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A Coupled Smoothed Particle Hydrodynamics-Finite Volume Approach for Shock Capturing in One-Dimension

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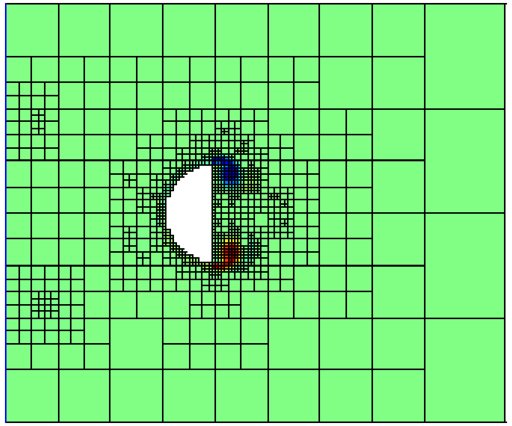
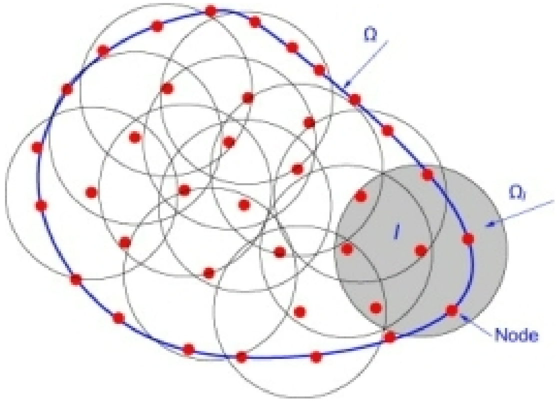
Motivation and Objectives

- Simulating shocks accurately and efficiently with traditional mesh-based methods is challenging
- Mesh refinement, higher-order methods, and sub-grid modeling can all be used to improve shock simulations
- Smoothed Particle Hydrodynamics (SPH) is a meshfree method that represents a system with physical particles
  - Particles are free to move, and interactions are computed directly between particles
- Objective: Investigate a hybrid grid-based/SPH method for improved shock capturing



[1] Spherical Shock Modeled with Adaptive Mesh Refinement



[2] Interacting Meshless Particles

Computational Tools

- Pyro2: A python framework for implementing various hydrodynamic solvers
  - Finite Volume Method (FVM) Discretization
  - Advection, Compressible/Incompressible Hydrodynamics
  - Multigrid Capability
  - Explicit time integration
  - 2-Dimensions
- A python framework for Smoothed Particle Hydrodynamics
  - Ability to write custom properties and equations for SPH particles
  - A large suite of integrators, kernels, and schemes is available as well as the option to implement new methods
  - Pre-built Cython libraries of core operations for improved performance
  - Parallelization support

FVM-SPH Coupling

- Coupling of SPH with traditional methods has been utilized for fluid-structure interaction, free surface flows, and multi-fluid problems [3,4,5]
  - No previous literature on hybrid SPH methods for shock simulations
- High gradient FVM cells flagged and populated with SPH particles
- Boundary cells/particles coupled through linear interpolation:

$$f(x_i) = \frac{f(x_l)(x_r - x_i) + f(x_r)(x_i - x_l)}{x_r - x_i}$$

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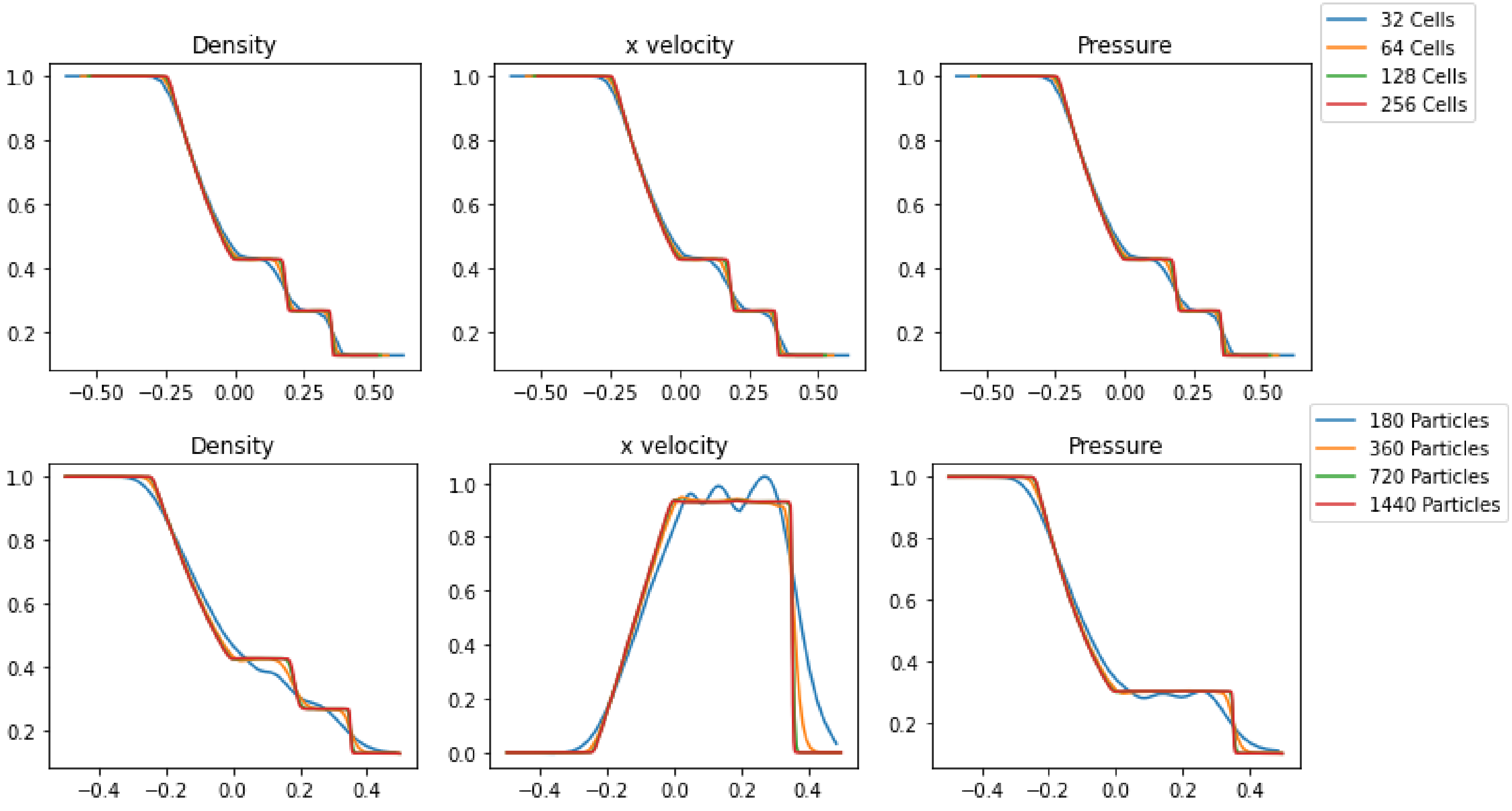
Sod Shock Tube

- Initial conditions:
  ρ(left,right) = (1.0,0.125)
  p(left,right) = (1.0, 0.1)
  u = 0
- t_final = 0.2

Pyro Results



PySPH Results

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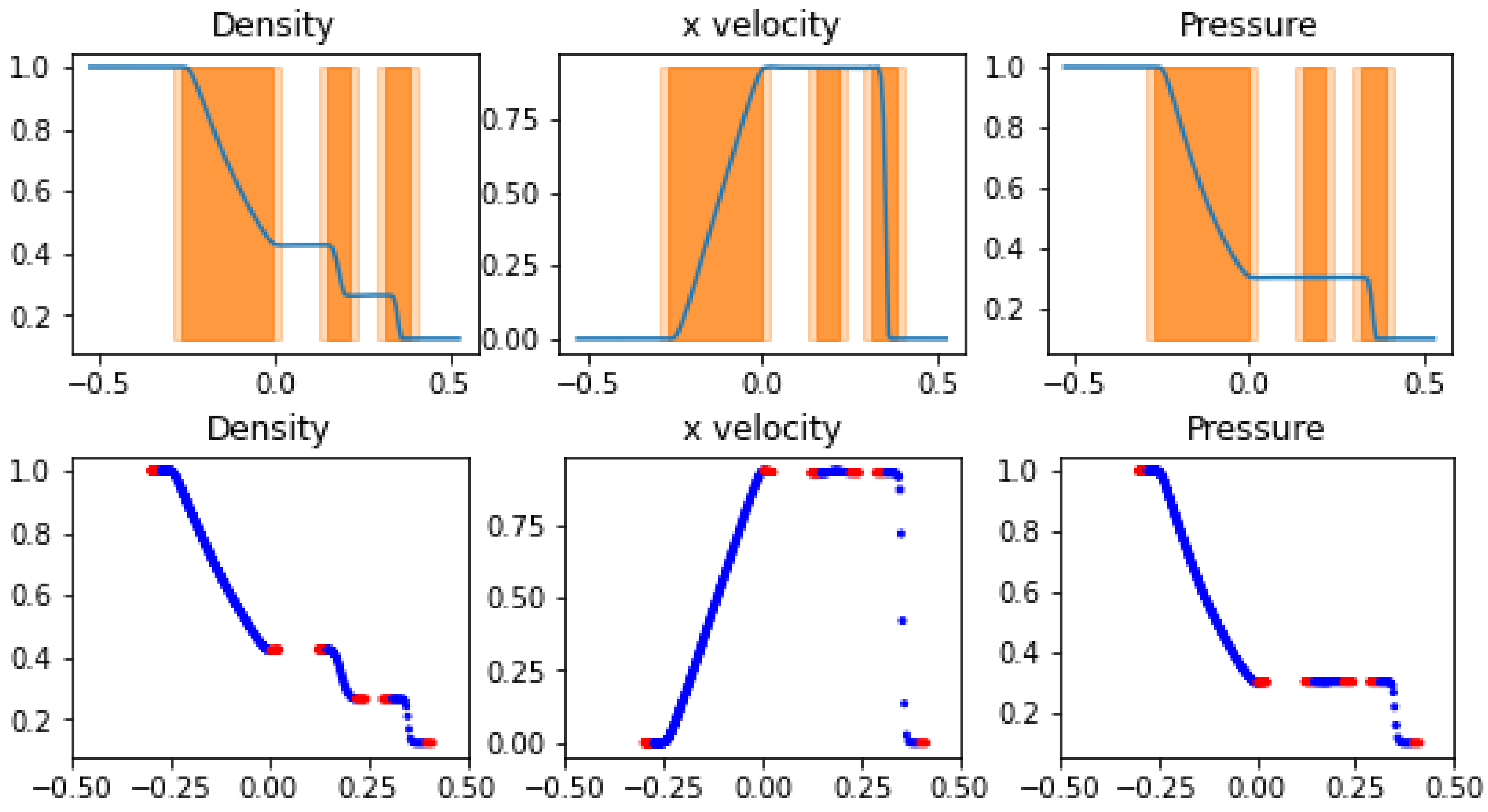
Sod Shock Tube

FVM Grid

SPH Particles



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Sod Shock Tube

Pyro2	Resolution	256 Cells	128 Cells	64 Cells	32 Cells
	Runtime	2.20s	0.965s	0.293s	0.110s
	L2 Norm	0.07779	0.09994	0.1268	0.1378
PySPH	Resolution	1440 Particles	720 Particles	360 Particles	180 Particles
	h	0.6	1.2	2.4	4.8
	Runtime	9.67s	9.30s	9.04s	10.37s
	L2 Norm	0.1910	0.1968	0.2734	0.4388

Hybrid simulation parameters: 32 cells, 720 particle resolution

- Runtime: 17.2s
- L2 Norm: 0.1928
- Particles at t=0.02: 302

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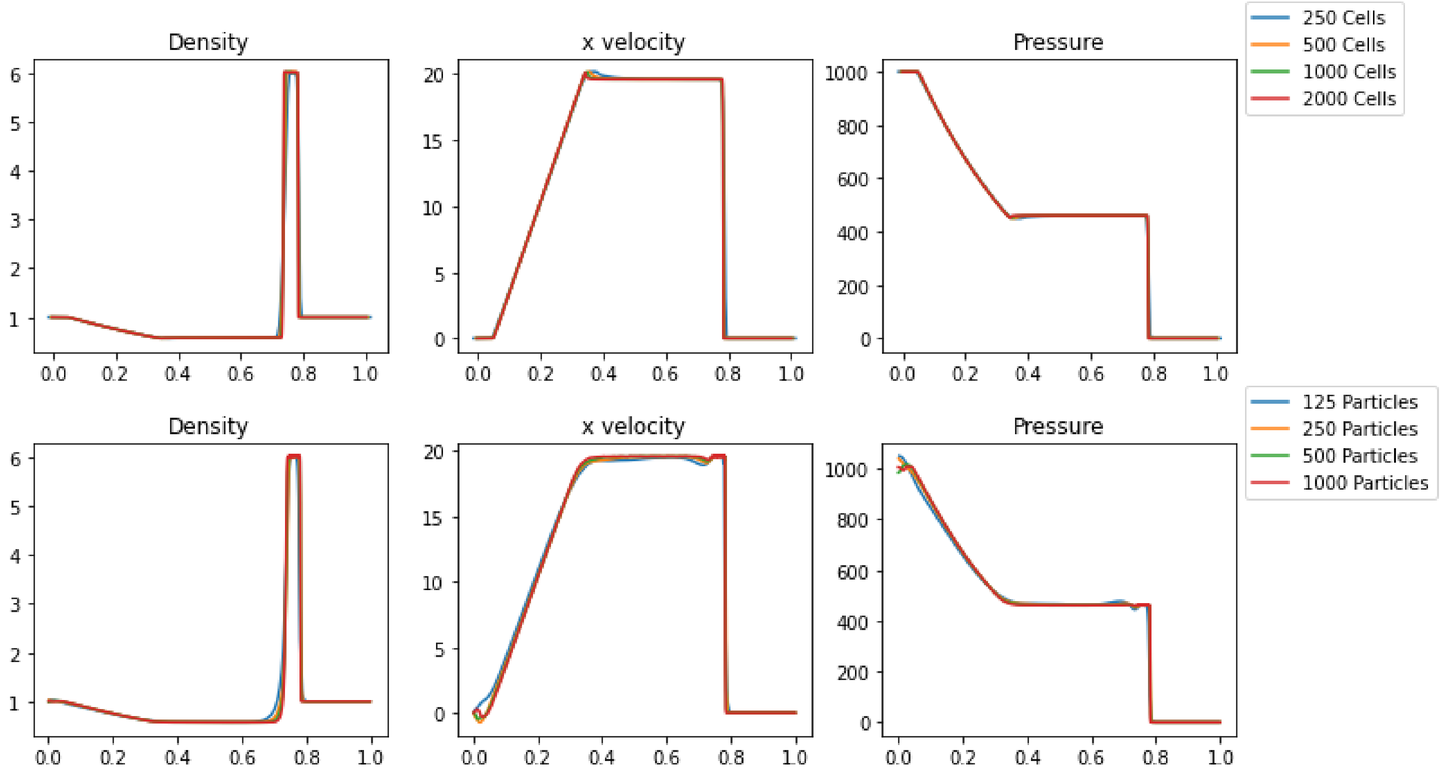
Strong Shock Problem

- Initial conditions:
  ρ = 1.0
  p(left,right) = (1000.0, 0.01)
  u = 0
- t_final = 0.012

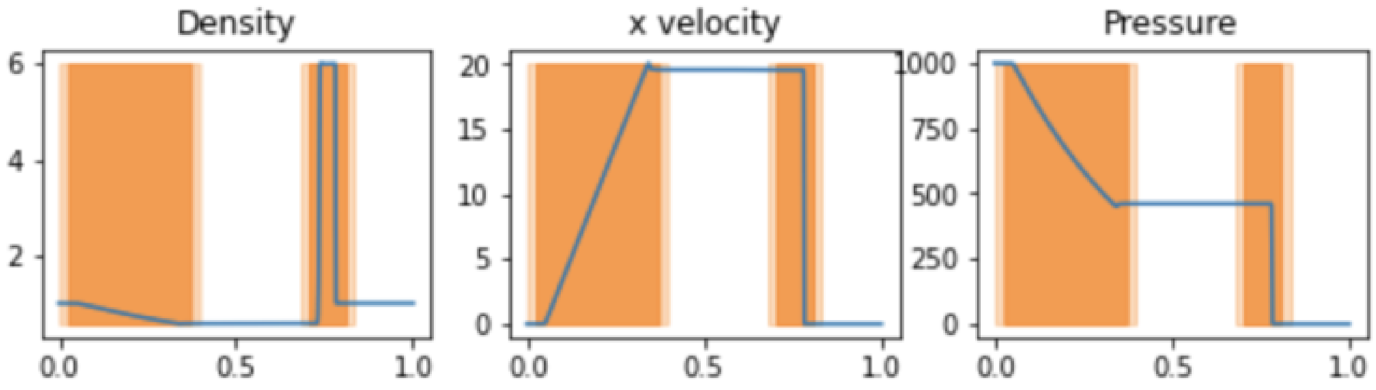
Pyro Results



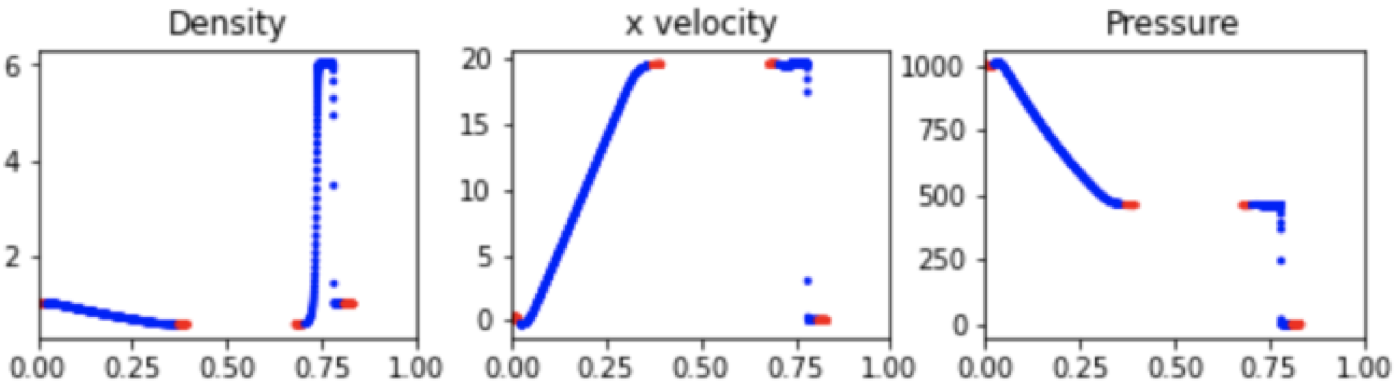
PySPH Results

Strong Shock Problem

FVM Grid



SPH Particles



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Strong Shock Problem

Pyro2	Resolution	2000 Cells	1000 Cells	500 Cells	250 Cells
	Runtime	222s	117s	61.8s	36.4s
	L2 Norm	1.849	2.611	4.155	4.406

PySPH	Resolution	1000 Particles	500 Particles	250 Particles	125 Particles
	h	1.5	3.0	6.0	12.0
	Runtime	30.1s	28.4s	20.9s	16.8s
	L2 Norm	2.262	2.749	4.343	4.675

Hybrid simulation parameters: 250 cells, 1000 particle resolution

- Runtime: 29.7s
- L2 Norm: 2.169
- Particles at t=0.012: 678

Woodward-Colella Blastwave

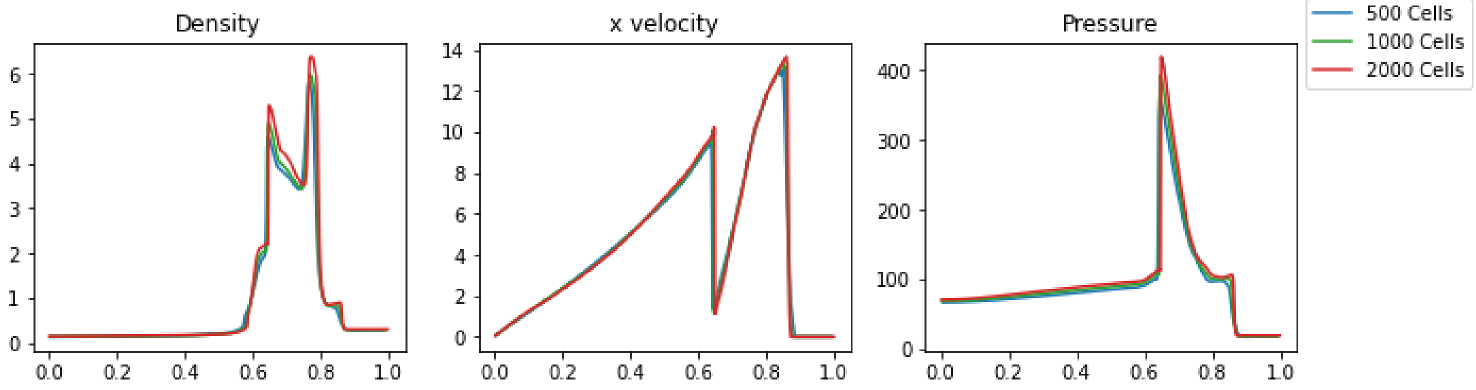
- Initial conditions:
  - Left: x<0.1; Right: x>0.9

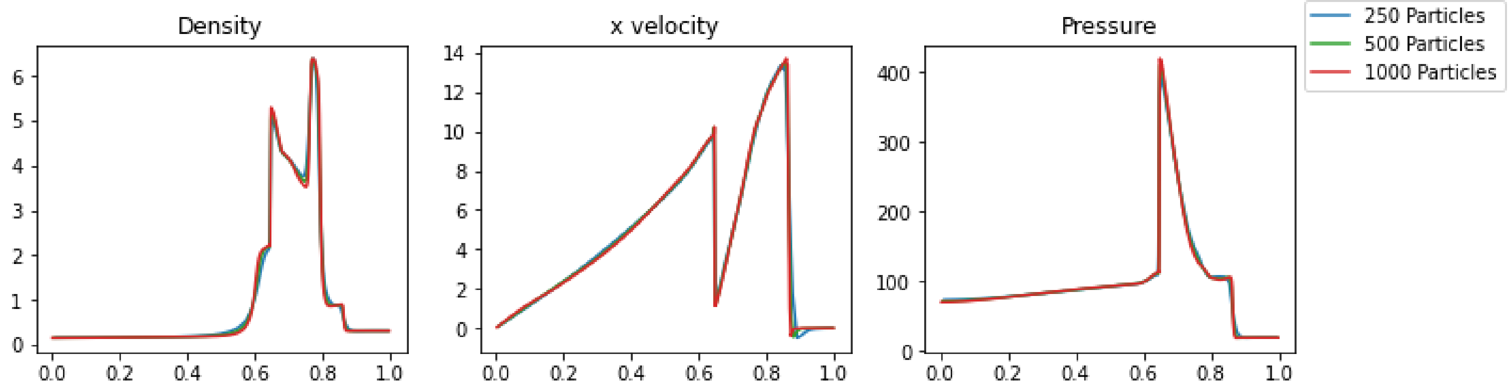
    ρ = 1.0

    p(left,middle,right) = (1000.0,0.01,100.0)

    u = 0
- t_final = 0.038

Pyro Results





PySPH Results

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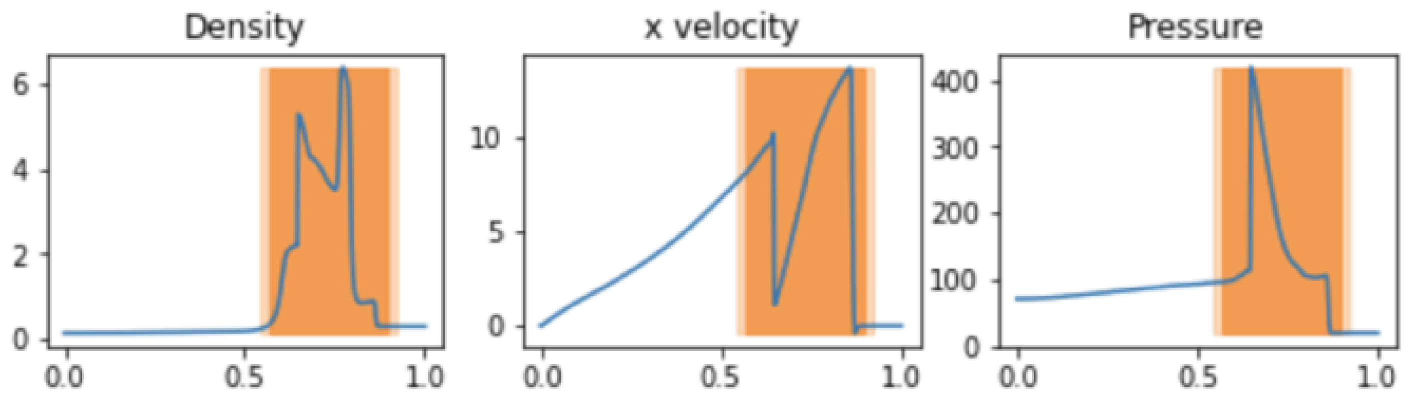
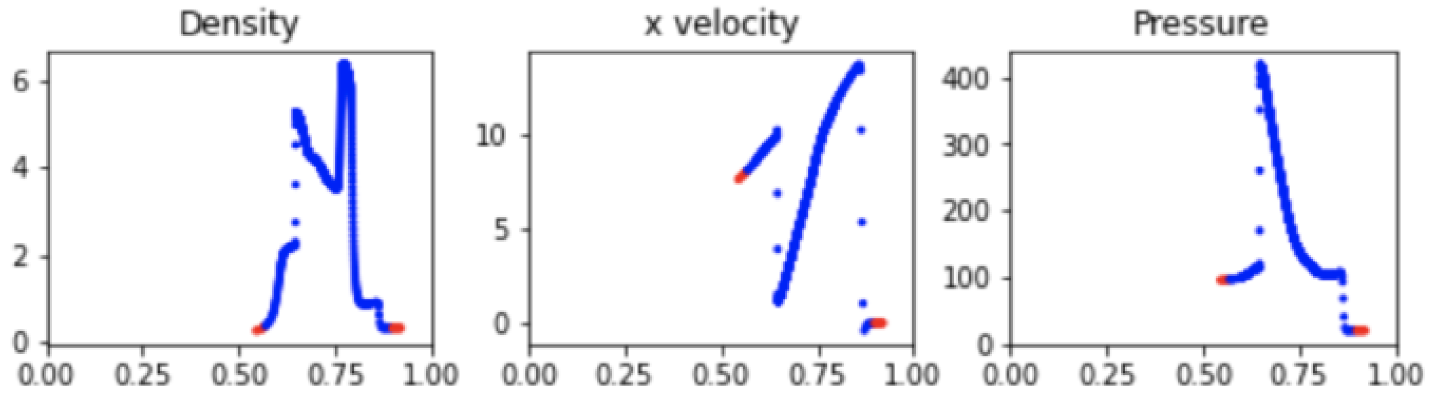
Woodward-Colella Blastwave

FVM Grid



SPH Particles



Woodward-Colella Blastwave

Pyro2	Resolution	2000 Cells	1000 Cells	500 Cells
	Runtime	697s	376s	205s
	L2 Norm	4.735	10.977	13.145

PySPH	Resolution	1000 Particles	500 Particles	250 Particles
	h	1.5	3.0	6.0
	Runtime	96.2s	71.8s	59.0s
	L2 Norm	2.532	3.238	4.921

Hybrid simulation parameters: 32 cells, 720 particle resolution

- Runtime: 84.3s
- L2 Norm: 2.550
- Particles at t=0.038: 784

Discussion and Future Work

- Coupling FVM with SPH enhances computational efficiency without sacrificing accuracy for strong shock simulations
- Advantages expected to scale in 2D; however, the computational cost of the coupling algorithm is also expected to increase
- Future Work: Extension of methods to 2D test problems, application of hybrid approach to full-scale blast simulation in HPC environment

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References

1. A. Adcrift, Basilisk/Gerris Users' Meeting 2017, Princeton University, Princeton, NJ (2017).
2. V. P. Nguyen, "Meshless methods: A review and computer implementation aspects", *Mathematics and Computers in Simulation*. 79-3 (2008) 763-813.
3. G. Fourey, C. Hermange, D. Le Touze and G. Oger, "An efficient FSI coupling strategy between Smoothed Particle Hydrodynamics and Finite Element methods," Computer Physics Communications, vol. 217, pp. 66-81, 2017.
4. S. Marrone, A. Di Mascio and D. Le Touze, "Coupling of Smoothed Particle Hydrodynamics with Finite Volume method for free-surface flows," Journal of Computational Physics, vol. 310, pp. 161-180, 2016.
5. B. Ren, C. Li, X. Yan, M. Lin, J. Bonet and S. Hu, "Multiple-Fluid SPH Simulation Using a Mixture Model," ACM transactions on graphics, vol. 33, no. 5, pp. 1-11, 2014.

Questions?

Appendix

Smoothed Particle Hydrodynamics (SPH)

- SPH is a meshfree method that utilizes simulated particles to represent a fluid
- Fields are defined at particle locations and entirely represented through particles
- Fields are approximated through the kernel and particle approximations

Starting Identity:

$$f(x) = \int_{\Omega} f(x')\delta(x - x')dx'$$

Kernel Approximation:

$$< f(x) >= \int_{\Omega} f(x')W(x - x', h)dx'$$

Derivative Approximation:

$$< \nabla \cdot f(x) >= -\int_{\Omega} f(x') \cdot \nabla W(x - x', h)dx'$$

For every particle:

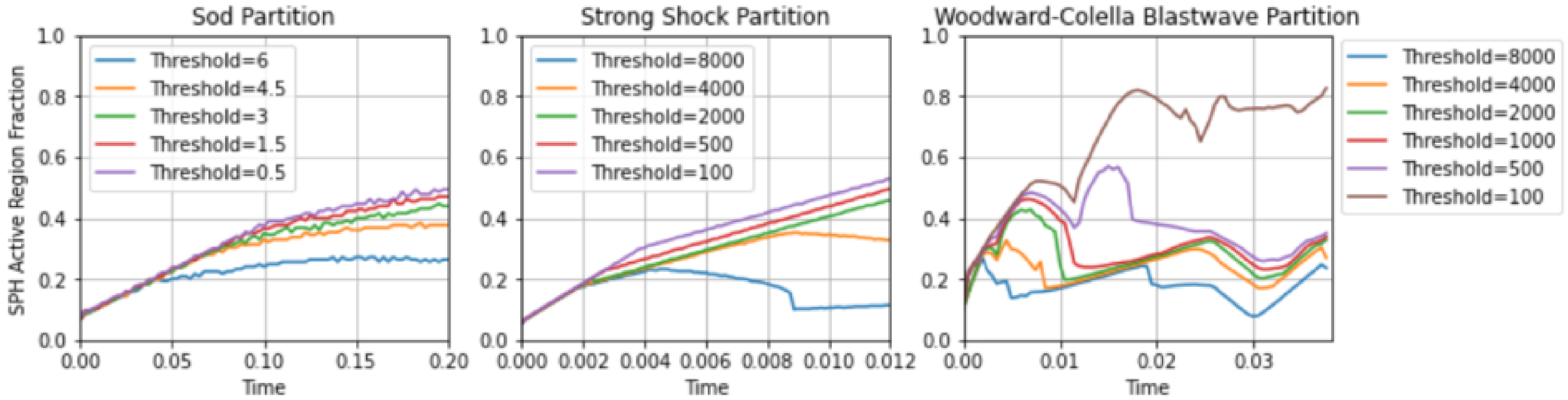
$$m_j = \Delta V_j \rho_j$$

→

Particle Approximation

$$< f(x_i) >= \sum_{j=1}^{N} \frac{m_j}{\rho_j} f(x_j) \cdot W_{ij}$$

FVM Flagging Threshold



- Relative parameter for determining the gradient flagging threshold for populating FVM cells with SPH particles
- Optimal thresholds (highest efficiency without sacrificing accuracy):
  - Sod: 3.0; Shock: 2000; WC Blastwave: 2000