CS 184 SP24 Final Project Proposal

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Title, Summary, and Team Members

Title: Ferrofluid Simulation
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Summary: For our final project, we want to make a particle-based ferrofluid simulation that responds to external magnetic fields. We want to simulate the creation of the characteristic spikes that occur when you bring a magnet near the fluid.

Problem Description

For our project, we would like to simulate Ferrofluids which is essentially a magnetic fluid. Ferrofluids have been reported to be used in multiple applications such as biosensing, medical imaging, medicinal therapy, water treatment, energy harvesting and transfer, and vibration control. Ferrofluid was first invented by NASA (Steve Papell) in 1963 originally to be a rocket fuel that could be drawn toward a fuel pump in weightless environments by applying magnetic fields. Being able to simulate Ferrofluid allows us to study its unique properties and apply it to many real world applications.

In Ferrofluids, the particles collectively exhibit properties like surface tension, but also can each be thought of as tiny little magnets. The total magnetic field of the fluid is zero because the particles are moving in random directions with random orientations. However, in the presence of a magnet, the particles tend to align themselves in the dominant direction, which causes the fluid to become magnetized. Any small perturbation in the surface bends the magnetic field lines and attracts neighboring particles which leads to an even larger bump, eventually becoming a spike.

We are modeling our solution after this SIGGRAPH paper written in 2019. They break down the simulation into two parts: the SPH solver with surface tension and the magnetic force computation.

ALGORITHM 1: SPH solver according to Adami et al. [2012].

```
t ← 0
while t < t_max do
    for i ← 1 to N do
        if 0 = t then
            //Force evaluation according to Algorithm 2:
            a_i(t) ← (1/m)(f_i(t) + MagneticForce(r)_i).
        end
        v_i(t + ½Δt) ← v_i(t) + (Δt/2) a_i(t)
        r_i(t + ½Δt) ← r_i(t) + (Δt/2) v_i(t + ½Δt)
        ρ_i(t + Δt) ← ρ_i(t) + Δt dρ_i(t + ½Δt)/dt
        r_i(t + Δt) ← r_i(t + ½Δt) + (Δt/2) v_i(t + ½Δt)
        a_i(t + Δt) ← (1/m)(f_i(t + Δt) + MagneticForce(r)_i))
        v_i(t + Δt) ← v_i(t + ½Δt) + (Δt/2) a_i(t + Δt)
    end
    t ← t + Δt
end
```

ALGORITHM 2: Magnetic force computation.

```
Input: r ∈ ℝ^{3N}, h ∈ ℝ, Γ ∈ ℝ
Output: f ∈ ℝ^{3N}
//Magnetization
Function G(m):
    for t ← 1 to N do
        H_t ← 0 ∈ ℝ^3; M_t ← 0 ∈ ℝ^3;
        for s ← 1 to N do
            H_t ← H_t + H(r_t − r_s, m_s) //Eq. (12)
            M_t ← M_t + m_s W(r_t − r_s, h) //Eq. (8,10)
        end
    end
    return H + M
end
Get h_ext(r) from external sources (see Eq. (16)).
Solve (GΓ − 1)b = −h_ext for b in the least-squares sense.
Employ G in a conjugate gradient solver.

//Magnetic force
for t ← 1 to N do
    U ∈ ℝ^{3×3}; U ← 0;
    for s ← 1 to N do
        if |r_t − r_s| < 4h then
            Get normalized distance: q ← |r_t − r_s|/h.
            Get the local coordinates as described in Figure 5.
            Get local source moment: m̃ ← R^T m_s.
            Evaluate local force tensor T̃_s: Eq. (24).
            Get world force tensor T_s ← R T̃ R^T: Eq. (25).
        else
            T_s ← μ_0 ∇H //Eq. (18,19)
        end
        U ← U + T_s
    end
    f_t ← U m_t
end
Add external magnetic forces.
return f
```

Goals and Deliverables

Goals:

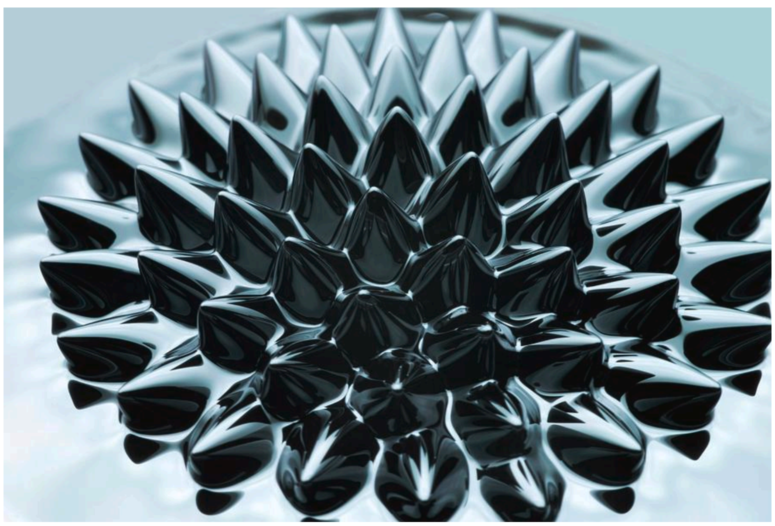
1. Implement a basic fluid simulation (filling containers, interacting with solids). This will be tested by qualitative simulation observations of the demo and comparing it to real-life behavior and/or other simulations. **(Plan to implement)**
2. Implement shaders to show the glossiness of ferrofluid (**Hope to implement)**
3. Implement magnetic fields (represented by points and magnitudes) and the correct behavior for ferrofluid interacting with these fields. This will be tested by comparing the behavior to the real-life behavior of ferrofluid. The deliverable will be taking a single magnetic point and moving across the fluid will produce similar results to real-life examples. Something close to the image provided. To measure quality, we plan to compare this to a control of having no magnetic field and to check for results when varying the strengths of the magnetic field. We plan to answer how the Ferrofluid reacts to adjusting the different parameters such as field strength and surface tension. **(Plan to implement)**
    a. 
4. Add objects with magnetic fields to reproduce real-world behavior. This will be tested in a similar manner by comparing simulation results to real-life behavior.

Image example provided. (**Hope to implement)**

5. Refactor code to increase performance in order to create higher definition simulations (more particles, more magnetic fields, computationally cheaper) (**Hope to implement)**

Deliverables:

1. Demo with simulated ferrofluid that reacts with inputted magnetic field points and possible objects.
2. A video of
    a. A standard fluid simulation with no magnetism (e.g. pouring fluid into a bowl of water)
    b. Several fluid simulations with different positions and magnitudes of magnets to showcase the behavior of the fluid
    c. (POSSIBLY) several fluid simulations with different magnetic objects

Schedule

Week 1 (3/31 - 4/6)

- Work on and submit Final Project Proposal
- Read over resources
- Transform Homework 4 code to be used for fluid simulation (IMPORTANT)
- Begin implementation of fluid simulation and SPH (smoothed-particle hydrodynamics)

Week 2 (4/7 - 4/13)

- Continue working on SPH implementation
- Validate working fluid simulation
  - Fill containers with fluid and verify that simulations are consistent or similar to real-world behaviors
  - Test interactions with solid objects, including spheres, rectangular prisms, and pucks
- Implement/validate shaders

Week 3 (4/14 - 4/20 [4/16 Milestone Due])

- Submit Milestone
  - Working fluid simulation
- Begin implementation of magnetic fields
  - Adapt the properties of our fluid to react to these magnetic fields (turning fluid into ferrofluid)
  - Define the magnetic fields for masses in a solid

Week 4 (4/21 - 4/27)

- Validate magnetic fields
  - Test how ferrofluid interacts with a magnet placed below it. Verify that simulations are consistent or similar to real-world behaviors (i.e. should see characteristic spikes in the fluid)
  - Test interactions with solid objects by dropping the fluid over magnetized objects, or magnetizing objects when there is ferrofluid at rest around it
- Work on any stretch goals (time-permitting)
- Begin recording videos for final presentation and begin working on final deliverables

Week 5 (4/28 - 4/30 [Due Date])

- Finish working on final deliverables
- Submit final deliverables
- Prepare to present!

Resources

Our main resource for this project is the SIGGRAPH Project *On the Accurate Large-scale Simulation of Ferrofluids (SIGGRAPH 2019)* (project page linked here). This project describes in detail the necessary components for a successful ferrofluid simulation, and will guide us in building our own.

The video that inspired this project is *How This Guy Makes Mesmerizing Fluid Sculptures | Obsessed | WIRED*. This video provides a description of ferrofluid and its physical properties that we may want to emulate.

We plan to develop this project in C++ using the code for Homework 4 as a basis for our physics simulation. We will run our simulation on both Windows and Mac computers.