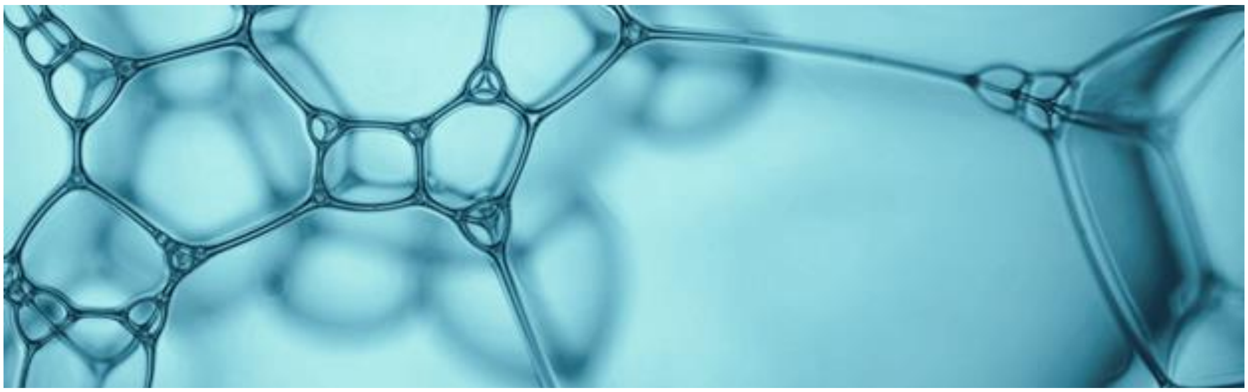


CM3070 Final Project; Fluid Mechanics a Virtual Reality Learning Experience

Submitted by: Garrison Jabs

ABSTRACT

Computational fluid simulations are powerful tools for providing understanding in education, interest, and curiosity. However, the herculean task of conducting simulations turns most applications into an esoteric tool. As a result, interested parties find the tools as unapproachable, as the topic of fluid mechanics. In spite of this, new opportunities for visualization and interactions are becoming possible: the recent reduction in the cost of virtual reality systems, advances in the efficiency of particle simulations, and commonplace ownership of powerful computers. By exploiting advances in fast particle simulations to create an application based around fluid mechanics, the present project proposes a learning experience that aids in general understanding. This will be achieved by taking advantage of the power of virtual reality to submerge a user in the material.

1 Introduction

1.1 Chosen Problem Template

Development of this project follows the second project template from the virtual reality path provided by CM3070 course material.

- *A Virtual Reality Learning Experience*

1.2 Project Concept

The project concept is a virtual reality lab experience that allows users to explore and learn about fluid mechanics in a hands-on experimental way. The proposed VR experience would first introduce some basic history on the subject matter. This would be done by allowing the user to explore a scene resembling a museum. Following this, the user would explore two basic labs involving hydrostatic properties of fluids: Buoyancy and Viscosity. Exploration of the labs is undirected: the user engages with the available equipment making changes and experiencing the results.

1.3 Context

Fluid Mechanics is a branch of classical physics that involves the study of fluids and their responses to forces applied to them. It can be further broken down into the three subfields: “Fluid Kinematics,” “Fluid Statics” and “Fluid Dynamics.” Fluid Mechanics is one of the oldest fields in physics and is notoriously difficult to approach. To understand it, it requires thinking in 3D at the micro and macro levels. Through employing virtual reality, it is not only possible to allow a learner to visualize these levels, but also to allow for real-time changes to be represented. Consequently, assisting in the overall process of understanding and making the subject matter significantly more approachable.

1.4 Project Motivation

Past work in computational representation of fluid mechanics has not produced many user-friendly tools to aid in understanding. Much of the work has been to produce tools for engineers and other experts. For example, the interactive models provided by the University of Colorado Bolder. The models are informative, however, unapproachable unless the individual has a clear understanding of the math involved. This completely neglects individuals who are in the process of learning about the field or are just curious. Alternatively, other products that simulate fluids have focused only on the entertainment side of things, which also neglects understanding. For instance, the game “Fluid VR”; this application lets a user model the flow effects of smoke in air and produces some beautiful simulations. However, none of the properties involved are explained, and a user is not able to explore any other aspects of fluid mechanics.

1.5 Scope and Considerations

1.5.1 Scope

Developing a learning experience application, that utilizes virtual reality as the interface for engaging with the material. The experience will consist of at least four Unity environment scenes:

1. Start Menu
2. Museum
3. Lab
4. End Credits

For this application to work it will be required to implement:

- Locomotion/Interaction system.
- Real-time physics engine for fluid simulations.
- User Interface for starting and stopping the simulation.
- Interactive asset models.
- Expected learning outcomes.

1.5.2 Considerations

There are challenges that cannot be ignored before beginning development of this project. The three most significant are:

1. Fluid Simulations along with virtual reality are notoriously resource hungry. Therefore, managing resource demands will be critical.
2. Creating simulations that are informative and engaging without relying on heavy explanation.
3. Project must be completed before March 13, 2023.

Based on the exploration of previous work and consideration of the most significant challenges, I will be developing:

- Small scale fluid simulations to minimize computational cost and development time.
- Simulations will be modifiable in real-time to experience the effect those changes have.
- The user will engage with the simulation: pressing buttons, turning knobs, pulling levers, and pouring.
- An available physics engine will be utilized to save developing one from scratch.

2 Literature Review

2.1.1 Methodology

The literature review followed a systematic approach that included three phases: Planning, Conducting, and Reporting. In phase one, “Planning,” an informal research question was asked, “What virtual reality fluid mechanics experiences exist?” This was to establish potentially neglected areas. Formal research questions were later established guided by the initial results and the selected domain of a “Virtual Reality Learning Experience.” The three formal questions were:

1. How to encourage the act of learning?
   1.1. Can VR deliver a better understanding of complex materials?

2. Is there a desire for educational VR simulations, and more specifically simulations related to fluid mechanics?
3. Is it possible to generate effective particle physics for real-time fluid applications?

In the second phase “Conducting,” search keywords were initially identified to narrow down and focus on relevant research. The search keywords used were combinations of “virtual reality,” “education,” “learning,” “experience,” “gamification,” “fluids,” “fluid mechanics,” and “dynamics.” Keywords were chosen according to the topic of “Fluid Mechanics,” and the goal of learning. The web searches I conducted were performed as formal and informal searches.

The biggest determining factors for including a research paper in this review was primarily whether it was part of an established peer reviewed journal and date of publication. The time frame for publications considered was between 2014 and 2022. This is because significant advances in “Computational Fluid Dynamics” simulations have occurred during this time.

In the final phase “Reporting,” the results of the study were organized into topics answering the three individual research questions and follows from this point.

2.1.2 Learning and Development

Learning is an intense emotional experience, which ranges from extreme frustration to elation. “There is a vast breadth of documented research that highlights how an individual's emotional states, excited by their perceptions, are essential for learning and development” [1]. Furthermore, this is fundamentally why play is so important in the process of learning. Play allows for an individual to explore ideas and concepts from a new emotional context [2]. For this reason, technology that can generate emotional responses from the relatively safe context of play (ex. physical and digital games), has been used to assist as a learning tool.

While classic play experiences have been successful in aiding in the process of learning, demand for these experiences has remained low. However, the recent change in affordability of virtual reality (VR) systems, coupled with the change in perspective that games could be more than just entertainment, has generated increased demand for virtual learning (VL) experiences [3].

But why has VR been so important for the development and encouragement of learning? To answer this correctly, it is critical to first define what VR and VL is.

2.1.2.1 Virtual Reality and Virtual Learning

- VR is an experiential process, whereby a user immerses in an interactive simulated environment. To the user, it can feel as if they have been transported to a different world. Broadly, the term VR can cover most forms of environmental simulations. However, in this context it refers to the illusion of being transported somewhere else, while remaining in place. An experience achieved through a combination of headset and hand-held remotes. These devices transmit the visual and audio data to the user, allowing the user to interact with the simulated world.
- VL refers to the process of using technology to deliver educational material, while minimising the requirement of face-to-face interactions [4].

The sympathetic nature of these tools creates an opportunity for exposing individuals to material that might otherwise be impossible to experience. Primarily due to its potentially dangerous or abstract nature. Furthermore, the material can be presented in the fashion of game, which encourages the individual to approach the learning from the perspective of play. This potentially deepens the engagement and allows for more of the material to be retained at the end of a session.

2.1.2.2 Virtual Reality as a Tool to Aid in Learning

The actuality that VR can simulate normally impossible scenarios, makes it an utterly unique medium for education and training. It gives the opportunity to experience ideas from new perspectives and to engage with them in new ways. This ability to arbitrarily change a perspective often can bring new insight and clarity to complicated structures. For instance, bio printed objects. Bio printed objects are complex 3D assemblies, constructed of multiple organic cell types [5]. One of the intended purposes of bio printed structures is the ability to print undamaged organs for transplant. This is significant to note as it dictates an exceptionally low margin for printing errors. Researchers wanted a faster method for identifying structures with flaws [5]. When sampling a bio printed structure for quality control, the typical method followed is; an expert physically examines a series of 2D MRI images, and then compares them to a histogram chart of the measured pixel distribution (cell distribution) [5]. This is a time-consuming process and can be challenging to spot potential problem areas within the print. However, when the researchers converted the 2D MRI images and pixel distribution to a 3D virtual representation, suddenly all printing errors were glaringly apparent. Even to the extent that an untrained individual could spot them. This was a clear improvement in the understanding of the complex visual data in this field.

However, bioengineering is not the only field dealing with data that could be better understood with a clear visual implementation. Most fields in science, technology, engineering, and math rely on abstractions. Often because, it is too costly or impossible to clearly represent a 3D concept in a textbook or classroom. A clear example is Fluid Mechanics. Almost all properties of fluids act in three dimensions and have a substantial number of nuanced properties. This is fundamentally why the study of fluid mechanics is so challenging. It often requires a practitioner to have a clear understanding of some of the most advanced subjects in mathematics [6]. For instance, looking at the process of mixing sugar in a drink, superficially the process appears easy to understand. However, there is so much going on; friction changes at the container wall, shear forces etc.; that engineers/scientists regularly study this process to better understand it. Math is often used to model the forces, but as the nature of this is three dimensional, the math alone often does not add much clarity without years of experience. This creates a large barrier for students learning about the process. As a result, researchers felt creating a VR fluid simulation showing the process of mixing and the related effects, would add significant clarity to the material for new learners. In this case mixing was the obvious choice to model, as it is a fundamental first step in most chemical processes [7]. In addition, when done poorly can mean the difference between success or failure of a production run.

To create a semi real-time simulation, the researchers built a two-way coupled tech stack. The data pipeline created, allowed the complicated solving of fluid forces to be handled by a separate machine. Which in turn, allowed a user to change design settings in real-time and view the visual changes to the mixing process [7]. The model produced by the application was still an abstraction. Regardless, the representation allowed the practitioners to better understand how the fluids moved in the tank, and how their changes either improved or obstructed the process. This kind of tool had clear advantages over traditional mathematical models in showing the mixing process. Which significantly decreased the level of experience needed to understand. In another study about fluid mechanics, conducted by "*Matar Fluids Group,*" students of fluid mechanics were allowed to explore multi-sensory virtual simulations of concepts they were learning in class. When students were later interviewed about their experience, there was an overwhelming response of improved understanding [8].

When applying VR as tool to aid in understanding, there are clear advantaged over traditional methods. However, VR cannot currently be applied in every situation equally. Simulations that require accurate physical feedback such as ones involving surgery, often require specialised equipment not available to everyone. As well as some physical interactions do not currently translate accurately to the simulated world. This has the drawback of reducing plausibility and engagement with the material. So, care must be taken when designing simulations to account for this, in order produce an effective tool.

2.1.3 The rising demand for educational Virtual Reality experiences

VR as we now recognise it, was initially introduced in 1968 [9]. Despite this, VR is arguably still in its infancy, which has created barriers to market penetration of the technology. Due to the cost of entry, many have stayed away from the technology. However, VR is finally finding its stride. The computer hardware capable of running these headsets is virtually mainstream at this point, and the costs of owning a VR headset has fallen dramatically [9]. Still, when curious about the need for increased content in an area, a good metric to examine is the market share it holds over time. This can be a great predictor of the current desire for a type of product and whether it is growing or shrinking.

Researchers wanting to discover which educational VR applications were most appreciated by users, completed a three-year market analysis to map available learning tools [3]. To do this, the researchers tracked the available educational and training VR applications hosted on the Oculus Store. This store was chosen because it had been determined to be the main distribution channel at the time [3]. The data was collected from 2019 to 2021. Within this time frame, the number of available educational application increased by 36% and dominated 24% of the available market [3]. Furthermore, when the market share was compared to the rest of the distribution, the researchers noted that educational applications controlled the largest share. With applications based around space, medicine, and engineering rating highest among users. This research clearly indicates, a strong and growing desire for educational applications. Also implying, that a learning experience based around fluid mechanics could be well received. However, just because a product is in demand, does not necessarily indicate that any educational application will be adopted. This is further elaborated by the thirteen-year longitudinal study researchers carried out, exploring the barriers to adoption of a university's experimentation with a VL environment [10].

The researchers wanted to determine the reasoning and point at which an innovation moved from fad to institutional standard. Also known as the threshold stage [10]. To do this they examined thirteen years of usage logs, archival documents and carried out fifty-one teacher interviews [10]. The researchers arrived at the conclusion, that the fundamental point occurred, when the individual cognitive divergence and collective cognitive consensus met [10]. In other words, when usership was 50% or more and individuals saw a value in the tool, even if the perceived value was different [10]. This evidence indicates that there are significant barriers when creating new software, but if a broad enough value can be shown, then these barriers can be significantly reduced. For example, if the proposed fluid mechanics simulation provides a perceived educational value to some users, but others only perceive an entertainment value, the odds of the tool being accepted greatly increases because of the cognitive consensus.

Despite the barriers to adoption, educational VR applications dominate the largest share of the available market with significant growth year after year. This Indicates a strong and growing desire for more products that fit this description. It can then be safely stated that there is a need for more content within this domain.

2.1.4 Virtual Reality and Real-time Particle Physics

As particle physics simulations and VR are notoriously expensive in terms of computer resources, establishing the plausibility of real-time simulations with VR is critical. Especially, with computational fluid simulations being at the extreme end of resource demand.

VR needs to be performative to avoid issues such as VR fatigue or simulator sickness. Any slowdown or stutter in the rendering of a scene can cause these afflictions. Beyond this, slowdowns also create problems with the illusions necessary for VR to work, such as plausibility and place. For these reasons, when designing an experience around real time simulations, the plausibility is a significant determining factor.

One solution to the issue of resource demand, is to allow a different machine to do the demanding work of solving the particle fluid interactions. This would leave the VR application to only display the results. As an added benefit, it would also allow the largest number of VR devices to run the application, since the computational load is only minorly affected. To this end, researchers proposed an automated data pipeline for converting native “Computational Fluid Dynamics” (CFD) data to a 3D model [11]. However, the produced models were mostly static fluid displays, where users could not interact other then rotating the model. Later, the very same researchers improved the data pipeline they had proposed, by creating a bi-directional system. This system allowed a user to influence the output through adjustable settings in real-time [7]. However, the produced models were still not real-time simulations, as the user could not affect the output through direct interaction. The importance of this research is in noting a good alternate solution in the case that real-time simulations are not possible.

Further investigation led to the discovery of the paper produced by researchers at Nvidia. For context, Nvidia is a company that specialises in producing hardware, optimised for generating graphical output. In this paper, the researchers developed a new unified system for solving particle physics simulations. This system allowed for real-time changes to be modeled on the fly. However, the researchers did note that some resolution and accuracy was sacrificed to increase the overall speed of processing. This means that this system would not be useful for simulations requiring a high degree of accuracy. An example of this is aerodynamics modeling for engineering. Nevertheless, it could be used in situations where perfect accuracy was not required, such as modeling general fluid interactions.

Although the simulation could run in real-time, the drawbacks were not insignificant. Simulation spaces were required to be bounded to small areas, and resource requirements were still quite high [12]. More recently, solutions to the small simulation space and resolution issues have been created. Researchers have proposed using voxels, a new way of bounding and associating particle interaction. This allowed for fast two-way force resolving, in a near unbounded display space [13]. This solution was able to produce fast simulations with millions of particles.

For VR purposes, simulations with this method in the scale of millions of particles is still too slow. Nevertheless, this method is effective enough that small scale real-time simulations (~2000 particles) are very possible.

With the proof that relatively low-cost fast particle simulations could be created, a good question to be investigated is: “Are there any ready-made solutions?” Answering this, led to the discovery of the “Obi Fluids” physics engine. A fluid simulator that implements these features and is optimised for performance with “Unity Game Engine.”

2.1.5 Study Limitations and Future Research

The research conducted never explored which techniques were most effective in educational delivery for VR learning experiences. This could create issues, as not all methods are equal and there is a very fine balance between user engagement and tune out. In the future it would be good to explore best practice when delivering learning material from a gamification perspective.

2.1.6 Conclusion

VR is a uniquely powerful tool for creating educational simulations, as it allows users to engage and interact with material from a new perspective, forming new ideas in the process. This in turn, can create better understanding of complex and even simple material. Furthermore, as VR becomes more commonplace, there is a steadily growing appetite for new learning simulations, which creates a need for ever-growing content. In addition, with the advent of new and improved solutions for particle physics operating in real-time; new types of learning simulations including interactive fluid mechanics have become possible.

2.1.7 Statement of Reliability

The credibility of the references chosen is felt to be strong. This confidence was first bolstered by much of the research being published in well-known, respected, peer reviewed journals. Secondly, most of the researchers either attached their datasets or gave instructions on how to acquire the dataset used. Thirdly, background research was well cited with clear references. Lastly, the methodology was clearly explained in the research papers.

3 Design

3.1 Overview

The intended project is a VR simulated lab environment with sandbox properties. A user will be able to explore, interact and experiment with fluid simulations to gain greater understanding about fluid mechanics. The initial experience will be focused on fluid statics, a subsection of fluid mechanics. The interactive labs will highlight properties of fluids, such as buoyancy and viscosity. Given enough development time, the other subsections of fluid dynamics and fluid kinematics would be included and expanded upon.

3.1.1 Template Domain & Problem

- Domain: Virtual Reality
    - Chosen Problem: Problem 2, VR Learning Experience

3.2 Software Domain & Users

3.2.1 Domain

The functional domain of this project is experiential educational entertainment. From the literature review conducted, it was established that educational entertainment can provide more engagement with learning material, and greater understanding in a shorter period [14]. Furthermore, there is strong evidence that VR educational software is currently in demand, with increasing yearly demand indicated by a trendline from 3-years of collected data [3].

3.2.2 Users

The targeted users of this application fits into three groups:

- Individuals who want to learn more about physics and the world.
- Individuals who want a better understanding of fluid mechanics.
- Individuals who are curious about fluids.

More specifically, this application would be well suited for students who want to interact directly with the concepts they are learning about.

As this application will have certain game like principles included, there could be overlap with users who enjoy playing video games.

The nature of this application does not preclude use and enjoyment by adults; however, they do not typically fall within the target audience.

3.3 Design Choices

3.3.1 Technology

Technology Choices	Justification
1. **Unity Platform**	Unity is a well-established development platform that offers: • Available Resources – Unity has a very active user and support community. With a large library of available assets easily added. • Unity VR framework – An established framework for developing VR applications for high end headsets. • Ease of Access – Unity offers a free use development license for all projects prior to earning 100,000 in profit. • Familiarity – I have prior experience developing with unity, which expedites the development process as there is less of a learning curve.
2. **C#**	C# is a well-established language frequently used in developing graphical based software. • Unity uses C# scripts for application development. • C# scripts is a modular way of organizing game behavior components. • C# is beginner friendly.
3. **Valve Index HMD**	A powerful high end VR headset • Steam – The Valve Index requires developing applications for the steam platform. This allows for easier distribution of completed software and natively is more VR HMD cross platform capable. • Ease of development – A active community offering knowledge and assistance. • Availability of HMD – The Valve Index is the HMD I have access to.
4. **Steam**	A distribution platform • Easier cross platform compatibility.

	• The Valve Index HMD requires developing applications for the steam platform.
5. Obi Fluid Physics Engine	Obi Fluids is a high-speed unity optimised physics engine. • Runs on the CPU saving the GPU for graphics. • Implements a real-time solver for fluid particles that does not greatly impact VR.
6. GitHub	• Is a well-established medium for maintaining source code and tracking changes over time.

3.3.2 Development

DEVELOPMENT CHOICES	JUSTIFICATION
1. **Small Fluid Simulations**	• Fluid simulations are computationally costly. Small simulations make the load more manageable for machines and minimize or eliminate graphical rendering issues. • Small simulations are faster.
2. **Lab Environment**	• Using a lab environment can give visual clues to the user, indicating what they are supposed to do. This increases user familiarity and decreases the application learning curve.
3. **Small Related Experiments**	• Available development time is limited; scale of available learning material is massive; initial scope must be kept small for a minimal viable product (MVP). • Clear learning outcomes. • Evaluating knowledge acquired by a user will be easier.
4. **VR Locomotion** • **Teleportation** • **Local Area Physical Motion**	• Teleportation and local area free physical movement are very effective for minimizing VR sickness and fatigue in users.

3.3.3 Expected Learning Outcomes

The expected learning outcomes for a user who has completed this experience are:

- A user will be able to describe some history of fluid mechanics.
- A user will be able to describe viscosity.
- A user will be able to describe the incompressible nature of liquid fluids, and the compressible nature of gaseous fluids.
- A user will be able to describe Archimedes Principle of Buoyancy, which relates the amount of fluid displaced by an object is equal to the weight of the object.
- A user will be able to describe Pascals Law, which states that any pressure applied to the surface of a fluid will be transmitted uniformly throughout the fluid in all directions, in such a way that initial variations in pressure are not changed. Also known as hydrostatic pressure.

3.4 Structure

3.4.1 Overview

The application allows a user to explore a lab environment, centered around completing a series of tasks. Tasks will build on each other, teaching the user about properties of fluid mechanics. This will reinforce the knowledge gleaned. The user will be rewarded at the completion of each task, and the simulation is over when all tasks are completed.

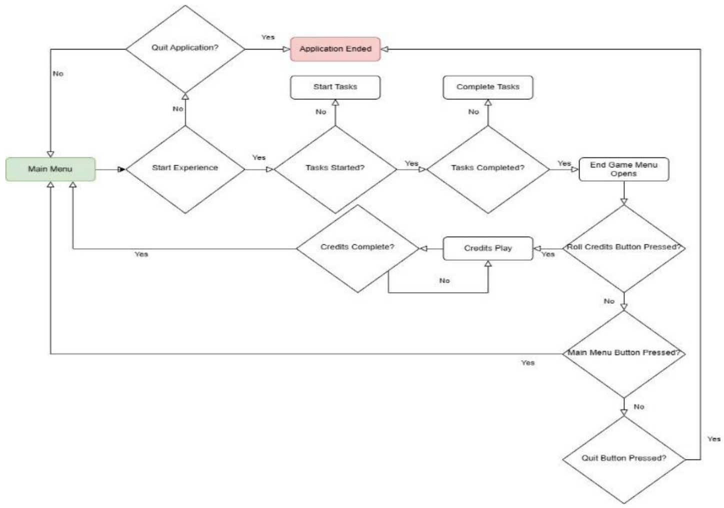


Figure 1. Example application flow

3.4.2 Required Components

- Assets
    - Environmental
        - Assets related to a science lab.
    - Character
        - Lab Coat
        - Goggles
    - Audio
        - Fluid Sounds
        - Clinking Glass
        - Breaking Glass
        - Hollow Object/Full Object
        - Humming of machines
- Animations
- C# scripts: scripts governing component behaviors, such as score keeping and glass breaking.

3.4.3 Required Technical Elements

For this project to function, several key technical elements are required to be sourced or created:

- An optimized fluid simulator, capable of running simultaneously with a VR system.
- A user interaction system, allowing interaction with objects and visual indication of interactable objects.
- A scoring system for tracking a user's success/failure rate with task completion.
- A movement system, allowing a user to navigate the experience space.

- Interactive models that respond to the user's actions.

3.4.4 Virtual Reality Interaction

The user will interact with the scene: picking objects up, turning them over, and generally exploring the room, as one might in real life. This is to facilitate plausibility and place illusion.

3.4.5 User Interface

Main Menu

Figure 2. Example menu design

The initial screen of the application will be a menu interface allowing the user to start, quit, or edit available settings. The theme of the menu will follow a color scheme and design that is representative of the experience about to be played (E.g., A beaker and graduated cylinder).

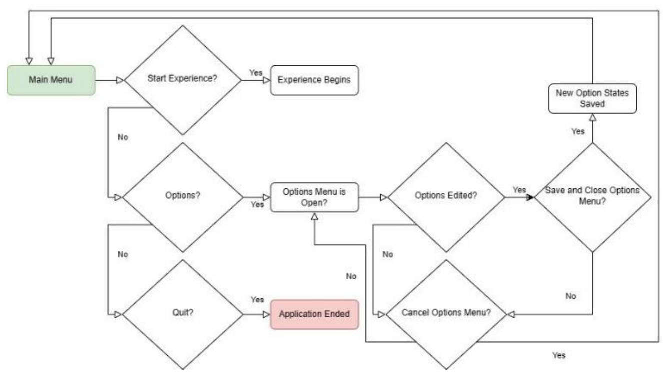


Figure 3. Example menu flow

Game Level

The experience will take place in a single lab environment like the image in figure 4. This will set the tone for the type of experience to be played. Ambient sound and effects will be used to enforce the user's sense of place. Objects that are to be interacted with will give visual feedback by highlighting when the user is looking at them and close enough to interact.

Figure 4. Example level design

When a user completes a task successfully, a pleasant tone will play. Alternately, when they get it wrong, a discordant tone will play. Experiments will be numbered to indicate specific order of operation. Lastly, when all tasks have been completed, a congratulatory statement will appear, indicating the successful completion of the lab environment. Button options will also appear allowing the user to: return to the main menu, quit game, and roll credits.

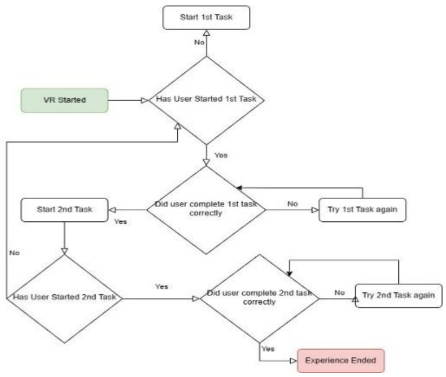
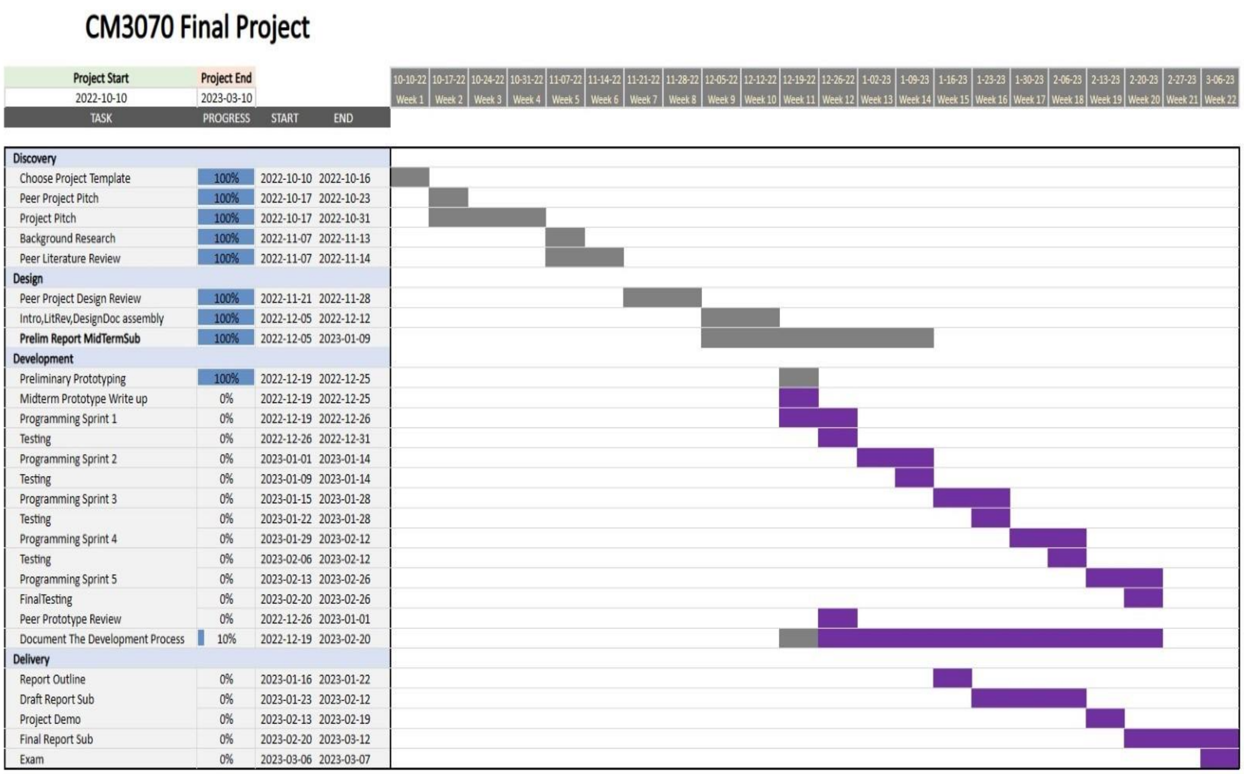


Figure 5. Example level flow

3.5 Work Plan



CM3070 Final Project

Project Start	Project End
2022-10-10	2023-03-10

TASK	PROGRESS	START	END
Discovery			
Choose Project Template	100%	2022-10-10	2022-10-16
Peer Project Pitch	100%	2022-10-17	2022-10-23
Project Pitch	100%	2022-10-17	2022-10-31
Background Research	100%	2022-11-07	2022-11-13
Peer Literature Review	100%	2022-11-07	2022-11-14
Design			
Peer Project Design Review	100%	2022-11-21	2022-11-28
Intro,LitRev,DesignDoc assembly	100%	2022-12-05	2022-12-12
Prelim Report MidTermSub	100%	2022-12-05	2023-01-09
Development			
Preliminary Prototyping	100%	2022-12-19	2022-12-25
Midterm Prototype Write up	0%	2022-12-19	2022-12-25
Programming Sprint 1	0%	2022-12-19	2022-12-26
Testing	0%	2022-12-26	2022-12-31
Programming Sprint 2	0%	2023-01-01	2023-01-14
Testing	0%	2023-01-09	2023-01-14
Programming Sprint 3	0%	2023-01-15	2023-01-28
Testing	0%	2023-01-22	2023-01-28
Programming Sprint 4	0%	2023-01-29	2023-02-12
Testing	0%	2023-02-06	2023-02-12
Programming Sprint 5	0%	2023-02-13	2023-02-26
FinalTesting	0%	2023-02-20	2023-02-26
Peer Prototype Review	0%	2022-12-26	2023-01-01
Document The Development Process	10%	2022-12-19	2023-02-20
Delivery			
Report Outline	0%	2023-01-16	2023-01-22
Draft Report Sub	0%	2023-01-23	2023-02-12
Project Demo	0%	2023-02-13	2023-02-19
Final Report Sub	0%	2023-02-20	2023-03-12
Exam	0%	2023-03-06	2023-03-07

Figure 6. GANT Chart Project Plan

3.6 Evaluation Methodology

To determine the quality of the VR learning experience, qualitative and quantitative methodologies will be used.

Initially, before a user engages with the experience, a short questionnaire will be administered. This questionnaire will be used to establish a baseline and gauge a user's pre-existing knowledge of the intended subject matter (See Appendix A Figure 1).

During the users play through of the experience, the user will be tracked on metrics of:

- How long did it take to complete the task.
- How many times the user asked for help.
- How many times the user made a mistake and had to start over.
- How long the overall experience lasted.

These metrics can be a good indication of how easy a task is to understand and whether the controls and objects make sense.

After completion of the experience, a series of questionnaires will be administered (see Appendix A). These questionnaires will be used to measure a user's experienced levels: simulator sickness, presence illusion, plausibility illusion, place illusion, and change in knowledge. Additionally, the user will be asked about their personal thoughts on the experience. The original baseline questions will be used to determine overall improvement in knowledge of the subject matter. The qualitative and quantitative questions will be used to evaluate the overall experience, and to give clues as to where the design had poor or confusing aspects.

4 Implementation

4.1 Overview

As VR experiences are simulated 3D environments, with the powerful illusions of place and plausibility, some implicit features will always be required to maintain those illusions. Features such as the ability for the user to move, and to physically interact with the environment. The topic of the proposed VR experience fluid mechanics gives an additional implicit requirement. This is the requirement of a fast real-time physics engine capable of fluid simulations. These guiding requirements were used to establish a working prototype and proof of concept. However, additional features were also required for the application to be considered a fully-fledged experience. Features including: scenes, scene changes, interaction elements (e.g., buttons, levers), and user interfaces (UI). The following documentation records all features implemented, the methods used to create effects, and an overall evaluation of the features.

4.2 Implemented Features

The following features and their listed boundary conditions were implemented in this project.

- Movement
  - Physical movement within the bounds of the user's play space.
    - Approaching the edge of physical space indicator.
  - Simulated movement within the available game space.
    - Indication of travel to location.
    - Indication of accessible areas.
- Object Interaction
  - Indication that an object can be interacted with.
  - Methods for manipulating the object.
- Scene Change

    - A way to cancel an accidental scene change.
- Interaction Elements
    - Clear indication of how to operate.
- UI
    - Clear indication of selected option.
    - Clearly indicated action event.
- Fast Real-time Physics Engine.

The following seven scenes were also implemented:

“Start Menu,” “Introduction/Museum,” “Lab Hub,” “Buoyancy Lab,” “Viscosity Lab,” and “Credit’s” (two separate implementations).

4.3 Code & Architecture

4.3.1 System Setup

The Valve Index Head Mounted Display (HMD) used in the production of this application was produced by the digital distribution company STEAM. As such, it has been optimized to operate with the company’s proprietary software. To avoid common issues encountered with the proprietary software API; STEAM has produced unity prefabs to aid in setup and initialization of VR projects. These prefabs were used in the initial set up of this application. It was required to download and include the Steam VR package with unity’s package manager to set this up.

4.3.2 Player Movement

Player movement was initialized by including the “Player” prefab in the “Game Object” hierarchy. This prefab allowed physical movement within the bounds of the play space, and a visual alert system when approaching the bounds as a standard. The system was able to do this by utilizing two always scanning physical sensors. These sensors would update location data in real-time. This was effective for initial testing purposes. However, it was necessary to also implement a teleportation system to allow the user to explore larger spaces.

```
//Trace to see if the pointer hit anything
RaycastHit hitInfo;
teleportArc.SetArcData( pointerStart, arcVelocity, true, pointerAtBadAngle );
if ( teleportArc.DrawArc( out hitInfo ) )
{
    hitSomething = true;
    hitTeleportMarker = hitInfo.collider.GetComponentInParent<TeleportMarkerBase>();
}
```

Ray casting was used to detect and show where the user was going to travel to (see Appendix B section 2.1.1.1 Figure 1). The ray casting was used in conjunction with an established teleport area to indicate allowed travel zones (see Appendix B section 2.1.1.1 Figure 2). This system made it possible to give visual feedback to the user if they were trying to travel somewhere they were not supposed to.

4.3.3 Object Interaction and Interaction Elements

Object interaction required using a combination of colliders, rigid bodies, and control scripts. Colliders were used to resist the user’s ability to pass through elements they were not supposed to, and to detect interaction attempts. Rigid bodies told unity to apply physics responses to objects. This allowed the user to move objects through touch. While this was effective, it was not enough as there was minimal indication to the user which elements were interactive. An “interactable script” was applied to the object with the purpose of detecting the user’s hand.

```
protected virtual void OnHandHoverBegin(Hand hand)
{
    wasHovering = isHovering;
    isHovering = true;

    hoveringHands.Add(hand);

    if (highlightOnHover == true && wasHovering == false)
    {
        CreateHighlightRenderers();
        UpdateHighlightRenderers();
    }
}
```

In cases where the user's hand was close to an object or hovering, it produced a yellow highlight and grab hint (see Appendix B section 2.1.1.2 Figure 3). This highlighted the interactive ability of an object. For a user to grab the object a second script was required. Originally, the script “Simple Attach,” allowed the user to grab an object and move it around (see Appendix B section 2.1.1.2 Figure 4).

```
if (startingGrabType != GrabTypes.None)
{
    hand.AttachObject( gameObject, startingGrabType, attachmentFlags, attachmentOffset );
    hand.HideGrabHint();
}
```

This was later replaced by the “Throwable” script as it added an ease in function to the players grab. It also made the object respond to a throwing action from the user. Some interactable elements also included audio sources, this was to increase the effectiveness of the plausibility illusion.

4.3.4 Scene Change

A teleport orb was created to allow users to travel between scenes (see Appendix B section 2.1.2.2 Figure 10). A scene change was initiated when the orbs collider interacted with the collider on the camera, which represented the user’s head. This was done by setting the collider as a trigger, which initiated the script “Transport Player” attached to the orb.

```
private void OnTriggerEnter(Collider ChangeScene)
{
    if (ChangeScene.gameObject.CompareTag("MainCamera"))
    {
        StartCoroutine(StartCounting());
        FadeToBlack();
    }
}
```

```
private void OnTriggerExit(Collider other)
{
    StopAllCoroutines();
    FadeFromW();
}
```

If the user pulled the orb away or released it, they could cancel the scene transition within a time limit. This was indicated to the user by a screen fadeout effect. Additionally, a script modified the mesh render of the orb to give it a soft body effect upon movement, like a water blob.

```
vertexArray = OrigionalMesh.vertices;
for(int i = 0; i < bv.Length; i++)
{
    Vector3 target = transform.TransformPoint(vertexArray[bv[i].ID]);
    float intensity = (1 - (renderer.bounds.max.y - target.y) / renderer.bounds.size.y) * Intensity;
    bv[i].Shake(target, Mass, stiffness, damping);
    target = transform.InverseTransformPoint(bv[i].Position);
    vertexArray[bv[i].ID] = Vector3.Lerp(vertexArray[bv[i].ID], target, intensity);
}
MeshClone.vertices = vertexArray;
```

4.3.5 User Interface

A user interface was created using a unity canvas and button elements (see Appendix B section 2.1.2.2 Figure 12). The button elements included audio events that fired, when a button was entered, a button was exited, and when a button was clicked. Using ray casting the user could point at the UI and interact with it (see Appendix B section 2.1.2.2 Figure 1, 2, 3). This was all controlled by the “VR_UI_Input” script.

```
private void OnPointerClicked(object sender, PointerEventArgs e)
```

```
private void OnPointerIn(object sender, PointerEventArgs e)
```

```
private void OnPointerOut(object sender, PointerEventArgs e)
```

4.3.6 Real-time Fluid Simulation

Fluid simulations were handled by “Obi Fluid,” an asset from the unity asset store. The physics engine “Obi Fluid” required some initial set up aside from the Obi Fluid package itself. This was to employ unity’s burst compiler as the physics solver, which was more efficient than the depreciate solver included. The required dependencies were: “Burst 1.3.3 or newer,” “Collections 0.8.0 or newer,” “Mathematics 1.0.1 or newer,” and “Jobs 0.2.9 or newer”. All packages were added and set up with unity’s package manager. To implement the physics simulator, four things were needed within a scene:

- Obi Solver: this solves all collisions and changes due to the physical properties of the fluid.
- Obi Emitter: this handles particle generation and color.
- BurstCollisionWorld: this exposes the particles to influence from changes in the world space.
- ObiFluidRenderScript: this handles how the particles are drawn to the canvas.

The first three elements are included in the game object hierarchy list, while the fourth is attached to the camera. Simulations operate at runtime (see Appendix B section 2.1.1.3 Figure 1).

5 Evaluation

The VR learning experience, “Fluid Mechanics,” went through several rounds of acceptance and user testing throughout development. However, the initial prototype was not part of the user testing cycle. This was because it was fundamentally a proof of purpose, and only required acceptance testing to confirm that all aspects were working as expected. Even still, this testing proved effective in isolating some initial issues with the experience.

The early methods implemented were user locomotion, object interaction, and a simple fluid simulation (see Appendix B section 2.1.1). The biggest issue discovered at this point was with the implementation of object interaction. When a user went to grab an object, the object would abruptly snap to the hand often in the wrong orientation. Even though the script “Simple Attach” did enable a user to grab an object, this was a fundamentally incorrect behaviour. The issue directly impacted plausibility and the usefulness of the method. To solve this issue the prefab “Throwable script” provided through the “Steam VR” package was used to replace the interaction method produced by myself. This script used an ease in function for controlling grabbing speed and object orientation. It also added the ability to throw objects by providing methods for interpreting a throwing motion from the user.

User studies were carried out with 10 different individuals on the later prototypes. Analysis was completed with qualitative and quantitative questionnaires (see Appendix A). These studies were to evaluate:

- The effectiveness of the chosen interaction methods.
- The effectiveness of the experience to generate plausibility and place illusions.
- The effectiveness of real-time fluid simulations in conjunction with VR.
- The effectiveness of the application in aiding in learning about fluid mechanics.
- User opinion of the experience.

The user studies carried out on early prototypes focused on the effectiveness of the real time fluid simulations, and interaction methods. Initial development and testing started in this area for two reasons:

1. it was the most important of the core experiences.
2. It was the costliest regarding computer resources.

Several different methods of user interaction with fluid simulations were tested. Methods such as:

- Filling a flask and pouring it on a physics object.
- Fluid emitters controlled by the user emitting directly on different sloped physics objects.
- Placing physics objects in different fluids to see the effect.
- Varying shapes of physics objects used.

Unexpectedly, interaction tests where the user was required to use a flask, or cup object to interact with a fluid proved to be the least effective method. Upon investigation it was discovered this was fundamentally because of an effect called tunneling. Tunneling is where a fluid particle seems to magically pass through the wall of an object, primarily occurring due to the draw function of the application. In other words, when the application gets around to redrawing the particle to the screen, the object holding it has already moved somewhere new, losing the particle in the process. All physics engines are susceptible to this effect to some degree. While there are ways of mitigating this effect, they proved as detrimental to the plausibility illusion as the problem itself. As a result, this interaction method was abandoned. Ultimately, the interaction methods selected for use in this application were based off user's preferred interactions, and measures of the plausibility illusion determined in this testing. The interaction methods that were rated the highest, were where the user moved a physics object to a fluid to see the result. In addition, different fluid properties, particle resolutions quantities of emitted particles, and quantities of concurrent simulations were also tested during this time. This was to determine an optimal setting for running simulations in conjunction with VR. Through this testing, it was found that three simulations and a total particle count of ~6000 emitted particles was the upper limit for this application. Past this point, rendering faults such as stuttering, and delayed reactions to user's movement began occurring. This increased the effects of simulator sickness, and fatigue within the testing group. The limitations of the fluid simulator discovered by this testing inspired separating the viscosity and buoyancy labs into their own respective scenes. This was done to minimise concurrent simulator costs. It also had the added benefit of creating a more focused lab environment, which improved most users' overall expressed opinion.

User testing that was carried out on later prototypes focused primarily on the effectiveness of user's sense of presence, and the effectiveness of the learning outcomes. Initial responses indicated that users felt a large sense of place. However, users had trouble with the plausibility of the simulation. Upon further investigation the lack of plausibility was due to missing or inappropriate ambient noises that were expected. There were often large silences within the experience, which served to highlight discrepancies in the ambient noises. An attempt to solve this proved to be surprisingly effective. Background music was included in the experience to make errors in the ambient noises less noticeable. This contrary to expectation significantly improved user's feelings of presence in the entire experience. And as such was included in all produced scenes.

To explore the effectiveness of the experience on improving understanding and knowledge retention within the selected subject matter; it was found to be beneficial to not only apply a pre and post questionnaire, but to also measure a users' opinion after each core element. Of the ten users questioned, seven reported they felt they learned the most from the interactive fluid simulations. This was in stark contrast to only four reporting similarly about the museum experience. Even still, all users performed better on the post experience questionnaire verses the pre. This indicated an overall improvement of knowledge. However, a short coming of this testing process was that users were not tested at a later data to see how much knowledge was retained over time.

5.1 Strengths and weaknesses

The biggest weaknesses of this investigation were the lack of test users from the defined domain, and the small sample size of testers. However, the real-time fluid simulation was found to be truly engaging for most users. Many of the testers took significantly longer with the fluid simulations, then what was required to conduct the experiment. This was because users ended up playing with the functionality.

5.2 Possible project extensions

The museum scene was the least interactive of the core elements produce for this project. This caused the museum to have the least amount of engagement from the testing group. A possible way of improving this experience would be to implement a scene, were users would get the opportunity to explore the working environment of the historical figures selected. In addition, because of the effectiveness of the fluid simulations produced, further fluid labs exploring other properties of fluids would be potentially effective as well.

6 Conclusion

The presented work fundamentally explored whether it was possible to produce a VR learning experience, which could effectively improve understanding and learning within the challenging subject matter of fluid mechanics. The results of user testing indicated that there was a strong opportunity to achieve this goal. However, the limitations of employing only real-time simulations with VR, also indicated significant limitations with the current available systems. This is in spite of the significant power of processing available to most individuals. This may change as optimization in real-time particle physics improves. In future work, the current system could be significantly broadened by implementing real-time simulations, coupled with cloud computing physic solvers that can handle significantly more particles, increasing the range of possible simulations.

7 GitHub Repository Link

https://github.com/cerrmor/cm3070FluidMechanics.git

8. References

[1] Lee, C. D. (2017, March). Integrating Research on How People Learn and Learning Across Settings as a Window of Opportunity to Address Inequality in Educational Processes and Outcomes. *Review of Research inEducation*, *41*(Disrupting Inequality Through Education Research), 88-111. https://www.jstor.org/stable/44668688

[2] Preston, T. (2020, May). Kappan authors on play and learning. *The Phi Delta Kappan*, *101*(8), 5-7. https://www.jstor.org/stable/26977112

[3] Smutny, P. (2022). Learning with virtual reality: a market analysis of educational and training applications. *Interactive Learning Environments*. Retrieved 11 23, 2022, from https://www.tandfonline.com/doi/full/10.1080/10494820.2022.2028856?src=

[4] kotobee. (2022, January 13). *What Is Virtual Learning and How to Benefit from It?* Kotobee Blog. Retrieved November 22, 2022, from https://blog.kotobee.com/what-is-virtual-learning/

[5] Gretzinger, S., Schmieg, B., Guthausen, G., & Hubbuch, J. (2022). Virtual Reality as Tool for Bioprinting Quality Inspection: A Proof of Principle. *Front Bioeng Biotechnol*. Retrieved 11 21, 2022, from https://www.ncbi.nlm.nih.gov/pmc/articles/PMC9218671/

[6] Ajanif, Y. (2022, January 17). *Is fluid mechanics hard? (solved)*. STEMISFUTURE. Retrieved November 23, 2022, from https://stemisfuture.com/index.php/2022/05/14/is-fluid-mechanics-hard-solved/

[7] Solmaz, S., & Gerven, T. V. (2022). Interactive CFD simulations with virtual reality to support learning in mixing. *Computers & Chemical Engineering*, *156*. https://doi.org/10.1016/j.compchemeng.2021.107570

[8] Matar Fluids Group (Director). (2019). *Immersive VR teaching for Fluid Dynamics at Imperial College London* [Film]. Matar Fluids Group. Retrieved 11 23, 2022, from https://www.youtube.com/watch?v=ccb0Lth1k2g (Original work published 2019)

[9] *History of Virtual Reality*. (2017, June). Virtual Reality Society. Retrieved February 9, 2023, from https://www.vrs.org.uk/virtual-reality/history.html

[10] Li, N., Zhang, X., Limniou, M., & Xi, Y. (2022). Meaning-making in virtual learning environment enabled educational innovations: a 13-year longitudinal case study. *Interactive Learning Environments*. Retrieved 11 21, 2022, from https://www.tandfonline.com/doi/full/10.1080/10494820.2022.2081582?src=

[11] Solmaz, S., & Gerven, T. V. (2021). Automated integration of extract based CFD results with AR/VR in engineering education for practitioners. *Multimedia Tools and Applications*, *81*(1198). Retrieved 11 21, 2022, from https://link.springer.com/article/10.1007/s11042-021-10621-9

[12] Macklin, M., Muller, M., Chentanez, N., & Kim, T. Y. (2014). Unified Particle Physics for Real-Time Applications. *ACM Transactions on Graphics*, *33*(4), 1-12. Retrieved 11 23, 2022, from https://www.researchgate.net/publication/274479082_Unified_Particle_Physics_for_Real-Time_Applications

[13] Wu, K., Truong, N., Yuksel, C., & Hoetzlein, R. (2018). Fast Fluid Simulations with Sparse Volumes on the GPU. *EUROGRAPHICS*, *37*(2). Retrieved 11 23, 2022, from https://people.csail.mit.edu/kuiwu/gvdb_sim.html

[14] Skosana, X. N., Mpofu, K., Trimble, J., & Wyk, E. A. V. (2022). An empirical framework for developing and evaluating a Virtual Assembly Training System in learning factories. *Interactive Learning Environments*. Retrieved 11 23, 2022, from https://www.tandfonline.com/doi/full/10.1080/10494820.2022.2039946?src=

[15] Walter, H., Li, R., Munafo, J., Curry, C., Peterson, N., & Stoffregen, T. (2019). *A brief explanation of the Simulator Sickness Questionnaire (SSQ)* [An example of how to calculate the overall effect to health from play the simulation]. University of Minnesota. Retrieved 01 01, 2023, from https://doi.org/10.13020/XAMG-CS69

[16] Freitas, S. d. (2018, April). Are Games Effective Learning Tools? A Review of Educational Games. *Educational Technology & Society*, *21*(2), 74-84. https://www.jstor.org/stable/26388380

[17] Witmer, Jerome, & Singer. (2019, July 5). *Presence/Presence Questionnaire (PQ)*. EduTech Wiki. Retrieved 01 01, 2023, from https://edutechwiki.unige.ch/en/Presence/Presence_Questionnaire_(PQ)

[18] Liou, H.-H., Yang, S. J.H., Chen, S. Y., & Tarng, W. (2017, July). The Influences of the 2D Image-Based Augmented Reality and Virtual Reality on Student Learning. *Educational Technology & Society*, *20*(3), 110-121. https://www.jstor.org/stable/26196123

[19] Walter, H., Li, R., Munafo, J., Curry, C., Peterson, N., & Stoffregen, T. (2019). *The Simulator Sickness Questionnaire* [A questionnaire for analyzing the impact on health from playing the simulation]. University of Minnesota. Retrieved 01 01, 2023, from https://doi.org/10.13020/XAMG-CS69

[20] Wikipedia. (n.d.). *Experiential learning*. Wikipedia. Retrieved November 22, 2022, from https://en.wikipedia.org/wiki/Experiential_learning

1. Appendix A

1.1. Evaluation Resources

1.1.1. Quantitative Questionnaire

1.1.1.1. Baseline/After Simulation

Questions	Answers: YES or NO	Value
1. Does the Pythagorean cup work by a syphoning effect?		10
2. Is the Pythagorean cup a historical Greek tool for teaching hydrostatics?		10
3. Which is more viscous oil or water?		10
4. Was Hero’s fountain invented by Heron of Alexandria?		10
5. Is viscosity a measure of a fluid's resistance to deformation?		10
6. Is Fluid Statics the study of fluids at rest?		10
7. Is the concept of a Pythagorean cup still used today?		10

Figure 1 Pre & Post experience knowledge gauge

1.1.1.2. Presence Questionnaire

Circle how responsive or compelling the experience was.

“1 = not at all” and “7 = very much so”

Involvement

1. How much were you able to control events? 1 2 3 4 5 6 7

2. How responsive was the environment to actions that you initiated (or performed)? 1 2 3 4 5 6 7

3. How natural did your interactions with the environment seem? 1 2 3 4 5 6 7

4. How much did the visual aspects of the environment involve you? 1 2 3 4 5 6 7

5. How natural was the mechanism which controlled movement through the environment? 1 2 3 4 5 6 7

6. How compelling was your sense of objects moving through space? 1 2 3 4 5 6 7

7. How much did your experiences in the virtual environment seem consistent with your real-world experiences? 1 2 3 4 5 6 7

8. How completely were you able to actively survey or search the environment using vision? 1 2 3 4 5 6 7

9. How compelling was your sense of moving around inside the virtual environment? 1 2 3 4 5 6 7

10. How well could you move or manipulate objects in the virtual environment? 1 2 3 4 5 6 7

11. How involved were you in the virtual environment experience? 1 2 3 4 5 6 7

12. How easy was it to identify objects through physical interaction, like touching an object, walking over a surface, or bumping into a wall or object? 1 2 3 4 5 6 7

Sensory Fidelity

13. How much did the auditory aspects of the environment involve you? 1 2 3 4 5 6 7

14. How well could you identify sounds? 1 2 3 4 5 6 7

15. How well could you localize sounds? 1 2 3 4 5 6 7

16. How well could you actively survey or search the virtual environment using touch? 1 2 3 4 5 6 7

17. How closely were you able to examine objects? 1 2 3 4 5 6 7

18. How well could you examine objects from multiple viewpoints? 1 2 3 4 5 6 7

Adaptation/Immersion

19. Were you able to anticipate what would happen next in response to the actions that you performed? 1 2 3 4 5 6 7

20. How quickly did you adjust to the virtual environment experience? 1 2 3 4 5 6 7

21. How proficient in moving and interacting with the virtual environment did you feel at the end of the experience? 1 2 3 4 5 6 7

22. How well could you concentrate on the assigned tasks or required activities rather than on the mechanisms used to perform those tasks or activities? 1 2 3 4 5 6 7

23. How completely were your senses engaged in this experience? 1 2 3 4 5 6 7

24. Were there moments during the virtual environment experience when you felt completely focused on the task or environment? 1 2 3 4 5 6 7

25. How easily did you adjust to the control devices used to interact with the virtual environment? 1 2 3 4 5 6 7

26. Was the information provided through different senses in the virtual environment (e.g., vision, hearing, touch) consistent? 1 2 3 4 5 6 7

Interface Quality

27. How much delay did you experience between your actions and expected outcomes? 1 2 3 4 5 6 7

28. How much did the visual display quality interfere with or distract you from performing assigned tasks or required activities? 1 2 3 4 5 6 7

29. How much did the control devices interfere with the performance of assigned tasks or with other activities? 1 2 3 4 5 6 7

Figure 2 Presence Evaluation [17]

1.1.1.3. Simulator Sickness

Subject _______

Are you motion sick now? Circle YES or NO

If you are sick, when did you first notice the symptoms? Time: _________ Date: ______

Circle how much each symptom below is affecting you now.

0 = "not at all" 1 = "mild" 2 = "moderate" 3 = "severe"

1. General discomfort 0 1 2 3

2. Fatigue 0 1 2 3

3. Headache 0 1 2 3

4. Eyestrain 0 1 2 3

5. Difficulty focusing 0 1 2 3

6. Increased salivation 0 1 2 3

7. Sweating 0 1 2 3

8. Nausea 0 1 2 3

9. Difficulty concentrating 0 1 2 3

10. Fullness of head 0 1 2 3

11. Blurred vision 0 1 2 3

12. Dizziness (eyes open) 0 1 2 3

13. Dizziness (eyes closed) 0 1 2 3

14. Vertigo* 0 1 2 3

15. Stomach awareness** 0 1 2 3

16. Burping 0 1 2 3

*Vertigo is experienced as loss of orientation with respect to vertical upright

**Stomach awareness is usually used to indicate a feeling of discomfort that is just short of nausea

Figure 3 Simulator Sickness Evaluation [19]

A brief explanation of the Simulator Sickness Questionnaire (SSQ)

Each item is rated with the scale from none, slight, moderate to severe. Through some calculations, four representative scores can be found. Nausea-related sub score (N), Oculomotor-related sub score (O), Disorientation-related sub score (D) are the scores for the symptoms for the specific aspects. Total Score (TS) is the score representing the overall severity of cybersickness experienced by the users of virtual reality systems.

The calculations in the Simulator Sickness Questionnaire

None = 0
Slight = 1
Moderate = 2
Severe = 3

Weights for Symptoms

Symptoms	Nausea	Oculomotor	Disorientation
General discomfort			
Fatigue			
Headache			
Eye strain			
Difficulty focusing			
Increased salivation			
Sweating			
Nausea			
Difficulty concentrating			
Fullness of head			
Blurred vision			
Dizzy (eyes open)			
Dizzy (eyes closed)			
Vertigo			

Stomach awareness			
Burping			
Total*	[1]	[2]	[3]

Score
Nausea = [1] x 9.54
Oculomotor = [2] x 7.58
Disorientation = [3] x 13.92
Total Score = ([1] + [2] + [3]) x 3.74

* Total is the sum obtained by adding the symptoms scores. Omitted scores are zero.

Figure 4 Simulator Sickness Evaluation [15]

1.1.2. Qualitative Questionnaire

1.1.1.1. User Impressions

Questions	Answers
1. On a scale of 1 – 10 how would you rate this experience where 1 is a very poor experience and 10 is amazing	
2. Did you find it easy to understand what you were supposed to do?	
3. Were the tasks fun to complete?	
4. Do you think a system like this will help you to understand the material better?	
5. Did objects respond the way you expected them to?	
6. What did you find most difficult to understand?	
7. Did the objects in the task make sense in relation to what you needed to do?	
8. Were the controls easy to use? If not, what was the issue?	
9. Were any significant issues or bugs encountered? If yes, what were they?	
10. Do you have any overall suggestions?	

Figure 5 Users exit interview/experience gauge

2. Appendix B

2.1. Supporting Images

2.1.1. Early Prototype

2.1.1.1. Level Navigation

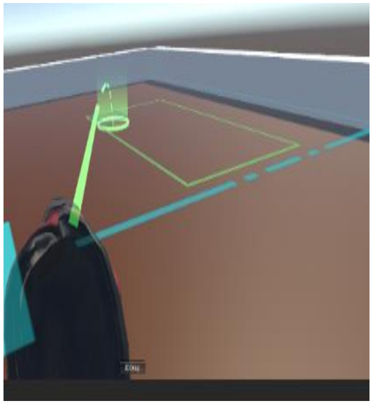


Figure 1 Teleportation

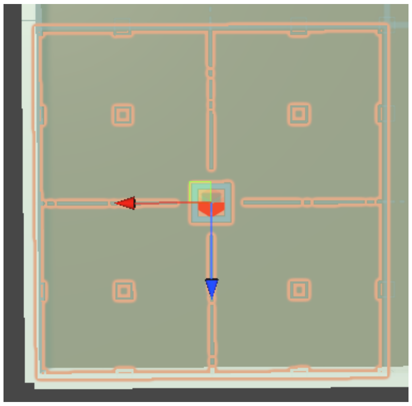


Figure 2 Teleportation Area Indicator

2.1.1.2. User Interaction

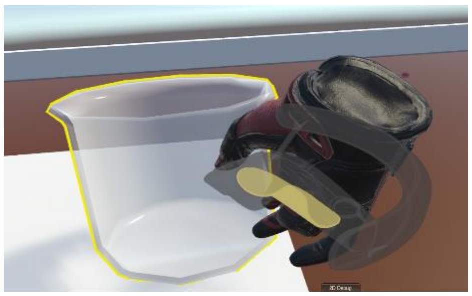


Figure 1 Object Interaction Alert

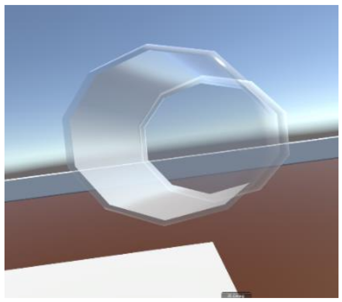


Figure 2 Object Interaction

2.1.1.3. Real-time Fluid Simulation

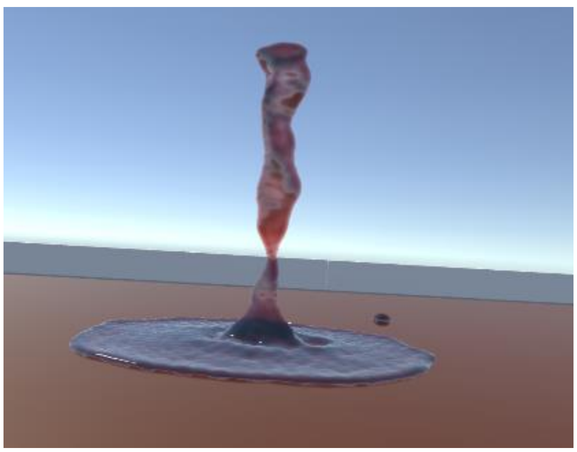


Figure 1 Fluid Simulation

2.1.2. Final Prototype

2.1.2.1. Environment Scenes

Figure 1 Start Menu Scene

Figure 2 Introduction/Museum Scene

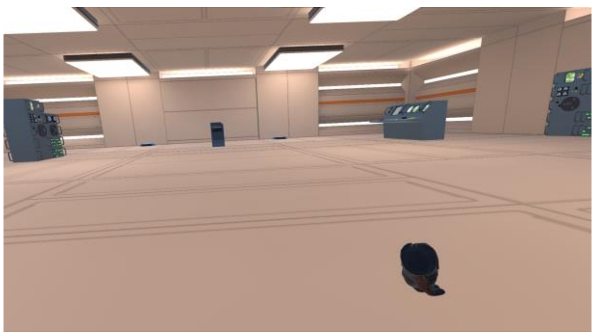


Figure 3 Lab Hub Scene

Figure 4 Buoyancy Lab Scene

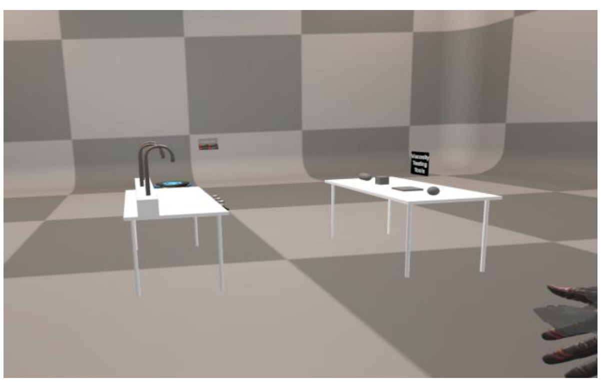


Figure 5 Viscosity Lab Scene

Figure 6 Credit's Scene

2.1.2.2. Interaction Elements

Figure 1 UI pointer

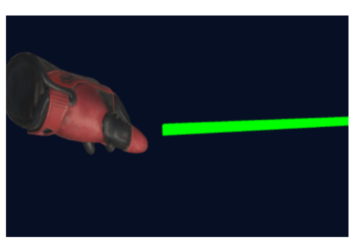


Figure 2 UI pointer click

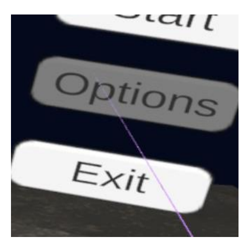


Figure 3 pointer interaction

Figure 4 Locomotion Hint

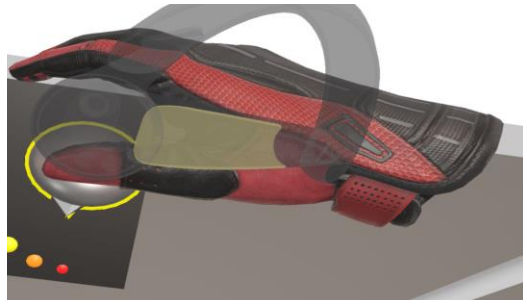


Figure 5 Interaction Hint

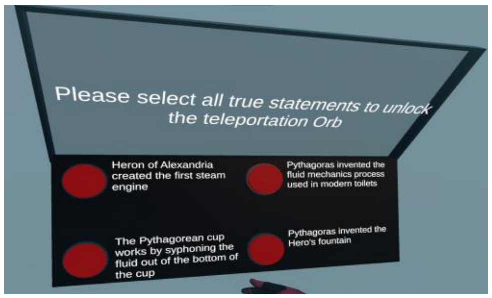


Figure 6 Interactable button system

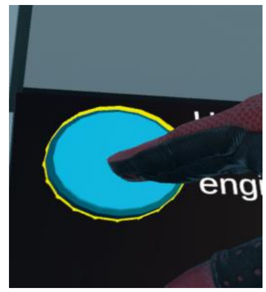


Figure 7 Visual Button Response

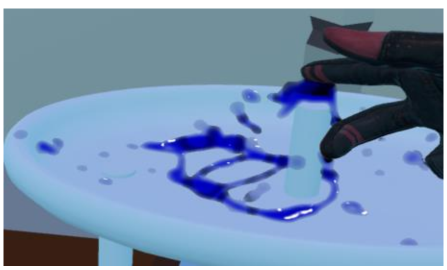


Figure 8 Interactable fluids

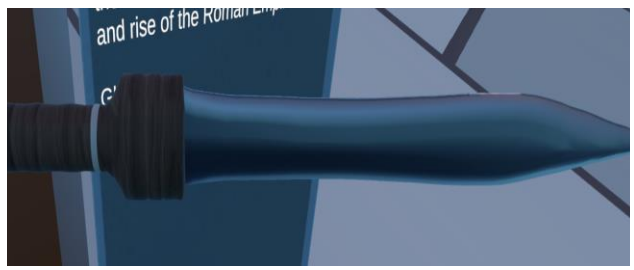


Figure 9 Movable objects

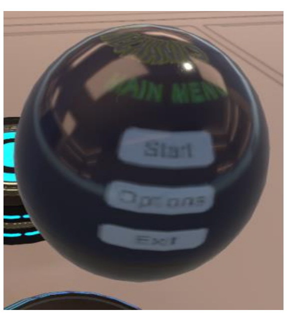


Figure 10 Transportation Orb

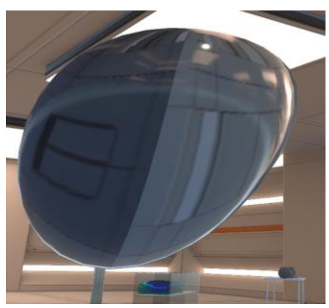


Figure 11 Soft body visual effect

Figure 12 User Interface

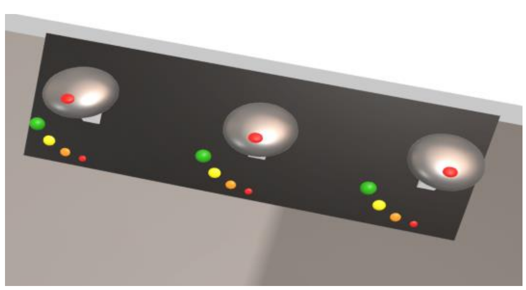


Figure 13 Simulated objects that respond according to their physical counterpart.

2.1.2.3. Core experiences

Figure 1 Heron of Alexandria

Figure 2 Pythagoras

Figure 3 Buoyancy lab

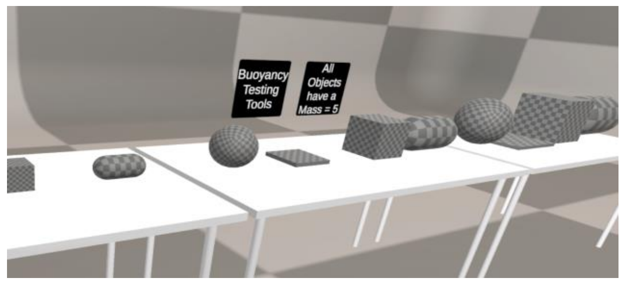


Figure 4 Buoyancy lab tools

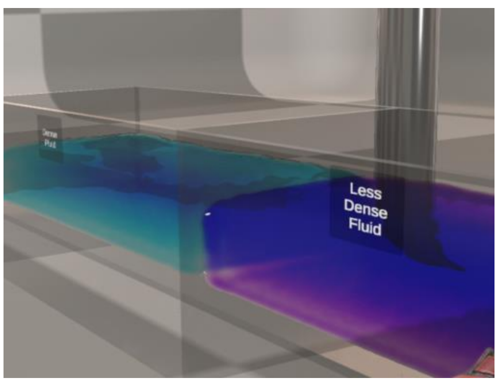


Figure 5 Buoyancy lab fluid tanks

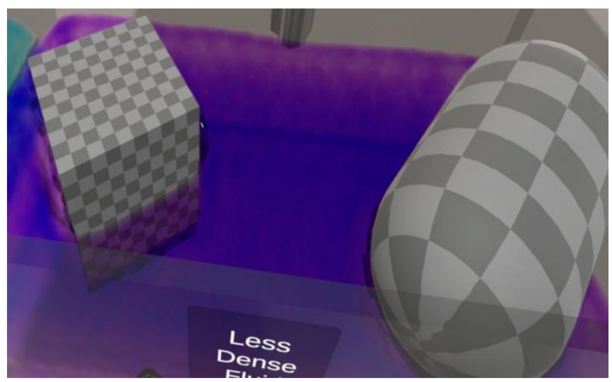


Figure 6 Buoyancy lab demonstration

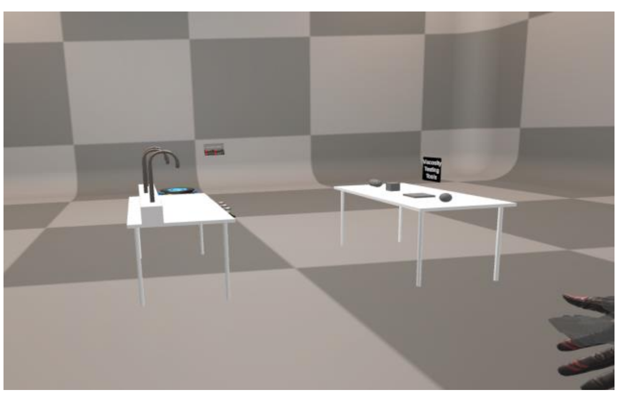


Figure 7 Viscosity lab

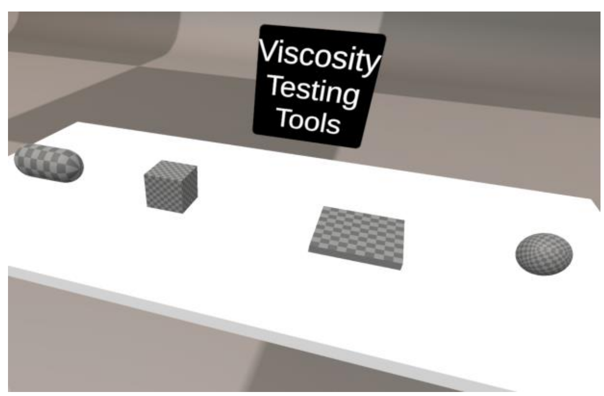


Figure 8 Viscosity lab tools

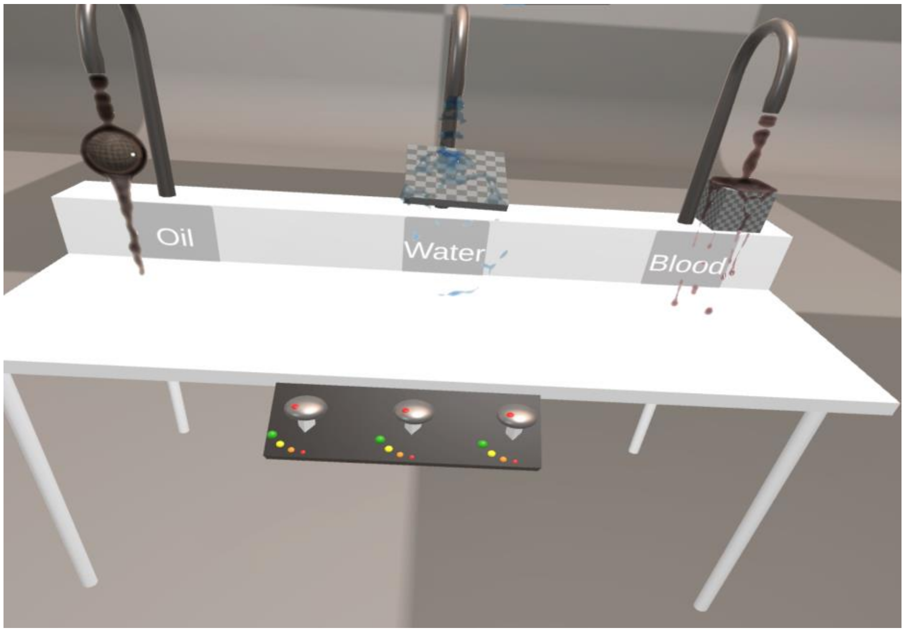


Figure 9 Viscosity lab demonstration