Realtime Computational Fluid Dynamics Simulations using the Lattice Boltzmann Method
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Abstract

Fluid simulations are useful in many different areas ranging from weather modelling to microscopic physics. Using the conventional method of solving the districtized Navier-Stokes equations is very computationally intensive and relatively hard to parallelize. The lattice boltzmann method instead uses the discrete Boltzmann equation to simulate Newtonian fluids using various collision models.

Keywords: computational fluid dynamics, lattice boltzmann methods, parallel computing

1 Introduction

Fluid dynamics are useful in a broad range of fields including meteorology, computer graphics, aerodynamics, and microscopic physics. The purpose of this project is to accelerate relatively new methods in the field of computational fluid dynamics in order to be able to run realtime simulations. This includes using new methods that can be parallelized more effectively and vectorizing these methods and running them on new hardware using GPGPU techniques.

2 Background

2.1 Boltzmann Equation

The Boltzmann equation

$$f(x + vdt, v, t + dt) = f(x, v, t) + \Omega(x, v, t)$$

describes the time evolution of system of particles that interact with each other via the collision operator Ω. It consists of two parts, streaming and collisions. During streaming, particles are moved according to their velocities. During the collision stage, the distribution functions (DFs) at each lattice point undergo a collision operator, which is left as a choice.

2.2 The BGK collision operator

$$\Omega_{BGK} = \frac{f - f_e q}{\tau}$$

Collisions tend to push the system towards local equilibrium. This model is computationally simple, yet accurate, making it ideal, and thus very popular, for use in lattice Boltzmann Simulations. It is the one that I am using for my project.

2.3 Lattice Gas Cellular Automata

One approach to fluid dynamics modelling is to make a hexagonal grid, with every grid point having a set of 7 possible velocities, each pointing to the neighboring lattice point, or staying still. No two particles can occupy the same point with the same velocity. At each time step, particles move to the next point dictated by their velocity. If another particle is also moving to the same space, a collision model is used to determine where each particle settles. From this microscopic model, macroscopic behavior consistent with the Navier-Stokes equations emerges.

2.4 Discretization of Phase Space

In order to solve Boltzmann equation numerically, the domain must be districtized in phase space, consisting of time, configuration space, and velocity space. Time is split up by time step. Configuration space is split apart into a lattice with a discrete set of velocities connecting neighboring nodes. Lattices are classified by a DnQm scheme where n is the number of dimensions and m is the number of velocities. For example, D2Q9 is a two dimensional lattice with 9 velocities connecting neighboring nodes (4 to each corner, 4 to each midpoint, and 1 stationary).

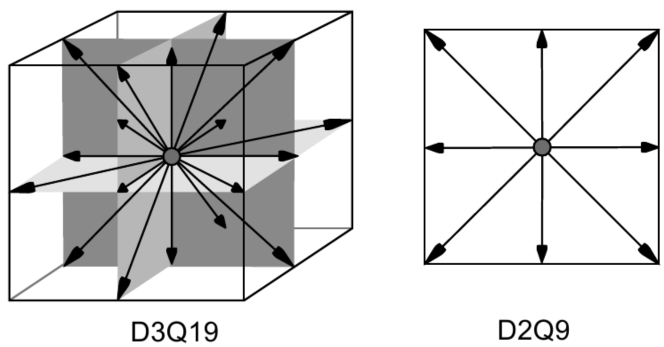


Figure 1: Various lattice and velocity configurations

3 Procedure

The first steps of this project are learning the physics behind the boltzmann equation and various collision operators. Then, I have to learn how the boltzmann equation is districtized into a lattice. Then, I will code a 2 dimensional simulation in order to get a basic simulation working. Then, I will expand it into 3 dimensions and start work on parallelizing and making sure it is working correctly.

4 Implementation Details

Currently, my simulation is a D2Q9 simulation using the BGK collision operator. It is programmed in the C programming language as this is a very performance intensive project and I am more comfortable in C than in Fortran. OpenGL is used to provide visualization display and input. For visualization, a grayscale image is presented with each pixel taking on the value proportional to the amount of fluid present at a lattice point. Mouse presses currently add stationary fluid at the pointer location. OpenMP is used for intra-node parallelism and MPI is used for inter-node parallelism.

5 Expected Results

The project will be expected to yield a CFD code that is able to simulate fluids in realtime. Physically correct results should be achieved, which will be measured using fundamental laws such as conservation of mass. This can be used in realtime predictions in various fields, for example control systems dealing with fluids. The speedup techniques used can also be applied to make larger simulations run faster.

6 Results

Current results consist of a simulation of a two dimensional fluid that can be conducted in realtime on a single processor on a 300x300 grid. The simulation is currently unoptimized since I copy the memory at each timestep, which while good for simplicity and getting a simulation up and running, is terrible for performance.

Physically, the simulation visually appears to model correct fluid dynamics behavior. However, using some code checks, I have found that mass in the simulation is not conserved. This is a problem, since mass should always be conserved. This is likely a result of the equilibrium distribution function I am using and so I will need to check this in the future.

7 Conclusion

Lattice Boltzmann methods are a very attractive alternative to conventional fluid dynamics solvers since they exhibit accurate results and are much easier to parallelize.

Figure 2: Visualization of an in progress fluid simulation

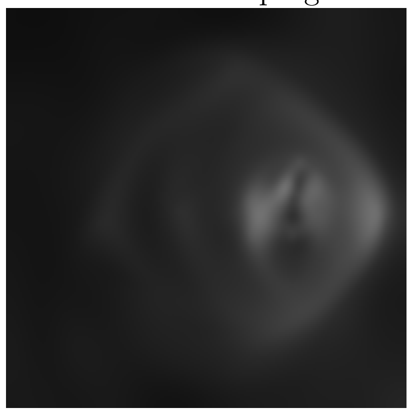
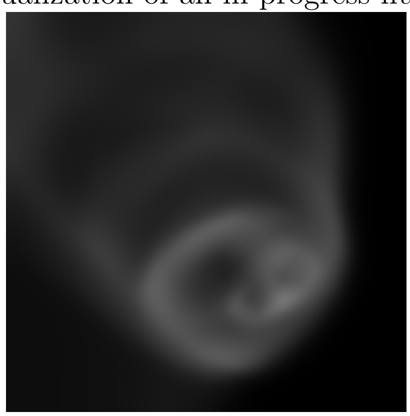


Figure 3: Visualization of an in progress fluid simulation



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