Individual/Team Final Project

ECE4122\6122 Project Name: **GPU-Accelerated Particle-Based Fluid Simulation**

Team Member(s): Ivan Mix, Jacob Dudik, Abhinav Vemulapalli, Nikola Rogers

Project Statement of work:

The goal of this project is to design and implement a smooth particle hydrodynamics (SPH) solver that utilizes NVIDIA's CUDA API to perform high-performance parallel fluid simulations on the GPU. The SPH method, a mesh-free Lagrangian approach to computational fluid dynamics, is widely used in scientific and entertainment applications such as real-time water rendering in games and particle-based fluid animations in Blender. Our objective is to demonstrate how the inherent parallelism of SPH computations can be efficiently exploited on modern GPU architectures to achieve substantial speedups compared to traditional CPU implementations.

The solver will numerically model basic fluid phenomena such as sloshing, splashing, and free-surface motion by solving the governing equations of continuity, momentum, and the equation of state for compressibility. Each particle will carry physical quantities such as mass, density, pressure, and velocity, and will interact with neighboring particles through smoothing kernels like the poly6, spiky, and viscosity kernels. The CUDA kernels will be designed to compute these interactions in parallel, with particular attention to minimizing global memory latency, optimizing thread-block configuration, and ensuring warp coherence to maximize occupancy.

The project will include both algorithmic and architectural optimization. Data structures will be carefully organized to promote coalesced memory access, reduce unnecessary synchronization, and handle large-scale simulations efficiently. A uniform spatial grid or cell-linked list structure will be implemented to accelerate neighbor searches, allowing each thread to efficiently locate interacting particles within its smoothing radius. The results will be benchmarked against a CPU-based baseline to quantify the acceleration achieved through GPU computing.

Visualization will form a critical component of the project. We will output the simulation data to visualization formats such as VTK for rendering in ParaView or integrate with OpenGL to enable real-time graphical display. The team will produce a final video demonstration showcasing a physically realistic fluid simulation, accompanied by a performance analysis that compares accuracy, stability, and runtime across GPU and CPU implementations.

If a team project then list a statement of work for each team member:

Team Member: Ivan Mix

Statement of Work:

Ivan Mix will be responsible for the design and implementation of the CUDA kernel framework, focusing on efficient GPU utilization, thread management, and memory optimization. He will handle the integration of the SPH equations into the CUDA environment and ensure that the solver correctly models particle interactions with minimal numerical error. Ivan will also develop the visualization and output modules using OpenGL or VTK and perform performance profiling to measure kernel execution times and identify bottlenecks. He will assist with code testing, parameter tuning, and the preparation of final plots and visual results for the project report.

If a team project then list a statement of work for each team member:

Team Member: Jacob Dudik

Statement of Work:

Jacob Dudik will take the lead on the mathematical formulation of the SPH model. Their primary focus will be on implementing the core physics equations that govern fluid motion, including the momentum equation with pressure and viscosity forces and the density-based continuity equation. They will design and test different smoothing kernels, determine appropriate parameters for the equation of state, and ensure that boundary conditions are correctly implemented to maintain physical accuracy and numerical stability. This member will also validate the model against reference data or benchmark test cases.

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If a team project then list a statement of work for each team member:

Team Member: Abhinav Vemulapalli

Statement of Work:

Abhinav Vemulapalli will focus on developing efficient data management and neighbor search algorithms. They will design and optimize a spatial partitioning system using a uniform grid or linked-cell method to efficiently map particles to spatial bins. Their work will ensure that particle–particle interactions are limited to nearby neighbors, significantly reducing computational complexity. They will also assist in developing data layouts that maximize memory coalescence and minimize thread divergence in the CUDA kernels, contributing to overall solver scalability for large-particle simulations.

If a team project then list a statement of work for each team member:

Team Member: Nikola Rogers

Statement of Work:

Nikola Rogers will be responsible for performance analysis, visualization, and integration of all project components into a cohesive simulation pipeline. He will handle the visualization subsystem, implementing techniques for real-time or offline rendering and ensuring that the simulation output is both accurate and visually informative. He will also perform detailed performance evaluations comparing the GPU and CPU versions, document speedup ratios and memory utilization, and compile the project's final report and presentation materials.