Interactive Simulation of Generalised Newtonian Fluids using GPUs

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Goal

- To interactively simulate and visualise Generalised Newtonian Fluids (GNF) using GPUs.
- Simulate Newtonian and non-Newtonian fluids using a common framework in realtime for reasonable domain sizes.
- Demonstrate the potential to scale to larger domain sizes using MultiGPU implementation.

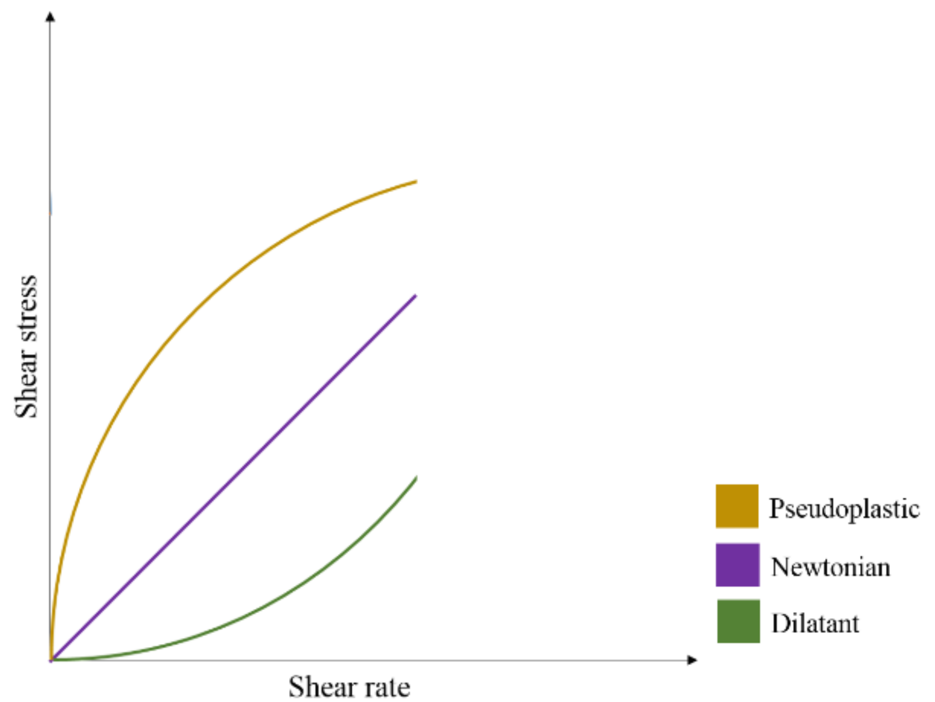
Generalised Newtonian Fluids

- Newtonian Fluids -
  Viscosity independent of shear rate

- Non-Newtonian Fluids -

  - Shear thinning or pseudoplastic -
    Viscosity decreases with increasing shear rate

  - Shear thickening or dilatant -
    Viscosity increases with increasing shear rate



Flow curve for
Generalised Newtonian Fluids

Related Work

- Lattice Boltzmann Method

(Ando et al. [SIGGRAPH'13], Thuerey et al. [SIGGRAPH'05], Thuerey et al. [Proceedings of Vision, Modeling and Visualization'06], Chen et al. [Annual Review of Fluid Mechanics'98])

  - Newtonian fluids simulation
  - Method on different grid types (tetrahedral and adaptive)

- Non-Newtonian Fluids (Modelling and Simulation)

(Phillips et al. [IMA Journal of Applied Mathematics'11], Boyd et al. [Journal of Physics A: Mathematical and General], Desbrun et al. [EGCAS'96])

  - Non-Newtonian fluid models
    - Cross, Carreau, Ellis Models etc.
  - Viscoelastic fluid simulation using conventional methods.

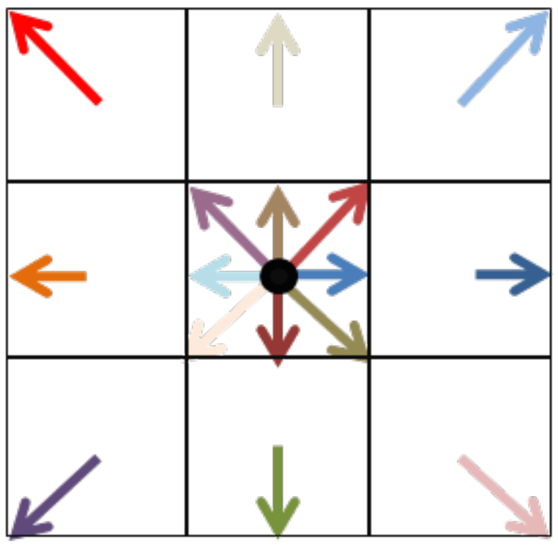
- Lattice Boltzmann Method on GPUs

(Januszewski et al. [Computer Physics Communications'14], Schreiber et al. [Procedia Computer Science'11])

  - Multi-component and Free Surface flows on single and multi-GPUs.

Our Approach

- Lattice Boltzmann Method (LBM) for simulation
    - A mesoscopic approach - particles (logical in nature) collide at grid centers and progress to neighbours in fixed directions.



Particle in a LBM grid

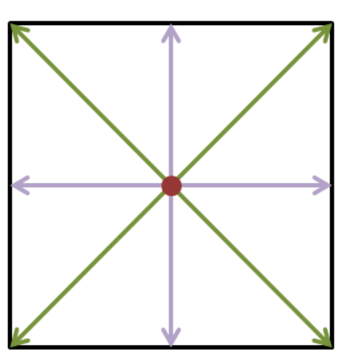
- Truncated Power Law to calculate the localised viscosity for non-Newtonian fluids
- Marching Cubes for visualisation of the fluid
- Exploit the inherent parallelism of LBM coupled with an efficient memory access pattern to create a fast GPU implementation

Why LBM?

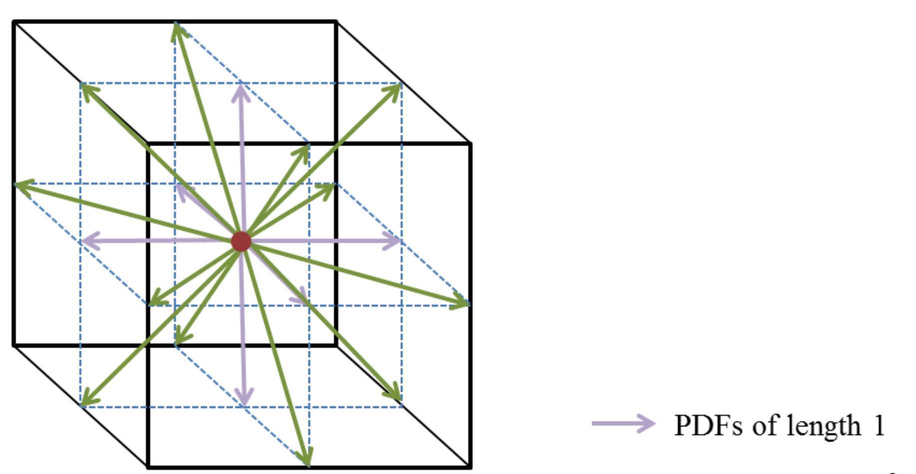
- A statistical approach - eliminates the need to solve partial differential equations
- Gives second order accuracy in contrast to first order accuracy displayed by conventional Eulerian and Lagrangian methods
- High parallelism because works on cartesian grids, with each cell independent of the other
- Easy to understand and implement

Lattice Boltzmann Method

- Works on cartesian discretisation of simulation domain in regular cells
- Particles constrained to travel in specific directions only
- We use the D3Q19 grid for simulation in 3-dimensions
- Velocity of particles given by $\mathbf{e}_i$



D2Q9 Lattice



D3Q19 Lattice

Vector	Direction
$\mathbf{e}_0$	$(0,0,0)'$
$\mathbf{e}_{1,2}$	$(\pm1,0,0)'$
$\mathbf{e}_{3,4}$	$(0,\pm1,0)'$
$\mathbf{e}_{5,6}$	$(0,0,\pm1)'$
$\mathbf{e}_{7\ldots10}$	$(\pm1,\pm1,0)'$
$\mathbf{e}_{11\ldots14}$	$(0,\pm1,\pm1)'$
$\mathbf{e}_{15\ldots18}$	$(\pm1,0,\pm1)'$

Velocity vectors for D3Q19

Particle Distribution Functions

- Each cell tracks the number of particles going in different directions using *particle density functions*

- Each cell unit sided and each particle unit massed

- Density for a cell given by

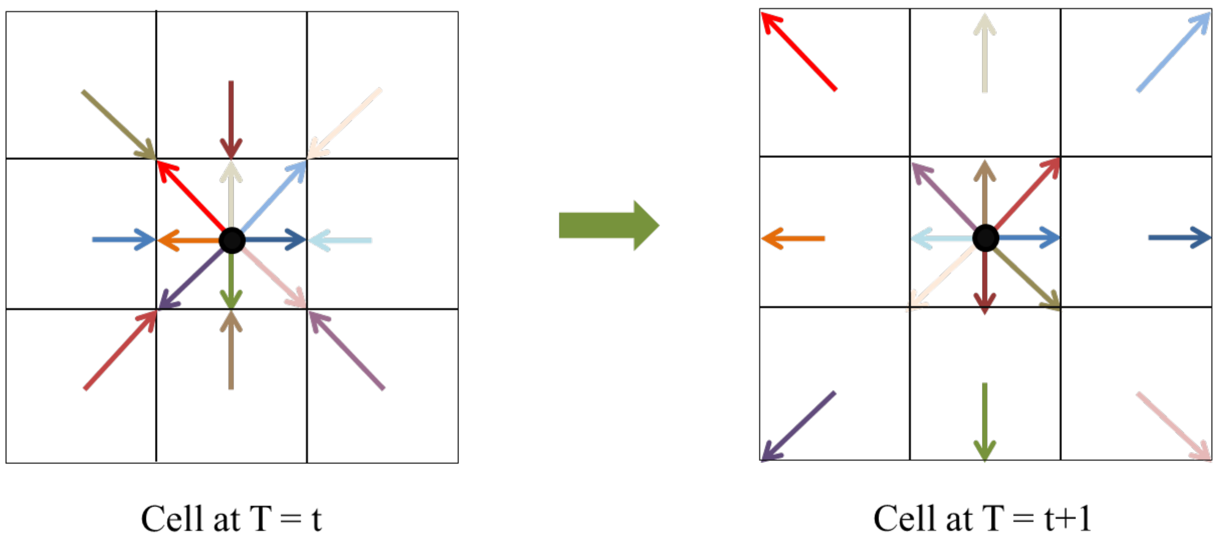
$$\rho = \sum df_i$$

- Velocity for a cell given by

$$\mathbf{u} = \sum df_i \cdot \mathbf{e_i}$$

Basic LBM

- Streaming step -
  Read neighbours' distribution function for corresponding directions and update



Streaming of DFs

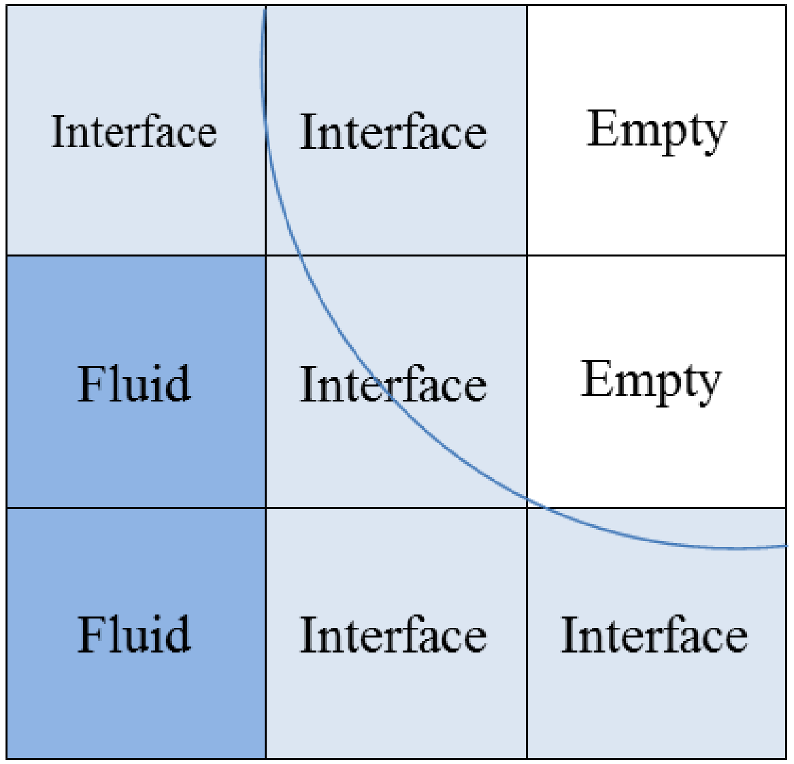
- Collision step -
  Calculate density and velocity for each cell, collide them and update the distribution functions using -

$$df_i^{eq}(\rho, \mathbf{u}) = w_i \left(\rho - \frac{3}{2}\mathbf{u}^2 + 3\mathbf{e_i} \cdot \mathbf{u} + \frac{9}{2}(\mathbf{e_i} \cdot \mathbf{u})^2 \right)$$

$$df_i = (1 - \omega) df_i + \omega df_i^{eq}$$

Free Surface LBM

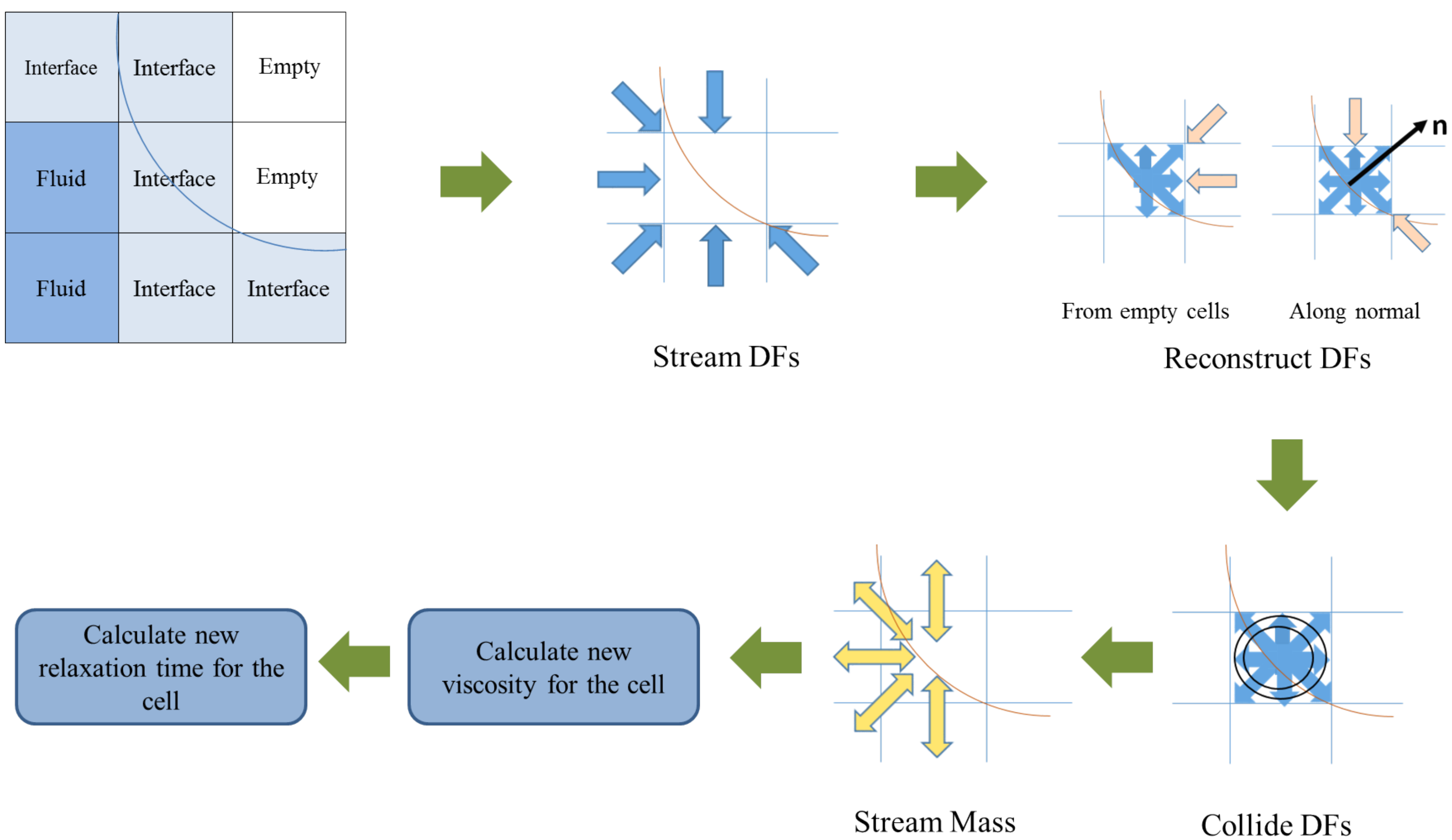
- Cells are differentiated on the basis of whether they contain fluid, gas or form the interface between them
- Interface cells are partially filled with liquid
- As the liquid progresses, the cells get relabelled according to the amount of fluid they hold
- The interface cells define the boundary of the fluid



Liquid surface and lattice cells

Overview of the algorithm

- TODO : Include this
  We build upon the algorithm given by "*Free Surface Lattice-Boltzmann fluid simulations with and without level sets*" by Thuerey et al



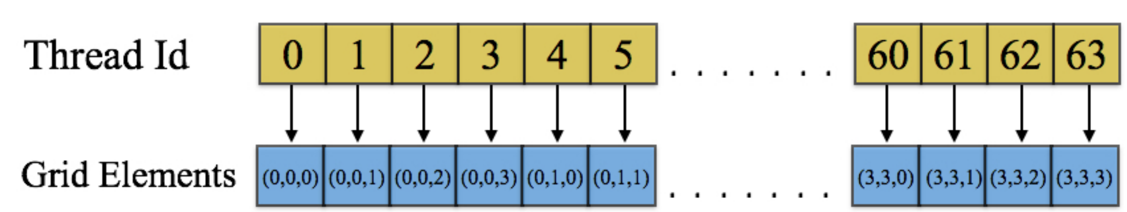
Overview of Free Surface LBM

Parallel Implementation using CUDA

- Data stored in global memory
- Double buffering for storing DFs
- Assigned one thread per cell
- Each warp works on cells lying in the same row, leading to optimised access

Data	Size	Use
Previous DFs	19 floats	Previous iteration distribution function
Current DFs	19 floats	Current iteration distribution function
Previous State	1 int	Type of cell in previous iteration
Current State	1 int	Type of cell in current iteration
Epsilon	1 float	Intermediate, visualisation purposes
Velocity	3 floats	Intermediate, visualisation purposes

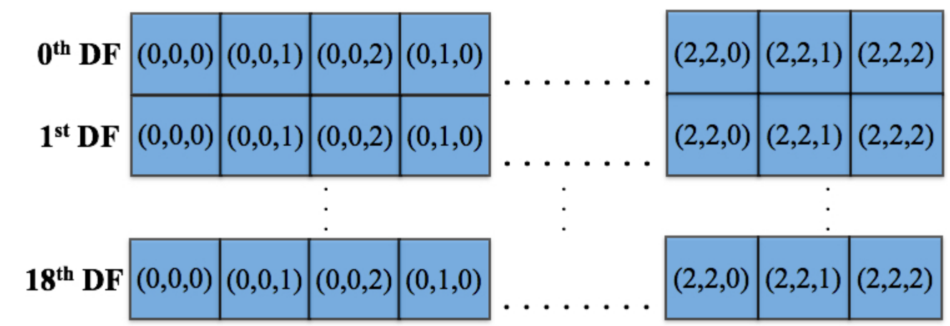
Table 2: Data Requirement for each cell



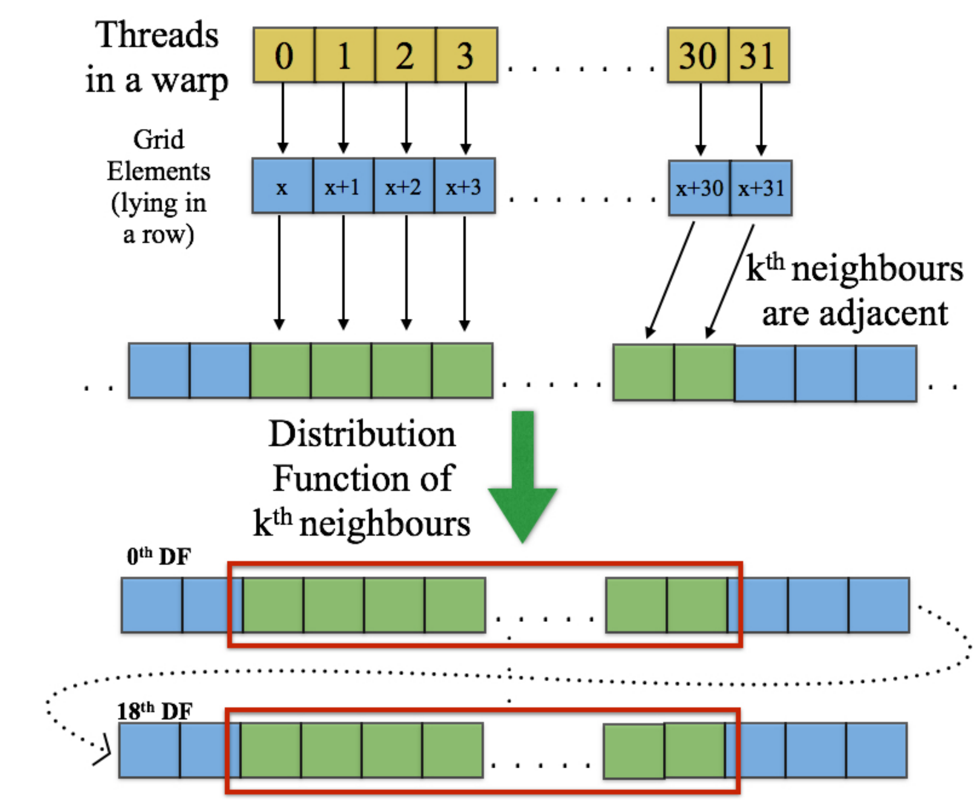
Thread Mapping with Grid Elements

Memory Access Pattern

- Data stored as Structure of Arrays
- Data for 3D grid stored linearly as a 1D array in row major format
- Threads in a warp read/update the DF for a particular direction simultaneously. These accesses fully coalesced because adjacent threads map to horizontally adjacent cells of the grid
- 75-100% kernel occupancy achieved for such accesses.



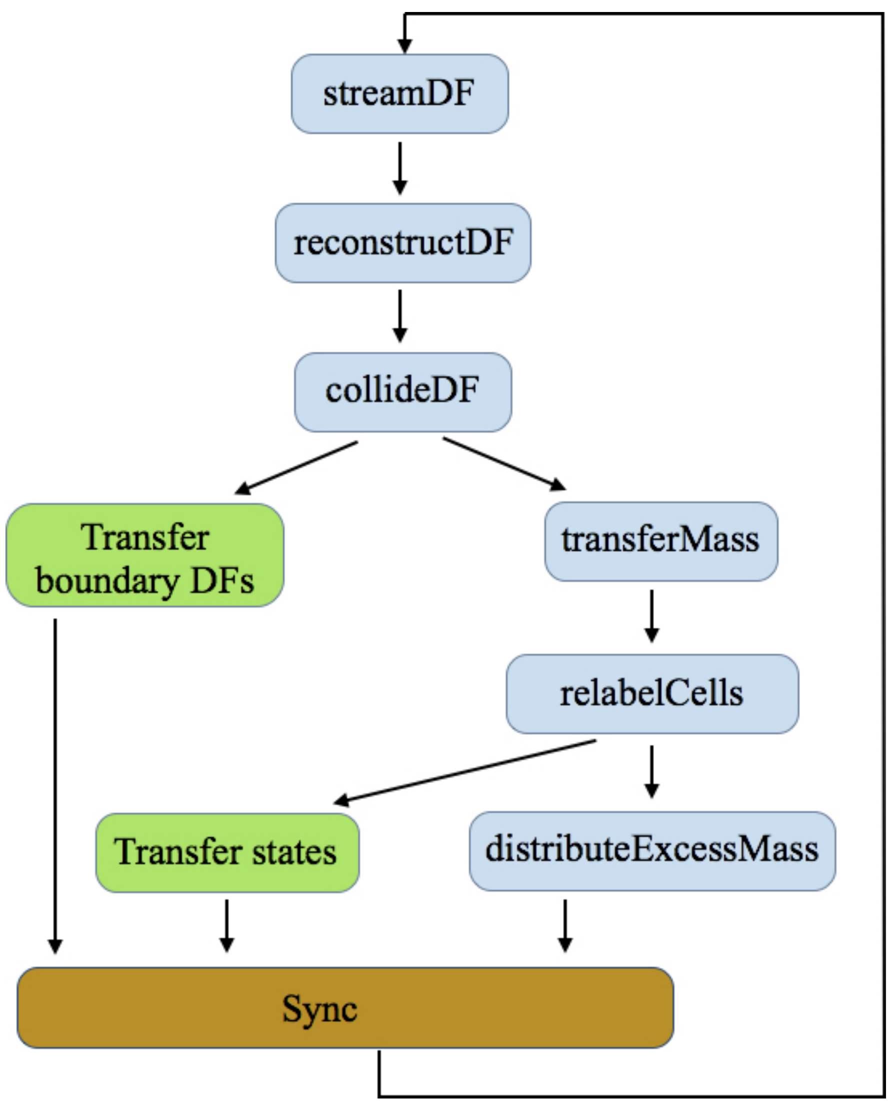
DF Layout for a 3^3 Grid, stored in row major format



DFs for k^{th} neighbours of adjacent cells

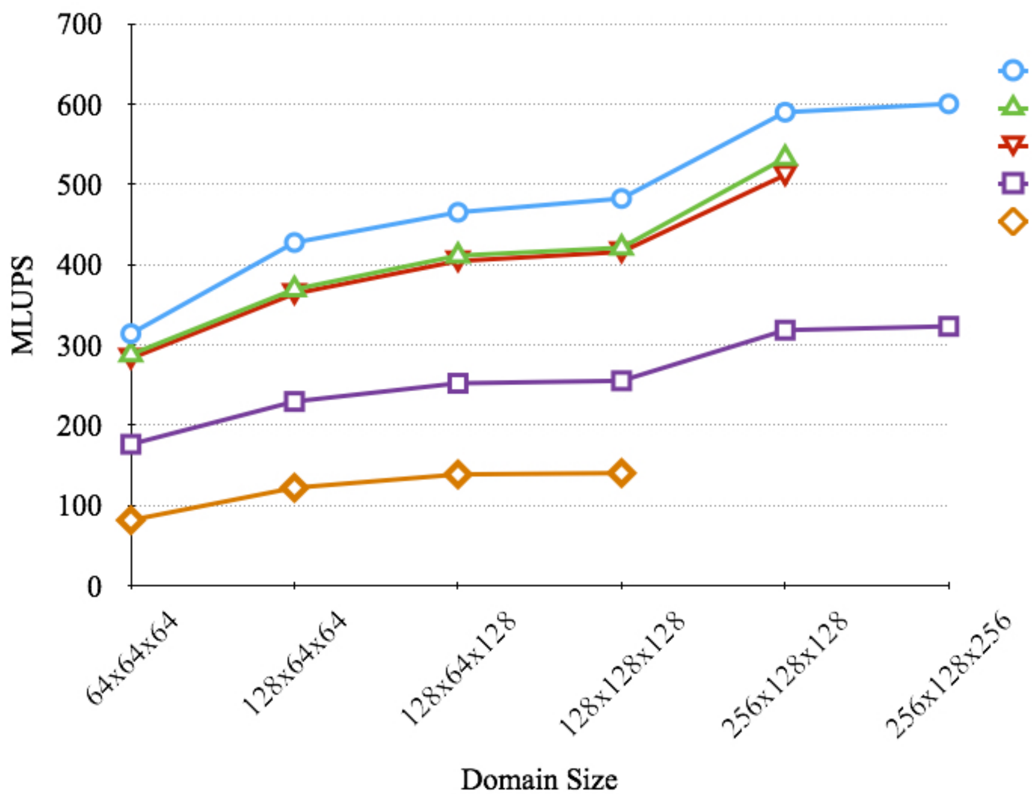
Multiple GPUs

- Use two GPUs on the same system to further scale the problem
- Data divided into 2 parts by slicing the grid along the z-axis
- For data on the boundary, neighbours reside on the other GPU, so boundary slice is transferred
- Data transfer overlapped with the computation.

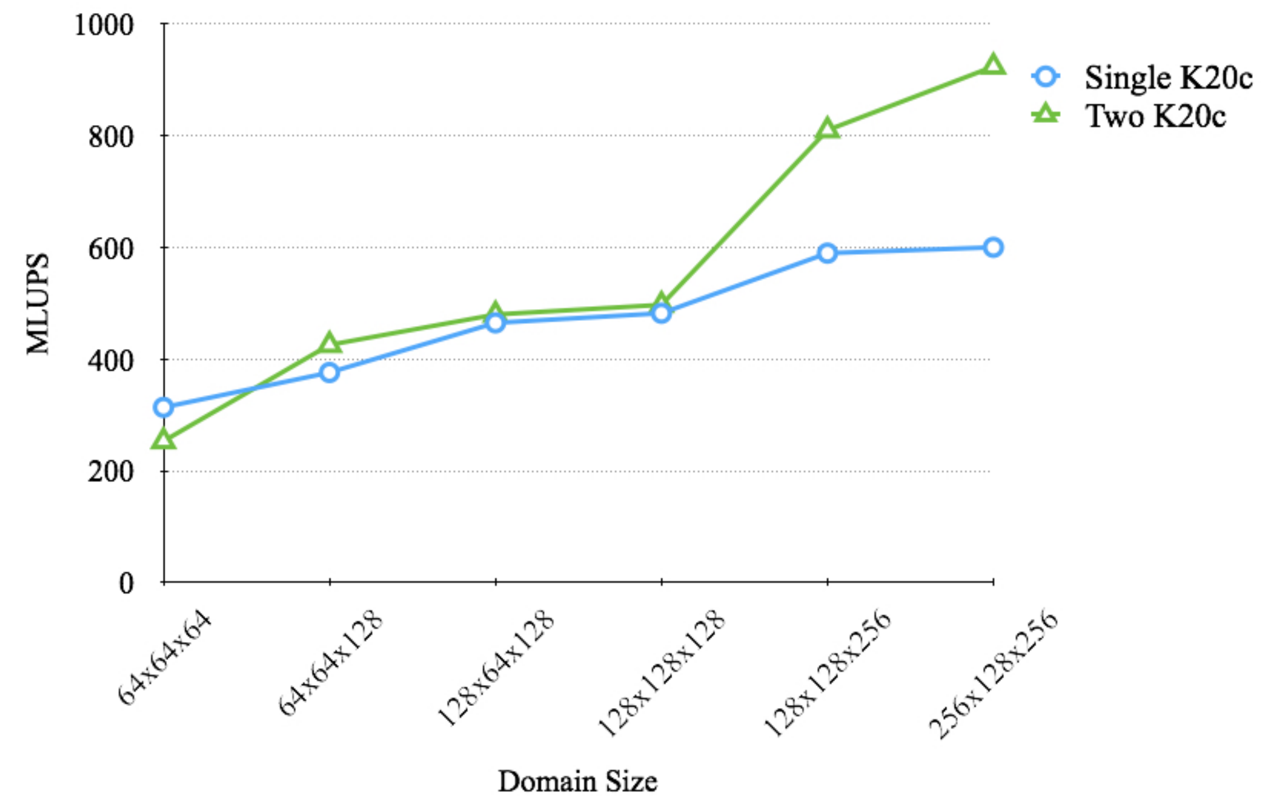


Overlap of data transfers with computation

Results



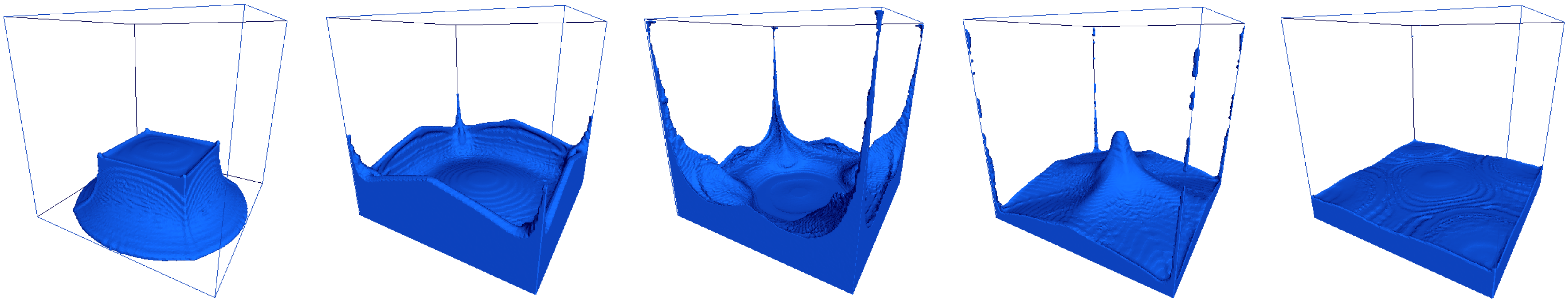
Performance of the Dam Break Experiment on various GPUs



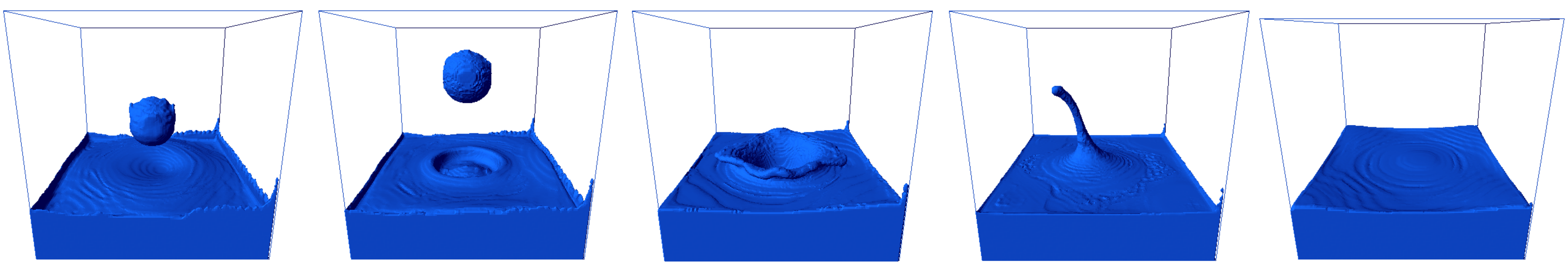
Performance of the Dam Break Experiment on single and multi-GPUs

Performance measured in Million Lattice Updates per Second (MLUPS)

Visualisation

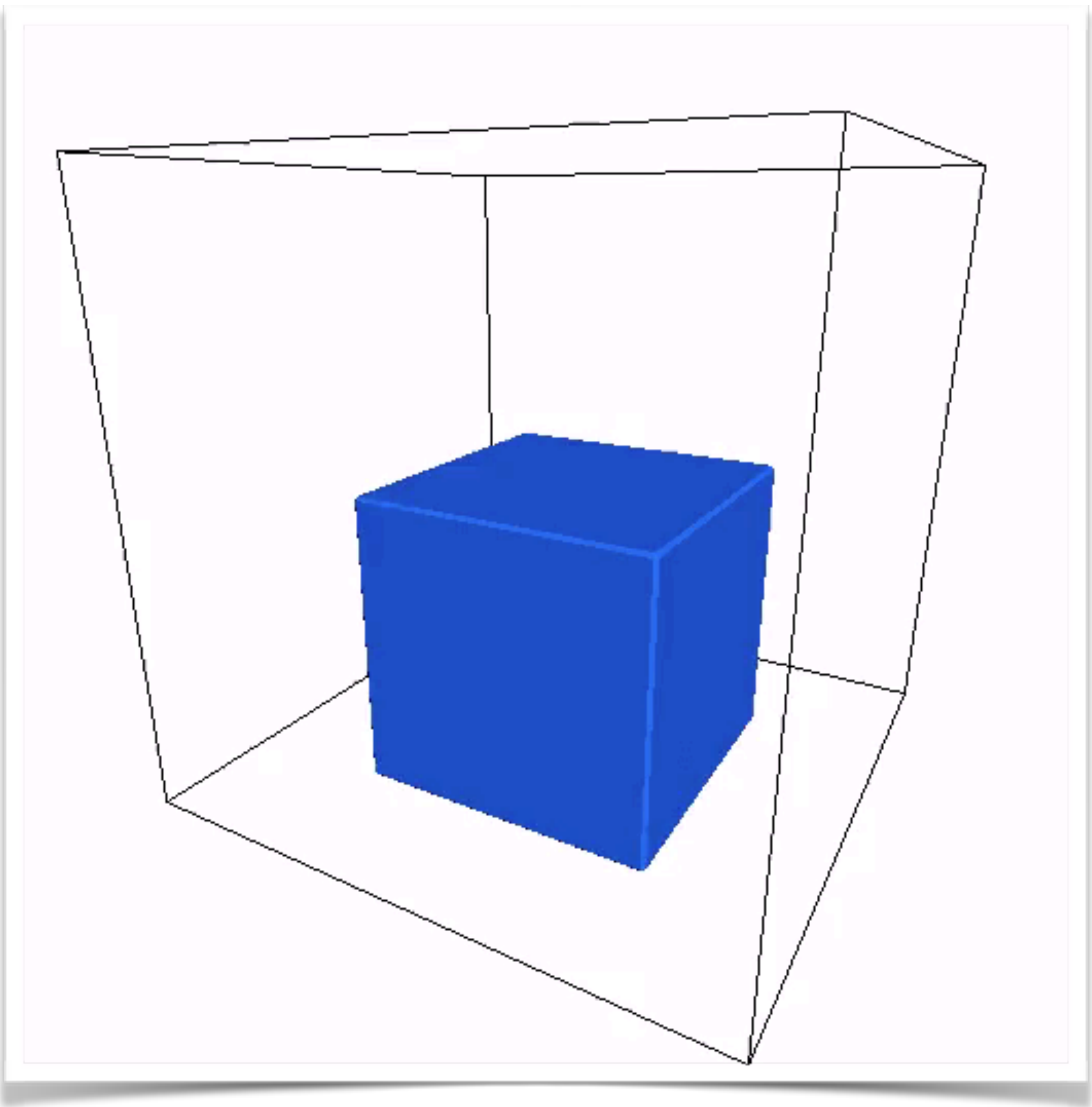


Intermediate frames for Dam Break Experiment for a Newtonian Fluid on a 128^3 grid, running at an average of 5 fps with 50 LBM iterations per frame

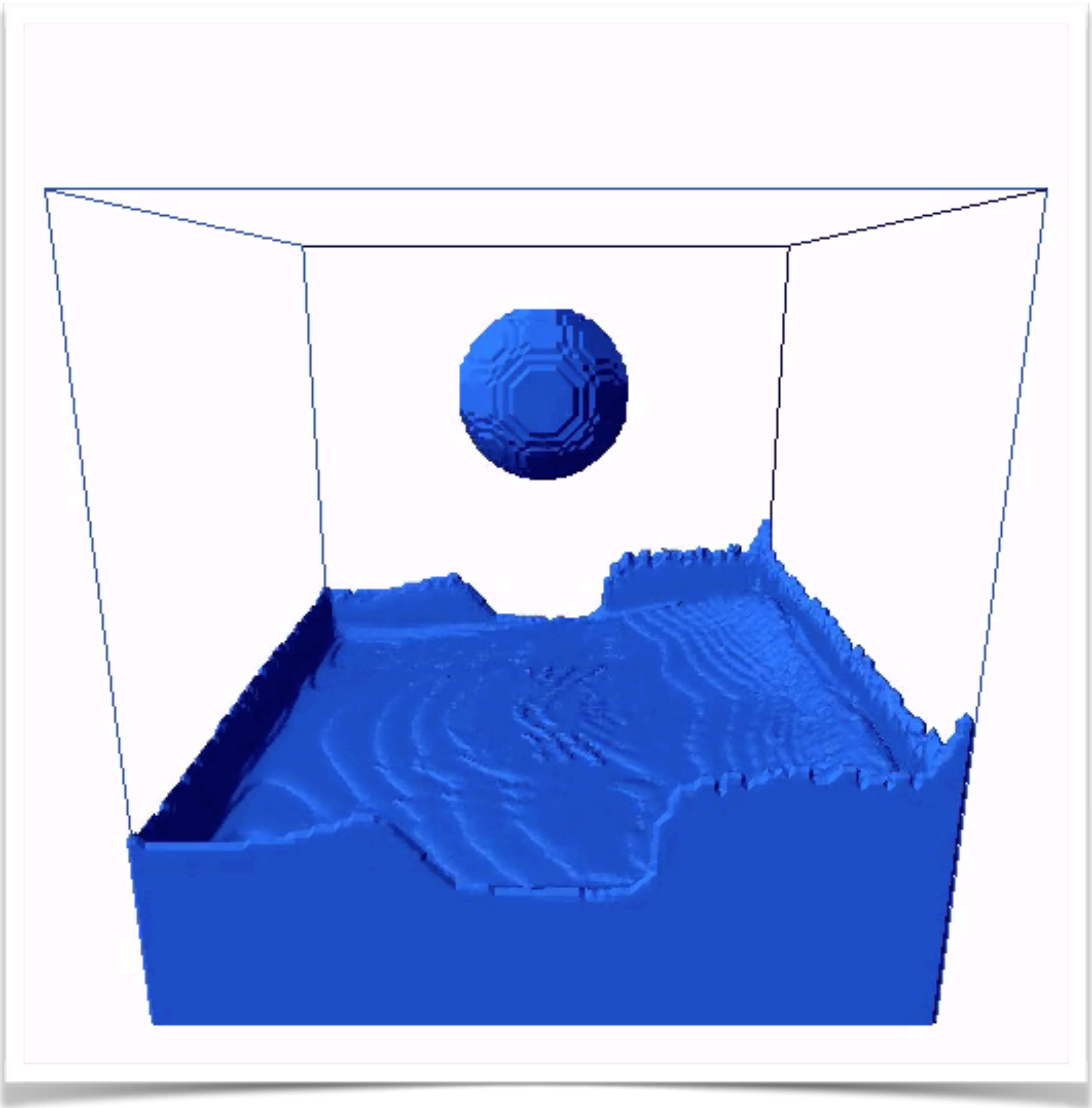


Intermediate frames for interactive simulation of a Newtonian fluid on a 128^3 grid, running at an average of 6.6 fps with 50 LBM iterations per frame. The user can add fluid drops while simulation is running

Videos



Dam Break



Interactive Newtonian fluid simulation

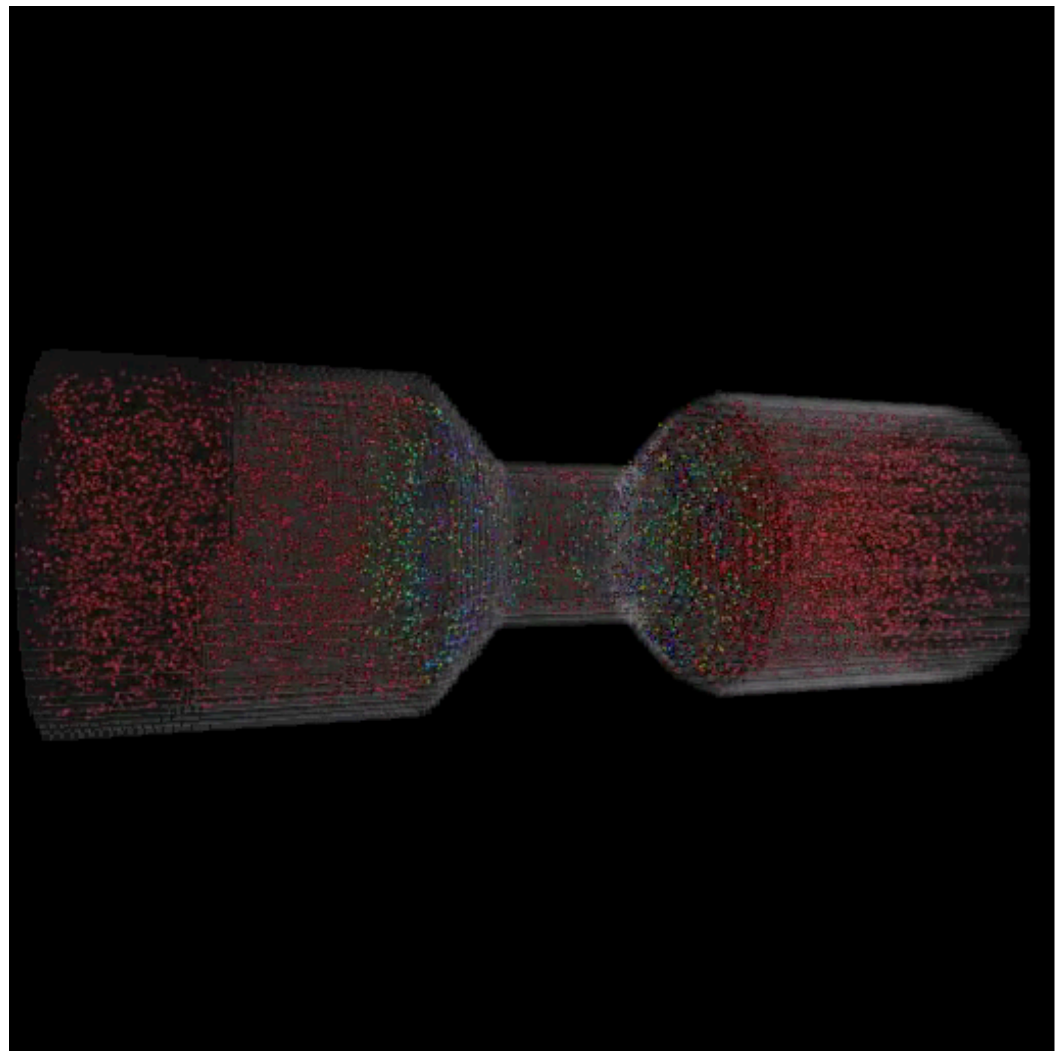
Non-Newtonian Characteristics

Shear Thinning
Displays more fluidity (decrease in viscosity) upon impact with the ground

Newtonian
No change in viscosity upon impact with the ground

Shear Thickening
Displays folding on itself, signifying resistance (increase in viscosity) upon impact

Flow through a tube

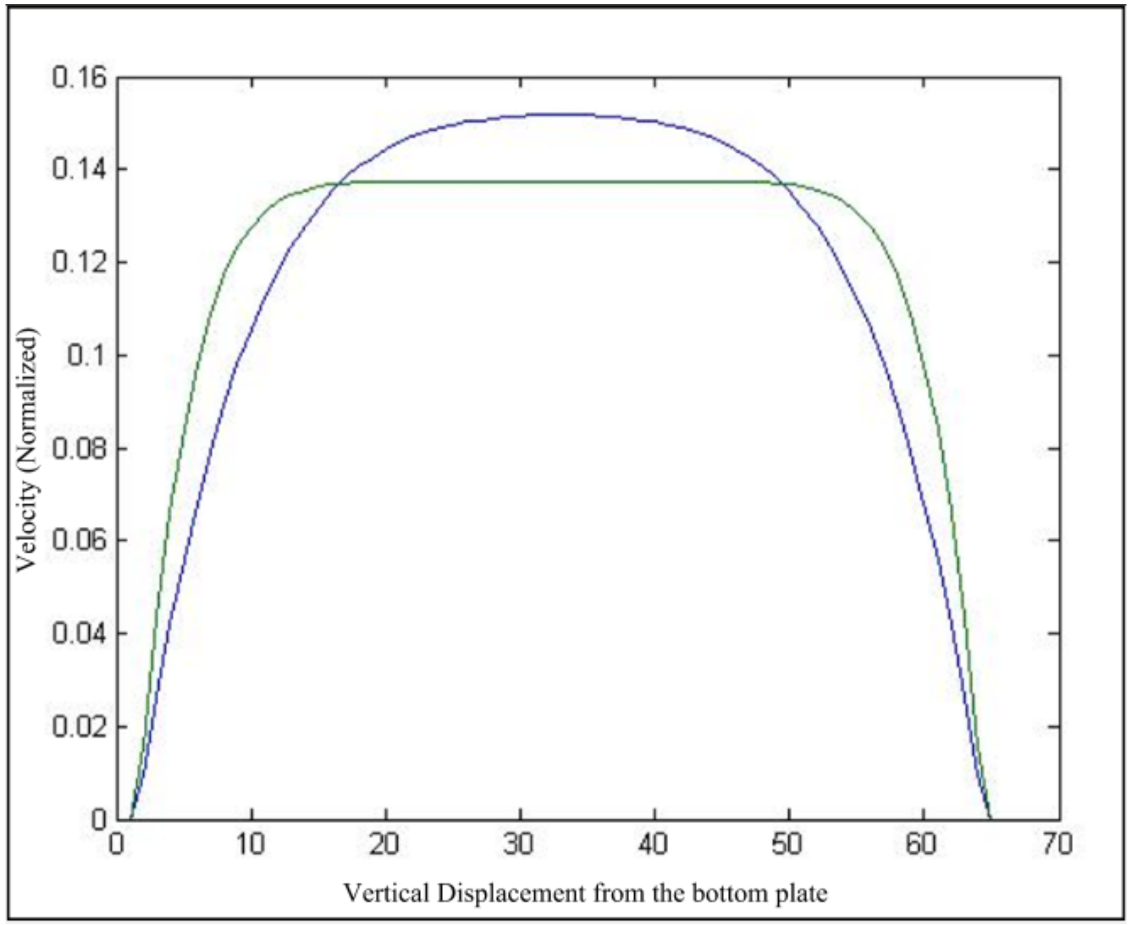


Shear thinning fluid through a tube of varying cross section. The dye particles change colour according to the change in viscosity.

Flow between parallel plates

- A motion parallel to two parallel is simulated. The fluid lamina in contact with the two plates will not move on account of its viscosity

- Newtonian fluid curve follows a parabolic path
- Non-Newtonian fluid curve flattens on approaching the center of the channel



Normalised velocity profiles for Newtonian and shear thinning fluids

Conclusions & Future Work

- Simulated both Newtonian and non-Newtonian fluids accurately at upto 600 MLUPS using a single GPU and 900 MLUPS using two GPUs
- We have dealt with laminar flows in this work. A study on turbulent fluids using LBM is an interesting area for future work.
- Visual quality of the simulations can be enhanced using ray-tracing.
- Building upon our work to simulate out of core grids (512^3 and above) is another interesting area for future work.

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Thank You!