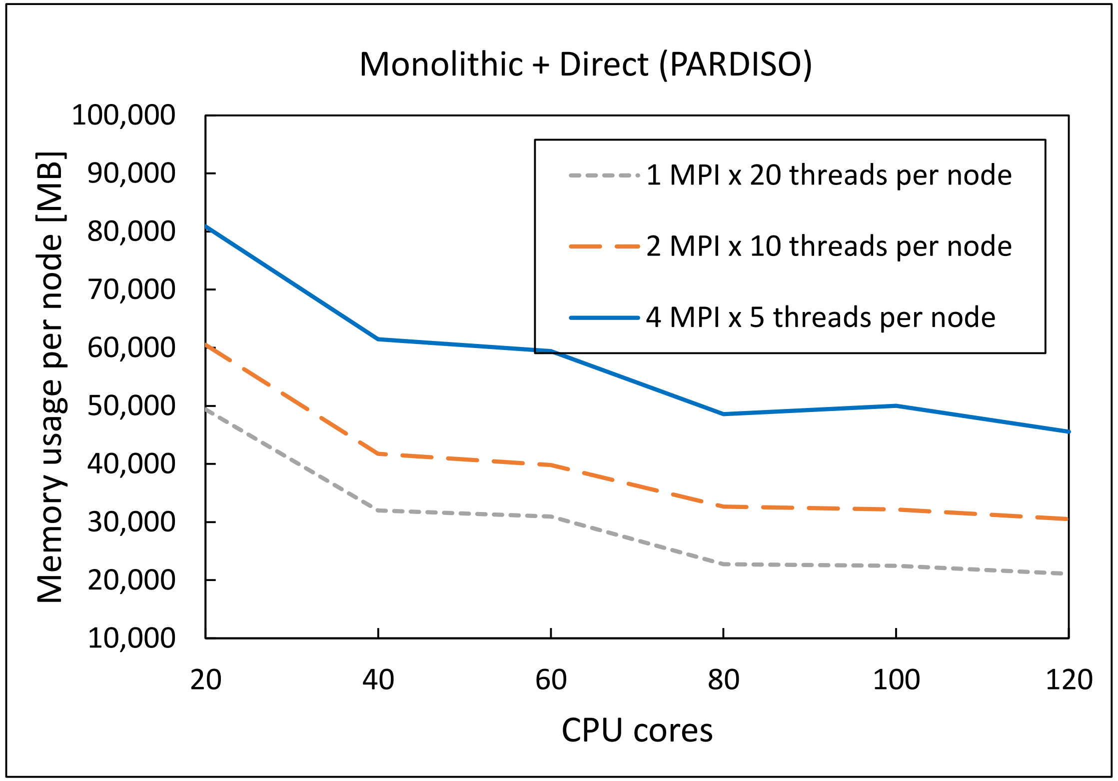


Multiphysics modeling approach: Monolithic (Fully-coupled), Partitioned (Segregated)

Linear system solver: Direct (PARDISO, MUMPS), Iterative (AMG, GMG)

Optimum hybrid computing configuration (MPI ranks x OpenMP threads)?

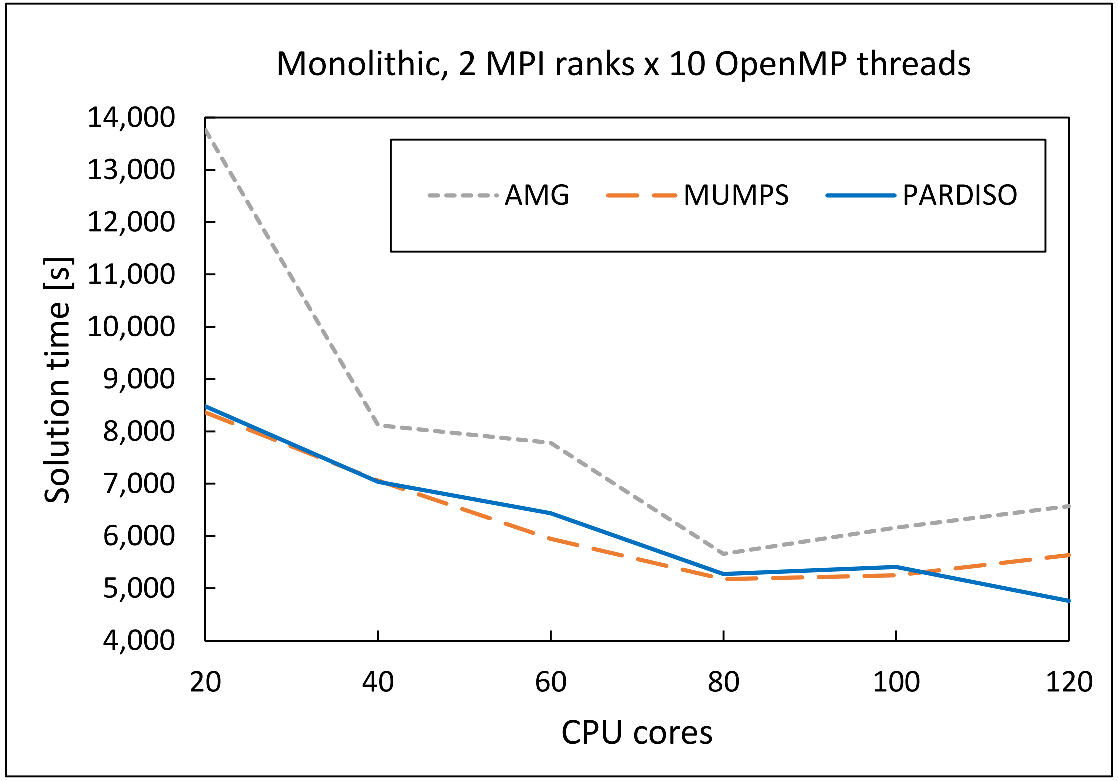


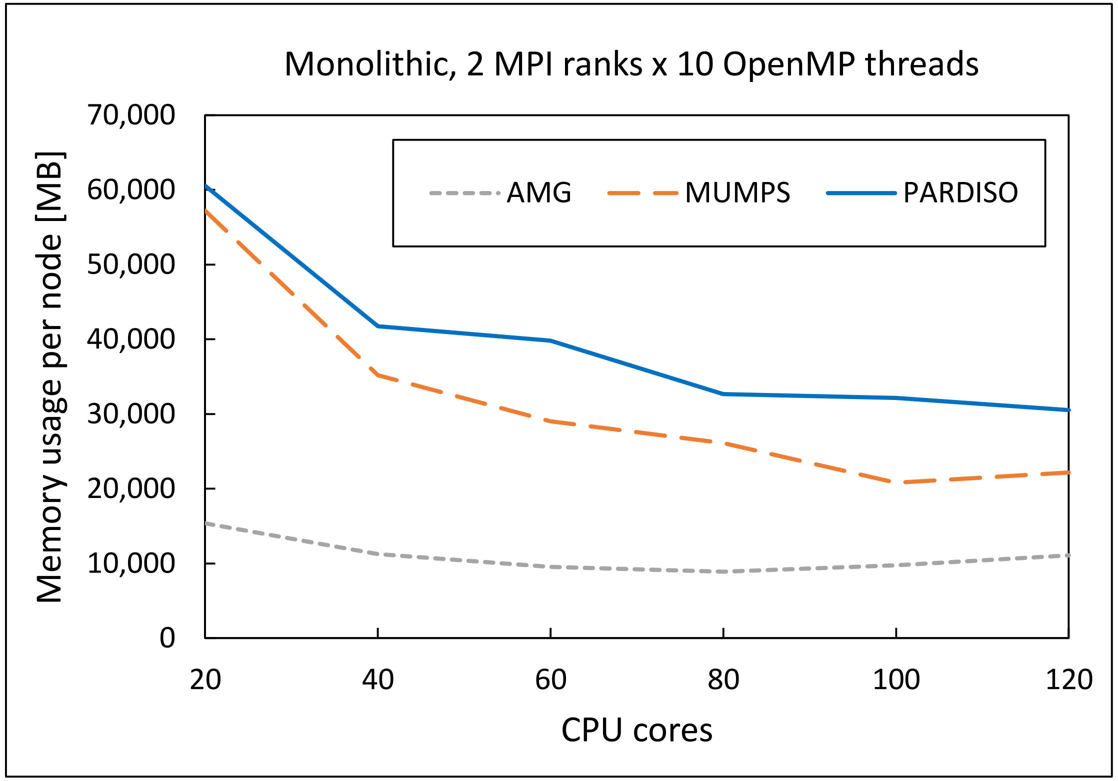


Problem size: 400k tetrahedral elements; Hardware specifications: Intel Skylake compute nodes with 192 GB RAM

2 MPI ranks x 10 OpenMP threads per node is optimum for a combined solution time and memory footprint consideration

Performance scaling of linear system solvers (PARDISO, MUMPS, AMG)

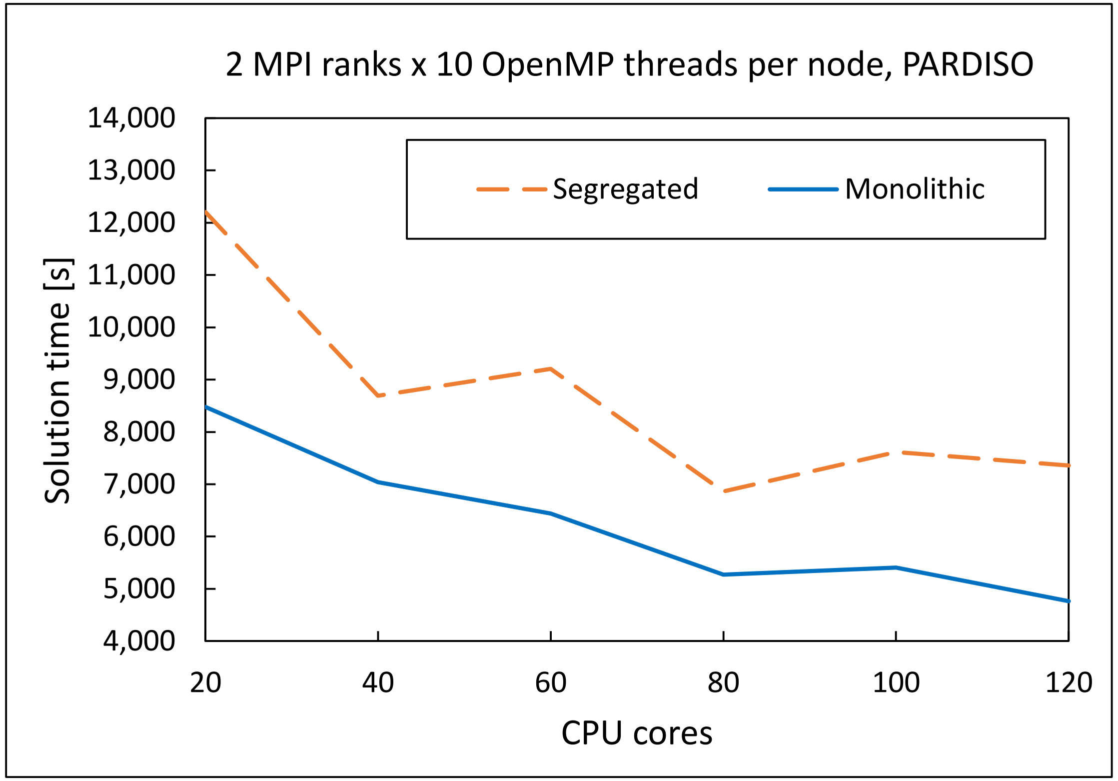


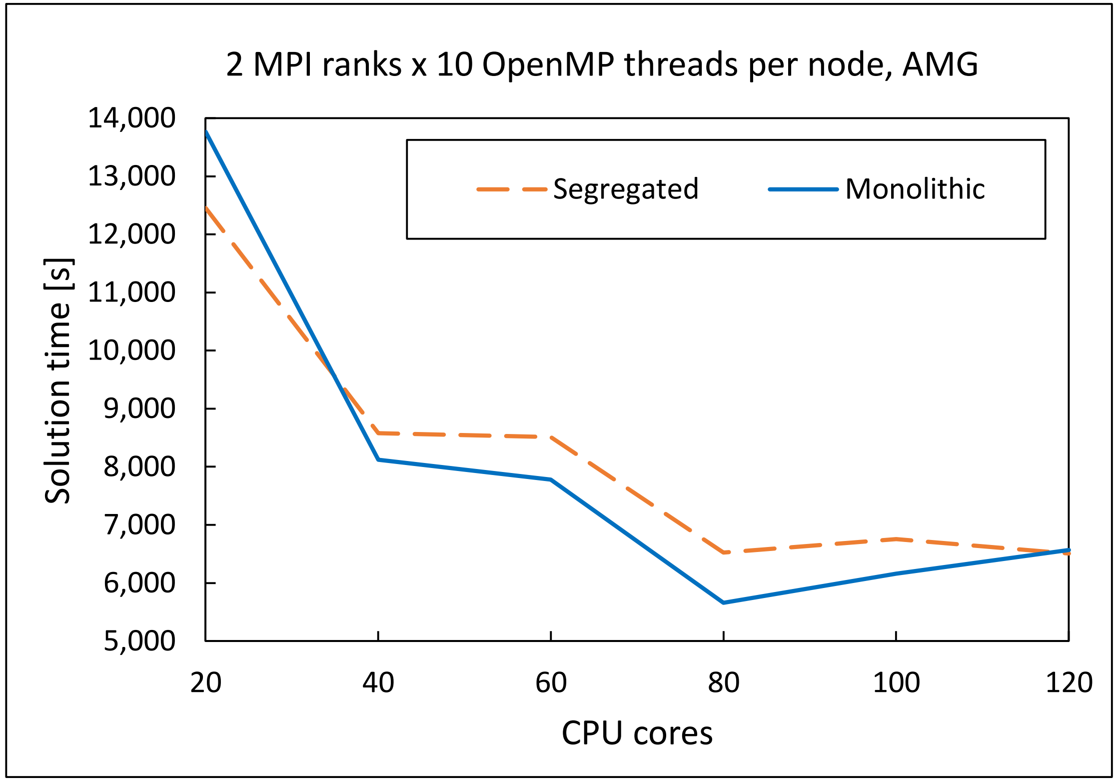


Direct solvers: Memory footprint prohibitive for large problems, steep performance degradation when out-of-core

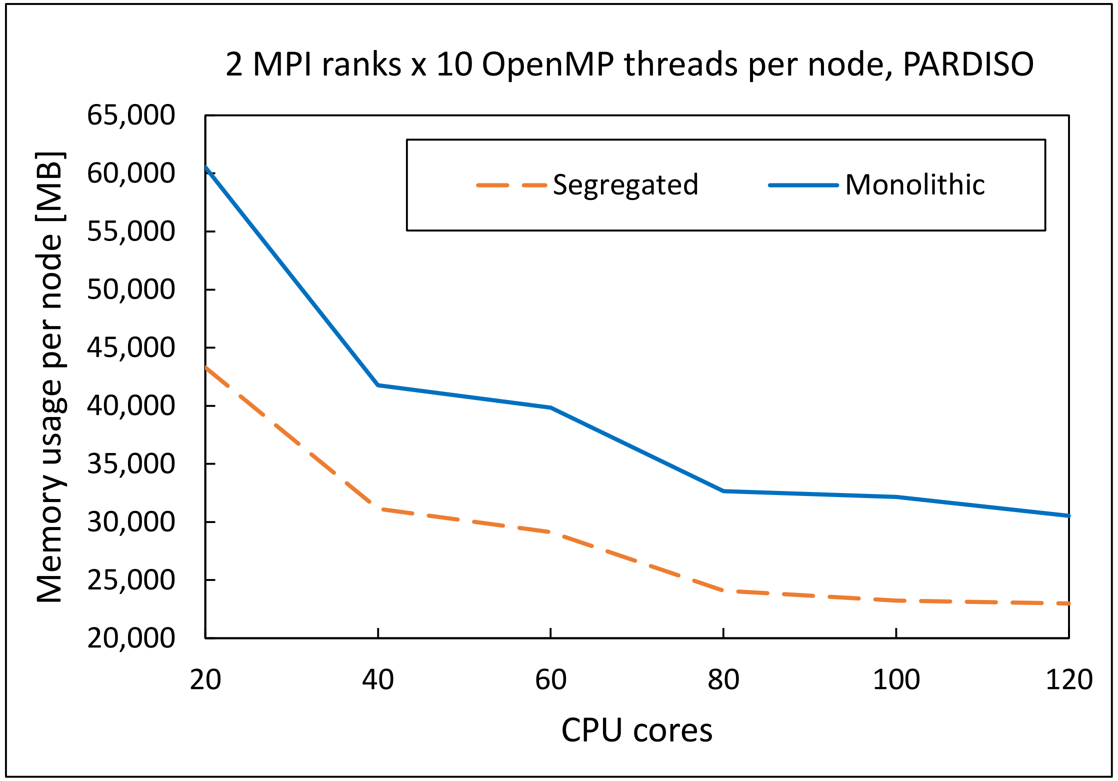
Iterative solvers: Not suitable for problems with high condition number and strong coupling effects

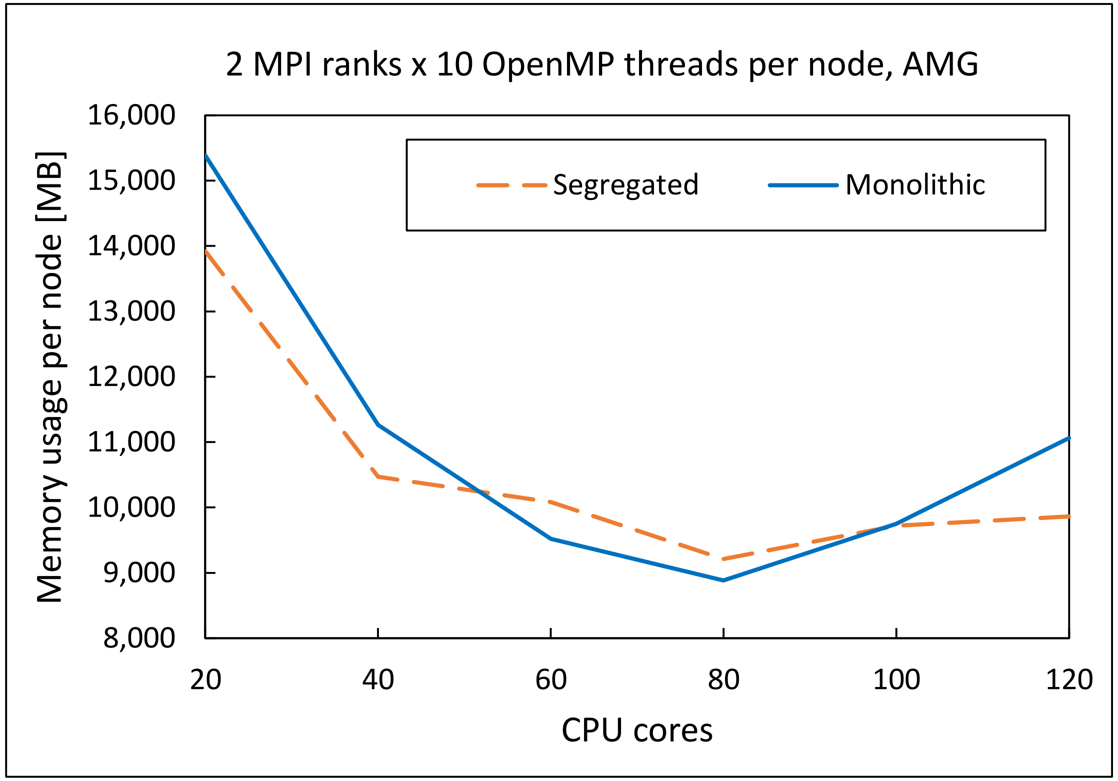
Monolithic vs. Segregated approach – scaling of solution time



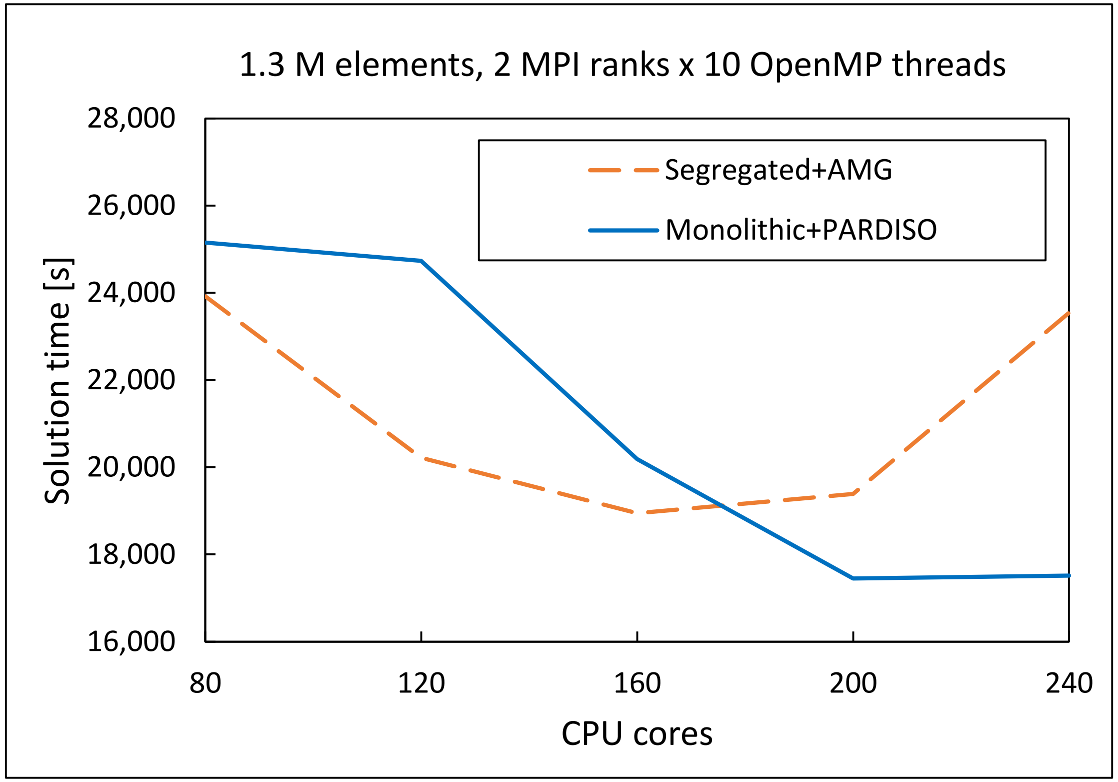


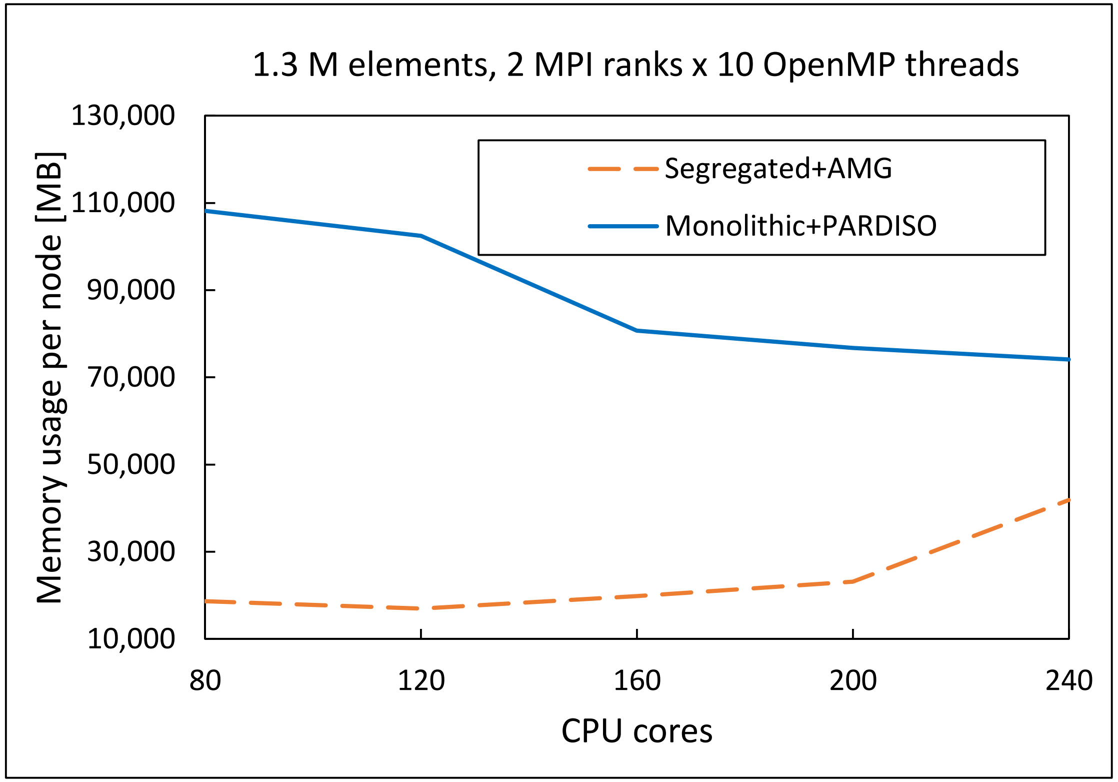
Monolithic vs. Segregated approach – scaling of memory footprint





Effect of problem size on performance scaling





Monolithic + PARDISO: Most scalable in terms of solution time

Segregated + AMG: Lowest memory footprint

Concluding remarks

- ❑ Grouping of highly coupled variables is needed for the segregated approach
- ❑ GMG solver failed to converge
- ❑ Memory footprint is critical for the performance of direct solvers
- ❑ PARDISO is the most scalable solver in terms of solution time
- ❑ More scale helps with more physics
- ❑ Computational efficiency is critical in high throughput parameter sweeps
- ❑ Simulation challenges are beyond the capabilities of today’s S/W and H/W

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