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Visual Comparison of Lagrangian and Semi-Lagrangian fluid simulation

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ABSTRACT

Context. Fluid simulations are an important part for enhancing the visualization of games, movies and other graphical applications.

Fluid simulations can be achieved in different type of context ranging between slow, high-quality simulations which is mainly used for movies, to fast lower-quality simulations which is primarily used for real-time applications such as games.

Objectives. The goal was to compare the visual appearance of a Lagrangian method and a semi-Lagrangian method when it came to realistic appearance.

Methods. Identical scenes of water being rendered are made for both the Lagrangian and the semi-Lagrangian algorithm. This is later measured by using a user study which will provide the result of which method that provides a more realistic appearance.

Results. The result of the tests showed that the visual realism between the semi-Lagrangian and Lagrangian were different depending on the scene environment.

Conclusions. The conclusion of the data presented in the result yields that the Lagrangian and semi-Lagrangian looks very much alike and there is no real realistic difference between the methods, some scene yields a vast majority of votes in the favor of one method.

Keywords: Fluid Simulation, Position Based Dynamics, Lagrangian, Semi-Lagrangian

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1 INTRODUCTION

Fluid simulation is a widely-used method in different graphical areas, such as games, movies and more. Where the technique is used to create different visual effects to enhance the experience for the viewer/user, involving fluid movements (water), smokes, and winds. Different techniques are always evolving and becoming more and more advanced and at the same time better looking than the previously proposed.

Various methods for simulating fluids have different purposes; The simulation speed might be of greater interest than the appearance of the simulation itself when it comes to real-time applications. That's not the case when it comes to movies for example where the simulation and rendering of the fluid are pre-calculated and rendered.

In this paper, the focus will be on the visualization of the simulations instead of the performance and rendering time itself.

1.1 Aim and Objective

The general aim of this thesis is to make an attempt at finding out which technique has the most realistic appearance from the two simulation methods chosen, where this could allow the reader to choose a more suitable simulation for an application.

The objectives are to explore two different methods for simulating fluids and create similar scenes of those methods for a later visual comparison.

The methods are going to be analyzed through a user study, where the participants will be answering questions regarding the realistic appearance.

1.2 Simulation Techniques

There are two primary methods which exist to solve the algorithms for simulating fluid, Eulerian and Lagrangian [2]. There is also a third method which is a combination of the two, semi-Lagrangian.

The different methods are composed of two major parts, simulating the fluid, and making the surface of the water. The surface of the water is what the user is seeing, which is the result of the simulation itself.

1.2.1 Lagrangian

A Lagrangian method is simulating the fluid by using particles to interact with each other's, these particles are given properties such as velocity and density. This can be seen in Figure 1.1.

A Lagrangian method like PBD (Position Based Dynamics) are one of the methods which are becoming more popular, mainly because of how efficiently they solve the mathematic equations. The fluid is made up of particles, and the algorithm skips the work of velocities and accelerations and focuses on moving the positions immediately from the collisions. The PBD technique is almost made to exist in games mainly. Mostly because PBD works well with interactive environments and the speed of the simulation itself is fast [3][4].

The surface of the Lagrangian scheme is tracking the surface through the particles for demonstrating the fluid.

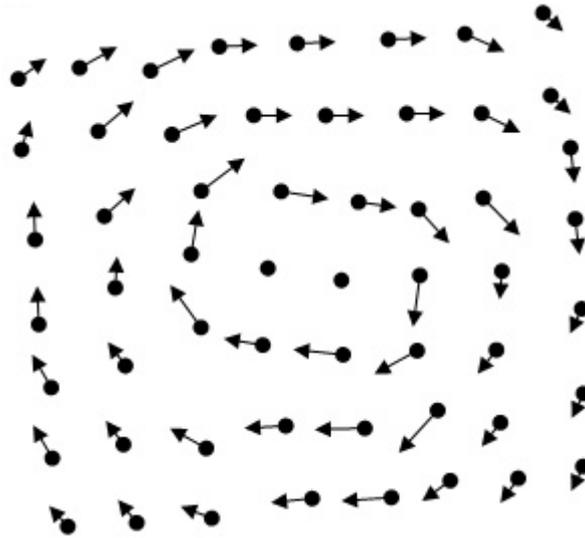


Figure 1.1: A 2D representation of the Lagrangian scheme, where particles are employed, and the velocity is displayed as arrows [11].

1.2.2 Eulerian

A Eulerian method uses a grid based formula to calculate the simulation instead of using particles. It does this by using different fields, such as a velocity field, density field, and a pressure field [7]. The grid cells are always static, and the only thing that changes is the property of the cells themselves. A representation of this can be found in Figure 1.2.

The Eulerian method is often generating a mesh for the display of the surface [9].

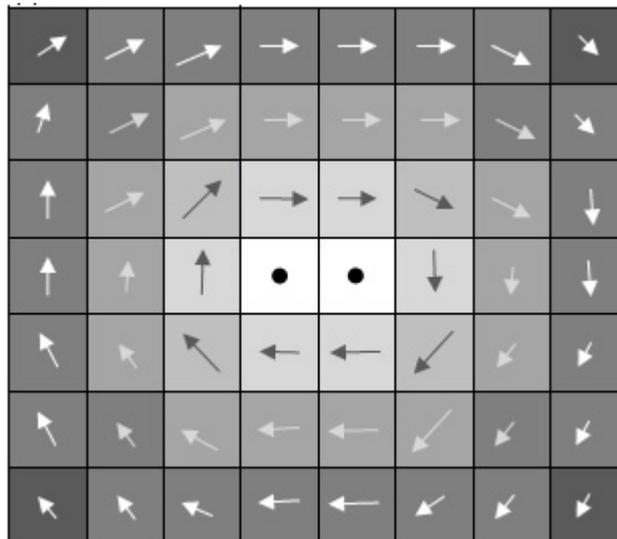


Figure 1.2: A 2D representation of the Eulerian scheme, Where the properties of the cells are matching the properties of the particles from Figure 1.1 [11].

1.2.3 Semi-Lagrangian

A combination of the Eulerian and Lagrangian method is called semi-Lagrangian. Wherein a grid system is used that works by assigning properties (velocity, density, pressure) to these static grid cells and let them evolve over time. A representation of this can be found in Figure 1.3.

Particles are still employed in semi-Lagrangian methods to track the surface. [1].

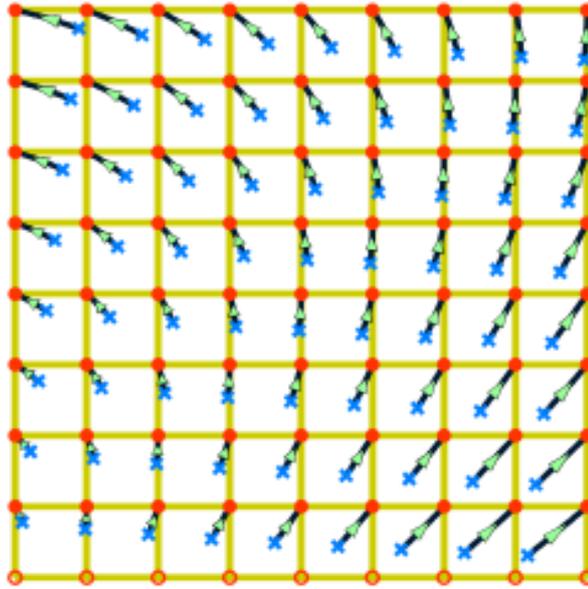


Figure 1.2: A 2D representation of the semi-Lagrangian scheme [12].

1.3 Approach

The goal of this paper is to analyze the lifelike appearance differences between the Lagrangian and semi-Lagrangian methods. Scenes are created to collect the desired data. The scenes will have different objects placed, and the water particles will be of various sizes, shape, and amount. Some scenes will contain identical objects, and the water will be of a different radius and quantity.

The purpose is to compare the visual differences between two fluid simulation methods. This means that both the Lagrangian and semi-Lagrangian method most have the same conditions as each other, like particle start positions and time-steps. The start positions are to be equivalent to each other, while the algorithm and structure are different.

NVidia Flex will handle the physics for the Lagrangian method [5], and the semi-Lagrangian method will be handled by a previous work by Christopher Batty [6]. A total of 5 separate scenes will be made, simulated, rendered and recorded. The equivalent scenes with the same conditions are to be edited in a split-screen behavior so that the scenarios can be analyzed. A user study with participants will answer a questionnaire about which method that has a more realistic approach to it. Graphs and text will display the data gathered from the user study.

1.4 Research Question

How does the Lagrangian and semi-Lagrangian fluid simulation compare to each other regarding realistic appearance?

2 BACKGROUND

This chapter of the paper will cover the background and the related work in the field Fluid simulations and realistic appearance.

Realistic water is one of the bigger visual effects in movies; this effect is often overlooked. The water becomes hideous if done incorrectly and becomes something that is more of a sore to for the eyes than some visual enhancing experience. Fluid simulations are used in a lot of high budget movies, such as Superman Returns, where a Smoothed Particle Hydrodynamic (SPH) is used. The SPH method is not only utilized in the Superman franchise but can also be seen in other places, such as Lord of the Rings [13].

The most realistic water as possible isn't always the direction a graphical programmer wants to go for, and a simulation / render time might be sought after. This is often used for real-time games, where the simulation time is an important part of the player experience. The realistic visualization of the fluid is still an important component for games, where it gives effects and response to the player, an example of games which use SPH is Alice: Madness Returns and Portal 2 [10]. It's also crucial to choose the correct technique when selecting fluid method for games. Some methods like PBD is suitable for dynamic interaction and is therefore chosen for games where that's needed.

2.1 Related Work

Previous work in the realistic appearance have been made where it has been explored with photo-realistic water effect [14]. The realistic water is poured into glasses, and ocean waves are simulated with the semi-Lagrangian scheme. A new technique for thickening the front of the surface, and changes the way of the extrapolation of the surface. These techniques yielded a higher realistic appearance, a big reason for this was a higher control of the wind blowing.

2.2 The selected Methods

The simulation techniques selected for this project is a Lagrangian method called PBD, and a semi-Lagrangian method. The reason is that PBD is often utilized for being in games [3] [4], while the semi-Lagrangian one is not optimized for being in games, but can be utilized for real-time applications if implemented correctly [9]. Which divides them into two options, real-time optimized method, and non-real-time optimized method. Finding out if the PBD is having a higher realistic appearance than the semi-Lagrangian makes this experiment interesting.

Other techniques were also an option, such as the Lagrangian Smoothed Particle Hydrodynamics (SPH), Eulerian method. The chosen techniques are different in many ways (real-time), and at the same time similar (surface tracking). Which makes the chosen techniques a more optimal selection for this thesis.

3 METHOD

This chapter will cover the methods used for implementing the correct scenes needed for the user study, as well how the user study was conducted.

For this thesis, NVidia Flex framework was selected for simulating the Lagrangian Position based dynamic (PBD) method.

To be able to answer the research question of this thesis, different scenes have been made which will simulate different scenarios with a different number of particles and solid objects. The scenes were originally simulated in NVidia Flex where the first frame was exported and imported into the semi-Lagrangian program where the particle position and radius were equivalents. This reason was that the scenes simulated should be as synchronized as possible, and this would be the result for a better comparison.

One of the most difficult parts was to implement rendering for the semi-Lagrangian inside the NVidia Flex framework. This is not something that the framework support. The original simulation method inside NVidia flex was paused, and the GPU buffer swaps information with frames read from files.

The semi-Lagrangian is operating its calculation in a grid-based behavior. The grid size is originally set as a hard-coded value, demonstrating the particle sizes and the grid scale. The way that the semi-Lagrangian operates is by taking the resolution and optimizing the particle radius for an optimal simulation time, the simulation time is only optimal when each particle fits exactly in each grid-cell of the grid-system. This process could be reversed by setting the grid width to a multiplier of 1, and the grid resolution could be extracted by doing the following shown in figure 3.0.

Both simulation methods are calculated at a time step of 1/60 of a second, which results in the same simulation time at any given frame.

```
float tdx = particle_radius / (1.01*sqrt(3.0) / 2.0);  
float gridWidth = 1.f;  
float resolution = gridWidth / tdx;
```

Figure 3.0: The programming code for calculating the resolution of the grid in the semi-Lagrangian field.

3.1 Scenes

Different scenes were designed to test for different scenarios which might occur during simulations. Each scene provided was kept in a boundary of a box with the dimension of 1x1x1 meters. The reason for this was that each scene should have one major thing in common which would result in an easier visual comparison between them.

Some of the scenes provided are similar in a way where the number of particles and the radius are the difference. A total of five pair of scenes were made, where one pair is independent of the others, and the other four pairs are grouped two and two by using the same liquid shape, volume, and the same static objects, what differs these scenes are the particle amount and the grid resolution.

The particle amount chosen for the different scenes were semi-random, where the grouped scenes had a high amount of change between the particles. The specific particle number is derived from a shape, of where a grid resolution is defined. The higher the resolution, the more particles. These particles are created as in the shape defined. The shapes defined can be seen in Figure 3.1 - 3.5.

A screenshot handler is implemented into the NVidia Flex framework; this handler is taking a screenshot of the scenes each frame. The screenshots then proceed to become a video by converting the image sequence to a video. The videos are edited into a split-screen scenario for later visual comparison. The video that visually shows the scenes used for this study can be found on YouTube [8].

The first frame from the different scenes is displayed here, with some data of the specific scene.

3.1.1 Scene 1:

Particle Amount	50'883
Particle Radius	0.01375m
Grid Resolution	127

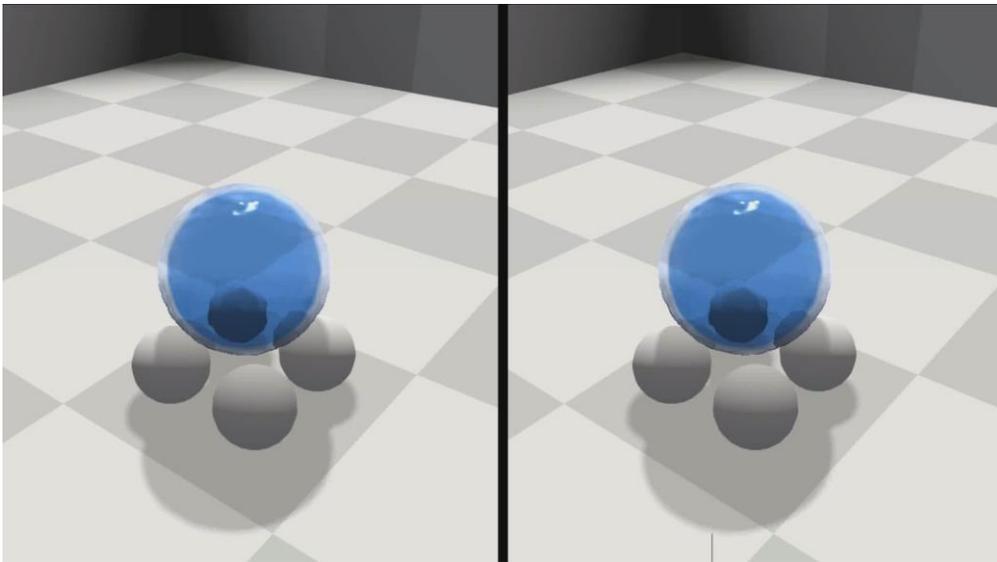


Figure 3.1: Particles shaped as a spherical object dropped on top of four spheres as solid objects.

3.1.2 Scene 2

Particle Amount	203'376
Particle Radius	0.011m
Grid Resolution	159

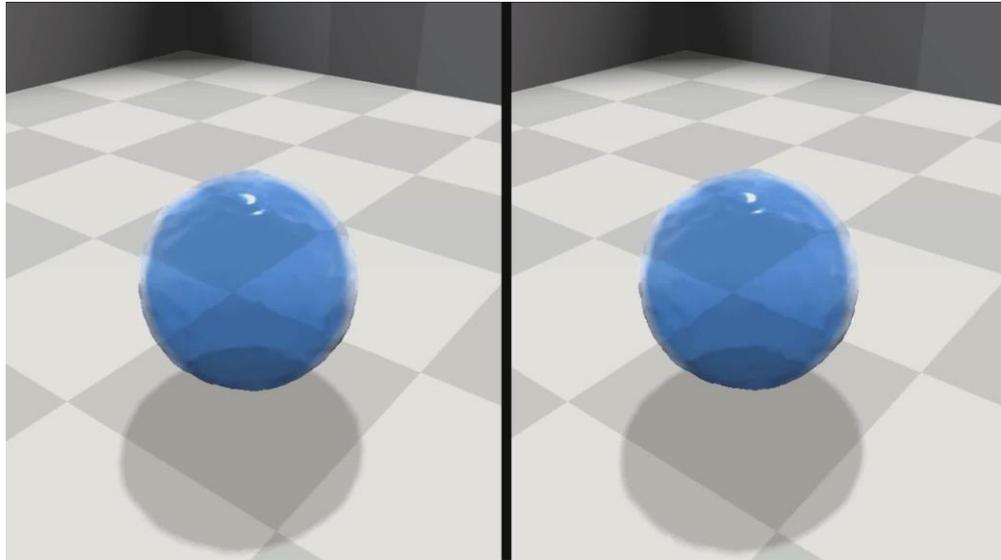


Figure 3.2: High number of particles shaped as a spherical object dropped into an empty scene.

3.1.3 Scene 3

Particle Amount	20'479
Particle Radius	0.0242m
Grid Resolution	72

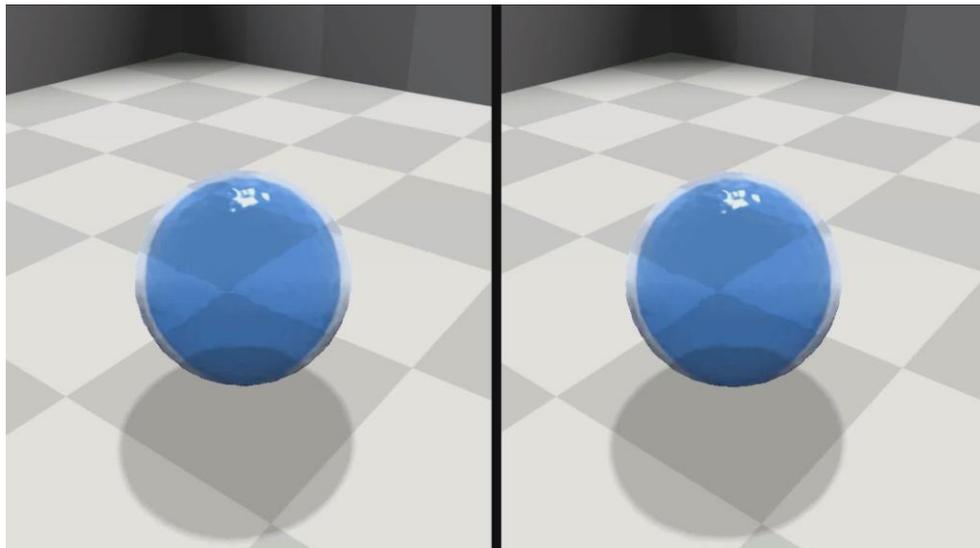


Figure 3.3: Low number of particles shaped as a spherical object dropped into an empty scene.

3.1.4 Scene 4

Particle Amount	199'424
Particle Radius	0.011m
Grid Resolution	159

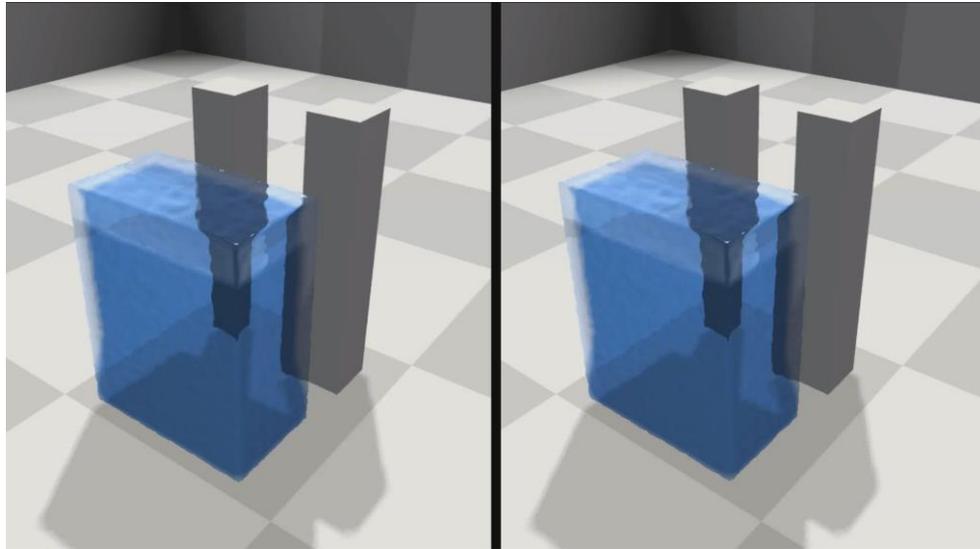


Figure 3.4: High number of particles shaped as a rectangular block dropped into a scene with two pillars as solid objects.

3.1.5 Scene 5

Particle Amount	38'258
Particle Radius	0.01925m
Grid Resolution	91

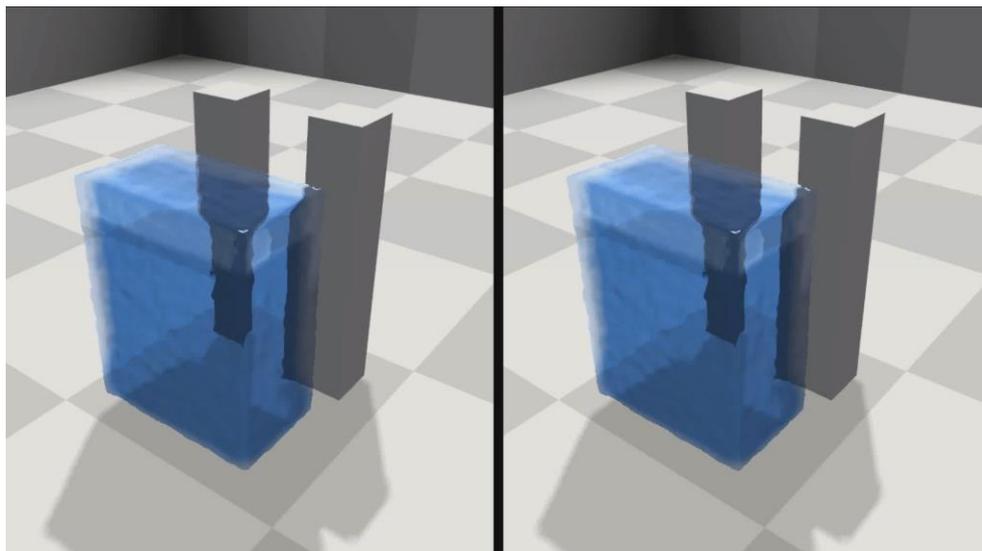


Figure 3.4: Low number of particles shaped as a rectangular block dropped into a scene with two pillars as solid objects.

3.2 Simulation framework

NVidia flex is responsible for rendering both simulation algorithms, and accountable for performing the simulation of the PBD [5].

Previous work by Christopher Batty will provide a “3D Liquid Simulator code”, which corresponds to the semi-Lagrangian method [6].

3.3 Experimental Design

This chapter will explain how the experiment is planned.

3.3.1 Experiment Scoping

Analysis of two different fluid simulations techniques, regarding realism. For finding a simulation method which suits better for realistic scenarios.

From the point of view of the test subject who is between the age of 18-30.

In the context of either doing a form online or taken place physically with the narrator. Watching two simulations simultaneously in a split-screen behavior, which is conducted with questions from the narrator.

The expectation is that the simulation chosen will be alike. However, the Lagrangian will get slightly higher score than the semi-Lagrangian. This is because the rendering is built to support the PBD, and the semi-Lagrangian method is an integration of the system.

The objective of the experiment is to find a clear result of which technique has the most realistic appearance. The goal is also to see if the particle amount between the two simulations has any major differences.

3.3.2 Experiment Planning

a) Context Selection:

The experiment will be conducted in both offline and online environment. The observer is sitting next to the narrator in the offline environment, and having a live conversation in the online environment.

b) Hypotheses:

$h1$: A higher number of particles will have a different outcome than a lower amount.

$h0$: A larger number of particles will not give any changes than having a lower number of particles.

c) Variable Selection:

The independent variables are:

Particles Amount: This will change the number of particles simulated in the scene.

Objects in scene: This will be placed around the scenes, with different shapes and amount.

Different fluid start shape: This is the form of which the fluid hold before the simulation has begun, this could be a sphere, box or a rectangular block.

The following dependent variable was chosen:

Realism: This variable is whether the participant found the specific simulation realistic or not.

d) Subject Selection:

The subjects that will be used for this experiment is participants ranging in age 18-30. This is mainly because the experiment wants multiple users who are experienced in the digital section (movies, games).

e) **Design Type:**

Randomization: This will occur in which the order the participants will make the test.

f) **Instrumentation:**

The experiment object will be a video, which is 50 seconds long where pair of scenes is played after each other's.

A form will be handed to the participant which contains 3 different parts. *Pre:* This part is done before the simulation is shown, and is about personal information, such as age, technical background and how much the participant plays video games.

In: This part is done simultaneously during the display of the simulations. The participant is asked here to choose which one of the two scenes that would reflect a more realistic appearance. There is a total of 5 scenes of which the participant is asked the same question.

Post: This part is done after the simulation is complete, and the participant is asked for any last comments of the simulation behavior.

g) **Validity Discussion:**

Conclusion Validity: The independent variables chosen for this experiment might not be the most optimal ones to find the most realistic scenario, but was chosen because they have an impact on the simulation itself.

Internal Validity: The test might be neglected if the independent variables are chosen or set to the wrong numbers. The test might provide different answers than the hypothesis.

External Validity: The hardware could be an impact if the test is done in an online environment. The video could be buffering or stutter if the hardware for the participant is outdated.

3.3.3 Experiment Execution Planning

The execution planning will be summaries in a numerical table:

1. Find test subjects to test the experiment, this is done by asking people about their age, and how digital oriented the person is.
2. The participant will read the Information letter provided and asked for consent to participate in the study.
3. The participant will fill then answer to part #1 in the questionnaire, Personal Information.
4. The participant will simultaneously watch videos of two different simulation scenarios taking place in a split screen behavior. This is done while filling part #2 in the questionnaire. The questions here are about which one of the two simulations shown shows a more realistic behavior.
5. The participant is asked for any final comment in the part #3 of the questionnaire. This questionnaire can be found in Appendix Questionnaire.
6. Analyze the data: Following 3.3.4 "Experiment Data Analysis Methods" after all user studies are done.

3.3.4 Experiment Data Analysis Methods

The data from the participants will be inserted into pie charts. This is because the answers only contain two different alternatives and the verdict can be made by analyzing the graphs visually. The data gather will further upon be analyzed in a Chi-Square test, where the hypothesis will be answered.

3.3.5 Conclusions and Summary

The conclusion could be drawn independently on how the result is. Meaning that a draw could mean that the specific scenario is optimal for both simulation method, and one method is better than the other in that scenario if it gets a margin of a higher vote than the other.

The experiment could yield different result depending on what variable that is being adjusted. The particle number chosen for each experiment might not be the most optimal for the boundaries chosen for the test; one thing to adjust could've also been to change the boundaries of the fluid simulation, instead of using a 1x1x1 dimension, a 2x3x5 dimension could be utilized.

4 RESULTS

In this chapter the user study result will be shown with pie chart. A bar chart will be displayed left of the pie chart, this chart is representing how much the participants play games, ranging from 1-5 days a week to 6-7 days a week, once a week and 2-5 times a week were combined into one column (1-5 days a week). There's a total of five scenes including short description of the parameters used and which image scene the image is representing. The study was conducted by a total of 20 people.

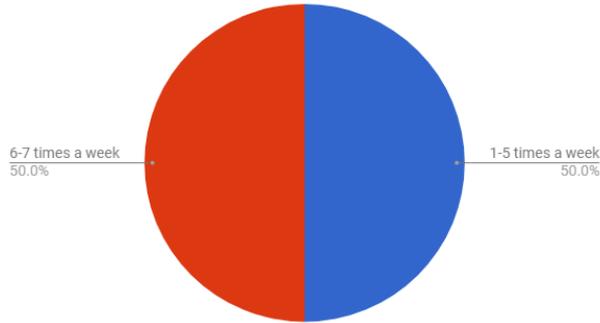


Figure 4: This pie chart represents the amount of games the participant's play.

4.1 A comparison of using Lagrangian and semi-Lagrangian

The following results are presented in a way where they are easily to compare with each other's. What differs the scenes are the following factors:

- Particle Amount
- Grid Resolutions
- Particle Radius
- Static Objects
- Liquid start position / shape / volume

The following results will be display in two different charts, bar charts and pie charts. The bar chart demonstrates the amount of votes a method received depending upon how much the participants play video games, and the pie chart demonstrates the total number of votes combined.

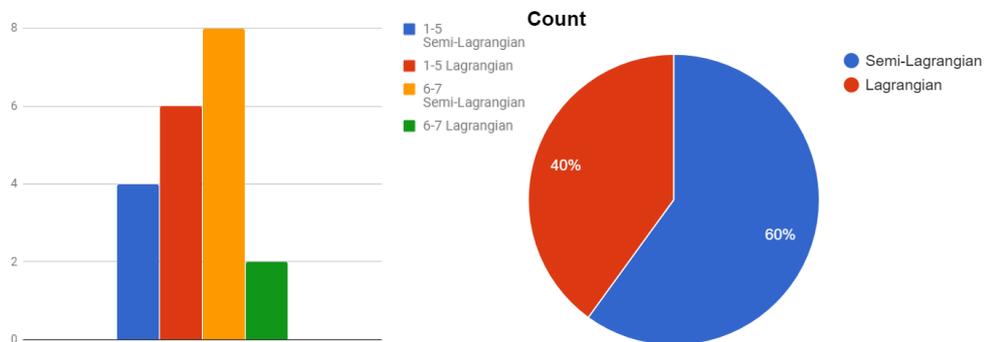


Fig: 4.1: The result of Scene #1. Where 50'883 particles are dropped, with the radius of 0.01375m and has the semi-Lagrangian resolution of 127. Image of first frame of the scene can be seen in Figure 3.1

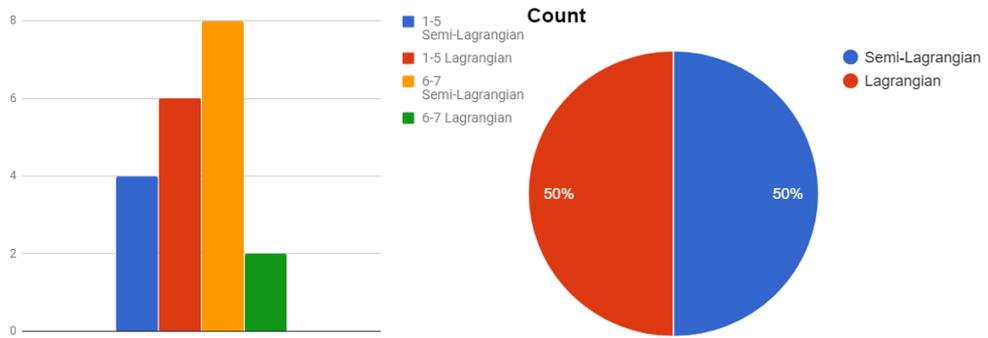


Fig: 4.2: The result of Scene #2. Where 203'376 particles are dropped, with the radius of 0.011m and has the semi-Lagrangian resolution of 159. Image of first frame of the scene can be seen in Figure 3.2

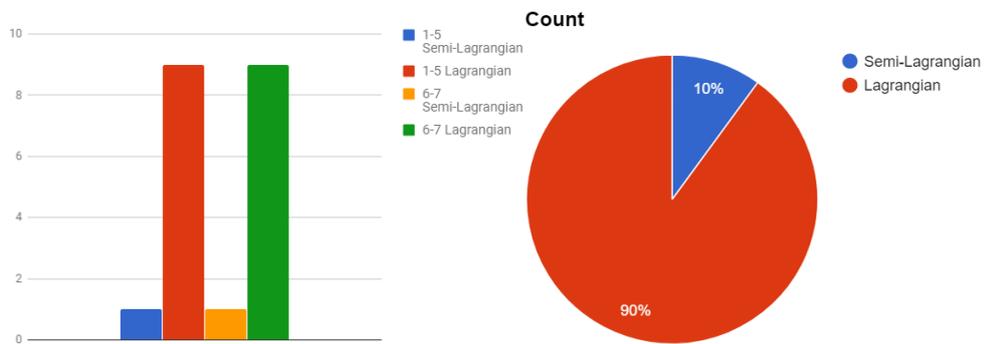


Fig: 4.3: The result of Scene #3. Where 20'479 particles are dropped, with the radius of 0.0242m and has the semi-Lagrangian resolution of 72. Image of first frame of the scene can be seen in Figure 3.3

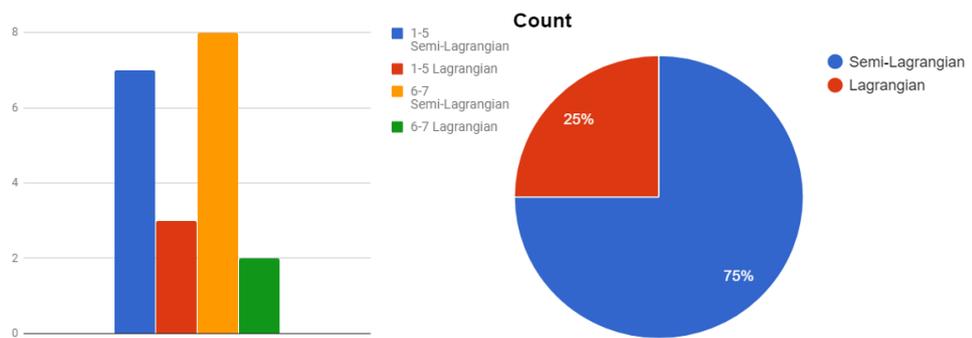


Fig: 4.4: The result of Scene #4. Where 199'424 particles are dropped, with the radius of 0.011m and has the semi-Lagrangian resolution of 159. Image of first frame of the scene can be seen in Figure 3.4

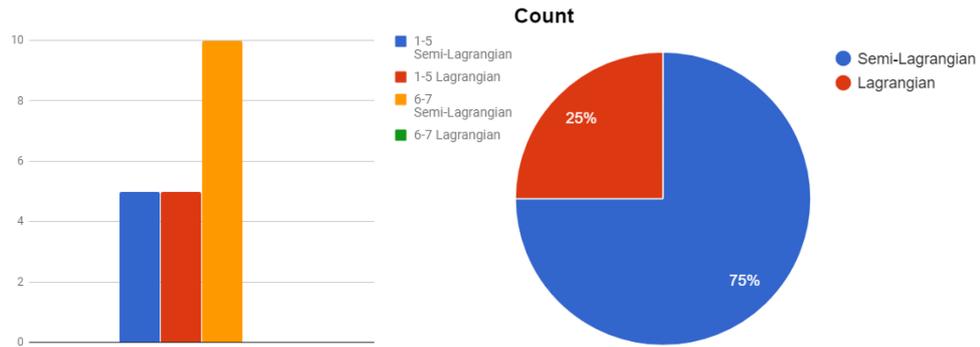


Fig: 4.5: The result of Scene #5. Where 38'258 particles are dropped, with the radius of 0.01925m and has the semi-Lagrangian resolution of 91. Image of first frame of the scene can be seen in Figure 3.5

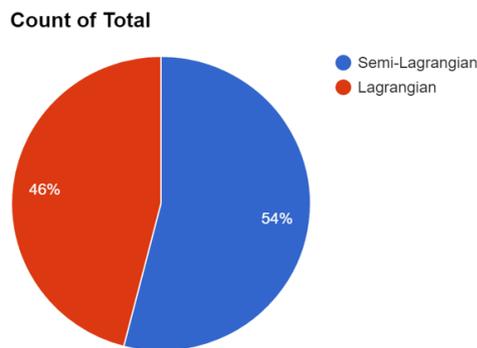


Fig 4.5: This pie chart shows the total of votes combined through all the scenes combined.

4.2 Chi-Square

The Chi-Square test were made from taking the combination of all the votes from the results, only counting the results where the scenes had an equal scene with a different number of particles. Taking the sum, counting the particles from all the high amount scenes (Scene #2, Scene #4) and the sum from all the low amount scenes (Scene #3, Scene #5). The sum from both the Lagrangian and the semi-Lagrangian are added together for a total sum. This yields the result for the scenes 2,3,4,5 combined.

	Semi-Lagrangian	Lagrangian	Total
High Amount	25	15	40
Low Amount	17	23	40

The data gathered is divided in either low number of particles, or high number of particles, and the expected and outcome is displayed here:

	High Amount	Low Amount
Expected	40	40
Outcome	40	40

The result for the Chi-Square test, where the degrees of freedom is 1

X^2	0
Xc^2	3.84
α	.05

5 CONCLUSION AND FUTURE WORK

This chapter will try answering the research question mentioned in 1.4 and the hypotheses referred to in chapter 3.3, by analyzing the result data provided in the previous chapter.

5.1 Conclusion

In answer to the hypothesis in chapter 3.3:

The number of particles changed the result dramatically in some scenarios. This can be seen in a visual comparison of figure 4.2 and figure 4.3. Where the same scene is rendered with the same volume, and no objects. The differences between these scenes are the particle amount and particle radius. The Chi-Square test analyzed the total of the scenes added together, which yields another result.

By analyzing the Chi-Square result in chapter 4.2. Where the result for the Chi-Square statistic is 0, and the Critical Chi-Square value is 3.84, which yield that the Chi-Square statistic is lower than the Critical Chi-Square value ($0 < 3.84$). This means that we fail to reject the null hypothesis, meaning that a larger number of particles will not give any changes than having a lower number of particles.

Answers provided from the participant yields similar answers, such as:

I preferred the one where the water quickly evened out.

Too much splashing for realism.

This could be analyzed as that the water shouldn't move too much for a realistic behavior.

In answer to the research question in chapter 1.4:

The Lagrangian and semi-Lagrangian had a different look and yields a different result depending on the number of particles, scene objects, and starting volume shape. Some scenes provide a much higher difference between the two methods and other results in a more stabilized similar effect. The overall votes between the two approaches can be seen in image 4.5. Where all the votes are taken to account, the result can be analyzed as an almost equal result. Meaning that none of the fluid simulation methods analyzed have a more realistic appearance than the other. This is interesting when considering the reason of the chosen techniques in chapter 2.1.

No participants said that they didn't see themselves as a technical person, and those who play more video game slightly enjoys the semi-Lagrangian look more than those who doesn't play as much video games. Which is interesting, because the semi-Lagrangian had higher viscosity look and had more splashing.

5.2 Future Work

This paper has many things which could have been implemented or been improved. For example, including a Eulerian technique for comparison. The case might be that the simulation method left behind might be the most optimal for realism. The scenes could also have been bigger with more advanced objects, such as meshes.

Larger user study of about 50 persons would've also stronger the conclusion of this work.

5.3 Contribution

This paper has shown that the realistic appearance between the Lagrangian and semi-Lagrangian yields different result depending on the scenario of the scene. It has contributed with user data comparing the two methods with different scene environment.

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APPENDIX A

6.1 Questionnaire

Subject #: _____

Questionnaire Fluid Simulation

Section I: Personal Information

1. How old are you?

2. Do you see yourself as a technical person?

- Yes
- No

3. How technical do you see yourself as?

- 1
- 2
- 3
- 4
- 5

4. How often do you play video games?

- Once a week
- 2-5 times a week
- 6-7 times a week
- Very rarely
- Never

Part 2: To be completed during software use

1. Here is where you will watch different scenes of two separate fluid simulations, you will have time to answer the question between the scenes. Here I would like you to observe carefully and decide which one that would reflect a more realistic appearance.

Scene 1

- Left
- Right

Scene 2

- Left
- Right

Scene 3

- Left
- Right

Scene 4

- Left
- Right

Part 3: To be Completed After the visual comparison

Any last comments on your decision making in the previous part?