UNIVERSITAT POLITÈCNICA DE CATALUNYA
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Centre de la Imatge i la Tecnologia Multimèdia

Four-dimensional geometry applied to video game design

Òscar Canales Villar

Director: Mónica Martín Mínguez

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Abstract

This project aimed to develop and evaluate "Realm Paradox," a video game designed to introduce the concept of the 4th dimension to a broad audience. The game had educational components and went through a rigorous playtesting procedure to see how well it will help players better grasp the fourth dimension. Through the analysis of playtest data and participant feedback, it was determined that the game successfully improved players' comprehension of the 4th dimension. Overall, "Realm Paradox" demonstrated its potential as an engaging and educational tool for exploring higher dimensional concepts.

Keywords

- Fourth-dimension
- Video game
- Educational
- Game Design
- Puzzle-solving
- Mathematical concepts

Links

Project Presentation video (Realm Paradox Trailer): https://youtu.be/eCycG_N_-MU

Github Repository: https://github.com/Osvak/4D-Game-TFG

Alpha Release (v0.1): https://github.com/Osvak/4D-Game-TFG/releases/tag/0.1

Beta Release (v0.5): https://github.com/Osvak/4D-Game-TFG/releases/tag/0.5

Gold Release (v1.0): https://github.com/Osvak/4D-Game-TFG/releases/tag/1.0

4th Dimension Explanation video: https://youtu.be/XsMaOmMkIXc

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Glossary

Blender: A popular 3D computer graphics software used for creating animations, visual effects, and models.

Bug: A software defect or flaw that causes unintended behavior or errors in a program or game.

Clipchamp: A free video editing software from Microsoft used to add captions and make edits to the video explanation.

Cross-Section explanation: A method of visualizing higher-dimensional spaces by representing them as slices or sections of lower-dimensional spaces.

Dimension: A measure of the minimum number of coordinates needed to describe a point in a geometric space.

Dimensional analogy: A conceptual tool used to explain higher-dimensional concepts by drawing comparisons with lower-dimensional scenarios or objects, such as the analogy of Flatland for understanding the fourth dimension.

Fourth-dimension: It is a mathematical theory that adds a dimension to a 3D space, allowing for the study of more complex shapes and relationships. Usually abbreviated to 4D

Hyperspace: A space with more than three dimensions, used in mathematics and theoretical physics.

N-dimensional space: A mathematical concept that extends the notion of three-dimensional space to any number of dimensions, where N represents the number of dimensions.

Orthogonal: Perpendicular; objects that intersect at a right angle.

Plane: A two-dimensional object formed by an infinite number of lines, extending infinitely in all directions.

Player controller: The system or component responsible for handling player input and controlling the movement and actions of the player character in the game.

Playtesting: The process of evaluating a game by allowing players to test it and provide feedback, helping developers identify issues and improve the overall gameplay experience.

Relativity: The theory of relativity, a fundamental theory in physics that describes the relationships between space, time, and gravity, developed by Albert Einstein.

Render: The process of generating the final images or frames of a scene from a 3D model, including the application of textures, lighting, and other visual effects.

Sketchfab.com: An online platform that hosts a vast collection of 3D models created by artists and designers, providing resources for various projects.

Slice: Is a cross-sectional view of a 4D object or space by intersecting it with a lower-dimensional space. Used when describing the current 3D space.

Slider: A graphical control element that allows users to adjust a value by sliding a thumb or indicator along a track.

Space: A set of points that form a geometric structure; often used to describe 3D space.

Spatial dimensions: Dimensions that describe the physical extent of an object or space, such as length, width, and height.

Temporal dimension: A dimension associated with time, often considered as the fourth dimension in the context of space-time.

User interface (UI): The visual elements, controls, and menus through which players interact with the game, including buttons, menus, and other interactive elements.

1. Introduction

1.1 Motivation

I came across the four-dimensional space theory, a subject that examines the idea of adding an extra dimension to a three dimensional space, as a result of the popularity of new video games that attempt to explore new worlds that do not follow our physical laws and allow us to see different realities that can only exist in theories.

Some people interpret the four dimensions—also known as the four-dimensional physics theory—as three spatial dimensions plus one additional dimension, which is time. You may be familiar with this concept because Albert Einstein popularized the term "spacetime" in his theory of special relativity in 1905.

Nonetheless, the mathematical theory involving four dimensions interests me. It is an abstract idea made up of four separate dimensions that are typically referred to as X, Y, Z, and W. It is utilized in many theoretical applications of mathematics, including higher-dimensional geometry, algebraic topology, and computer modeling, although it has no inherent relationship to the actual world.

It took me a long time to understand this complex topic, but during my research I discovered that using visual aids and interacting with tools, especially video games, helped me the most. These tools also made it easier for me to see how four-dimensional objects interacted with one another and play with a purpose.

As a result, I want to make it simpler for the general public, but especially the younger generations, to learn about this issue. This is because technology is developing swiftly and more people are needed to explore complicated topics that might benefit the entire population.

1.2 Problem formulation

The four-dimension mathematical theory comprehension and exploration is a challenge for many individuals due to the abstract nature. Although new uses are being found for this mathematical concept, there is a gap in making this complex topic more accessible and engaging for the general public, particularly the younger generation. Also, traditional means of teaching these concepts to the broad audience lack the ability of allowing the user to visualize these concepts and interact with them while having an objective in mind.

1.3 General objectives

Develop a video game that allows the player to interact with four-dimensional geometry.

Make the complex topic of four-dimensional space easier to understand for a broader audience, while making it enjoyable.

1.4 Specific objectives

Understand the mathematical concept of the four-dimensional space in depth.

Research how developers have worked with this topic and how game design can be used to explain it.

Make a short video animation (30 s) to simplify as much as possible the visualization of 4D space and geometry.

Render 4D objects in a game engine.

Design puzzles that test your understanding of the 4D space.

Program interaction between multiple 4D objects.

1.5 Scope of the project

Due to the main objective of this project is to make easier to understand the topic of four-dimensional space, the broad public will benefit from it, but mainly, people interested in beginning to comprehend complex mathematical theories; In particular, the younger generations that maybe with an early introduction of the concept, will get inspired to start investigating more about this subject and see that it is not as complex as it seems at first glance. The video game would be published for free in a public repository, so everyone has access to it.

The main problems that can be found during the development of the project is the difficulty with programming the four-dimensional space in a video game engine that is only designed to render in 3D, but there is currently an interview arranged with one developer of the video game “Miegakure”, one of the firsts 4th dimensional games in the market. The main objective of these interview is to see how other people that have worked with this topic see the future for 4D video games, and understand how games have to be designed to explain this complex theory.

2. State of the art

2.1 Explanation of four-dimensional space

In considering a four-dimensional space (4D), it is important to note that it expands upon the three-dimensional Euclidean space that humans inhabit. This three-dimensional space is characterized by width, height, and depth, denoted by the axes X, Y, and Z, respectively. The introduction of a fourth dimension creates an additional axis that is perpendicular to the other three dimensions. While visualizing this axis may be challenging, observing its interaction with our familiar world can provide insights.

To grasp the concept of four-dimensional space, it is often helpful to draw analogies with lower dimensions. As three-dimensional beings, we are limited to perceiving the world in three dimensions. Consequently, attempting to visualize a four-dimensional object is akin to a two-dimensional entity trying to comprehend a three-dimensional object. This analogy gained popularity with the publication of "Flatland: A Romance of Many Dimensions" by Abbot in 1884.

To illustrate this concept, let's consider an example involving a two-dimensional stick figure named "Bob" who possesses a valuable item—a coin—and desires to safeguard it.

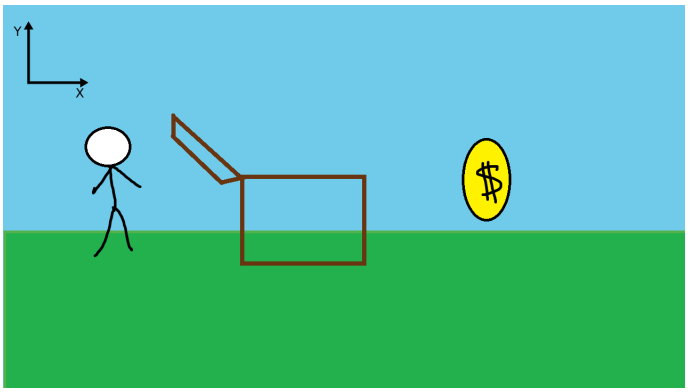

Figure 1: Visualization of 4D spaces #1

The coin, hidden by Bob within the chest in the two-dimensional world, undergoes a movement that aligns with Bob's understanding of his environment. However, when we shift our perspective to that of a three-dimensional being, we gain an extra dimension – depth – that enables us to perceive the scenario differently.

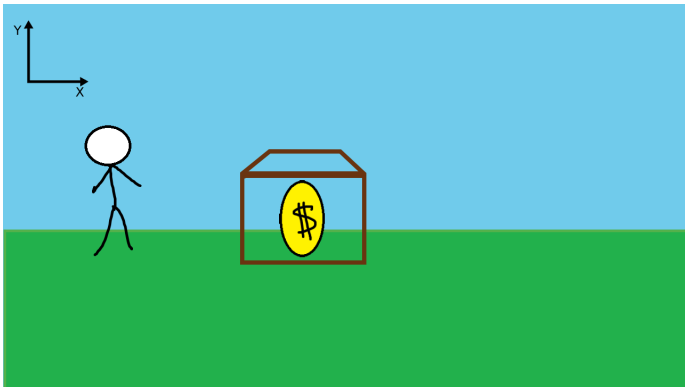

Figure 2: Visualization of 4D spaces #2

From the three-dimensional viewpoint, the chest can be conceptualized as a three-dimensional object characterized by length, width, and height. When the chest is closed by Bob, the movement of the coin surpasses the limits of Bob's two-dimensional understanding. The introduction of an additional dimension enables the coin to assume a different position within the three-dimensional space, causing a modification in its location relative to Bob's frame of reference. Although Bob remains unaware of this spatial transformation, the displacement of the coin becomes discernible when examined from the expanded perspective of a three-dimensional observer.

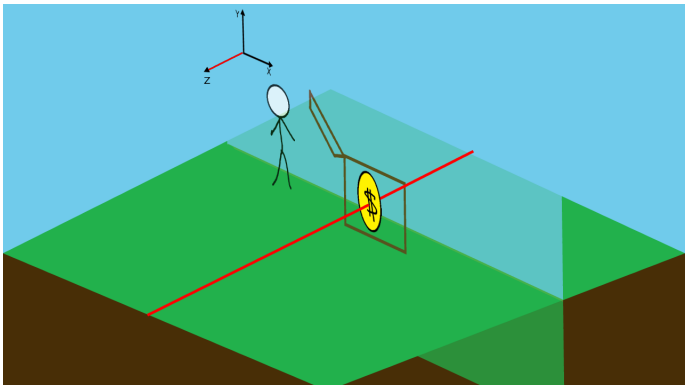

Figure 3: Visualization of 4D spaces #3

An intervention occurs as the three-dimensional being decides to manipulate the coin's position by utilizing the third dimension, depth. From Bob's limited perspective, the coin appears to have abruptly disappeared, leaving no discernible trace or indication of its whereabouts.

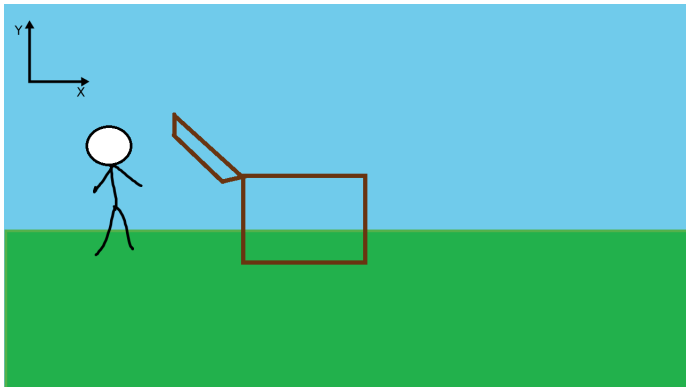

Figure 4: Visualization of 4D spaces #4

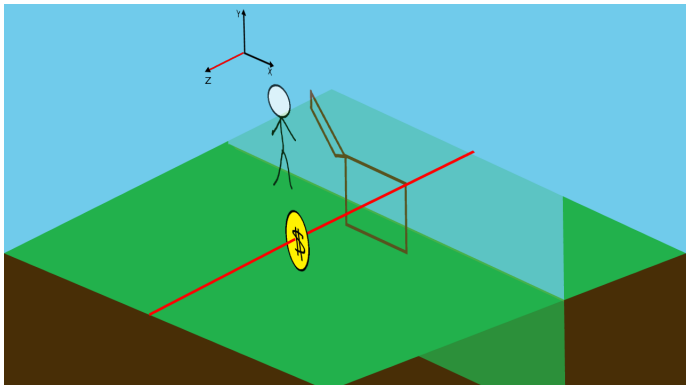

Figure 5: Visualization of 4D spaces #5

The understanding of four-dimensional space can be grasped by envisioning it as an extension of three-dimensional spaces, resembling extrusions or slices. This analogy draws parallels to the previously discussed 2D to 3D transition. In a three-dimensional representation of four-dimensional space, objects can appear to vanish when they are moved along the fourth dimension, as they are effectively transferred to a distinct three-dimensional slice.

While we have the ability to interact with four-dimensional objects, our perception is limited to width, height, and depth. Consequently, we can only visualize a three-dimensional representation of these items, unable to fully perceive the fourth dimension.

Similar to three-dimensional space, geometric primitive shapes find their counterparts in the fourth dimension. These shapes are often referred to as 4-polytopes or polycells. They consist of interconnected vertices, edges, faces (polygons), and cells (polyhedra) (Contucci et al., 2010, p. 598).

Examples of such shapes include the Hypercube or Tesseract, which corresponds to the 3D cube, the Hypersphere or Glome, analogous to the 3D sphere, and the Simplex or pentatope, akin to the 3D tetrahedron. The measure of space in four dimensions is referred to as the content or volume.

2.2 Four-dimensional spaces in non video game medial

The concept of the four-dimensional space was developed by Swiss mathematician Ludwig Schläfli in the 19th century, building upon the earlier work of August Ferdinand Möbius. Further contributions came from Charles Howard Hinton with his essays "*What is the Fourth Dimension?*" in 1880 and "*A New Era of Thought*" in 1888, where he introduced a method for visualizing the fourth dimension.

In the field of physics, the theory of the fourth dimension was overshadowed by Albert Einstein's Special Relativity Theory in 1905, which incorporated the idea of time as a fourth dimension to explain physical interactions in our world.

However, the concept found significant reception among mathematicians, particularly in the context of vector analysis with the introduction of quaternions, as well as in geometric algebra with other four-dimensional algebras like bicomplex numbers and coquaternions.

Its primary impetus for research has been in the realm of mathematics, especially in higher-dimensional geometry. This branch explores the properties and interactions of 4-polytopes and utilizes the concept in data analysis and visualization. Developing a profound understanding of four-dimensional spaces can aid in uncovering trends and patterns by projecting and reducing data to lower-dimensional spaces.

The popularization of the idea of four-dimensional space can be attributed to the book "*Flatland: A Romance of Many Dimensions*" by E. A. Abbott in 1884 (as seen in section 2.1).

While originally intended as a satire of Victorian society, it became renowned for its explanation of 4D spaces. The book was later adapted into a film titled "*Flatland*" in 2007, and an animated short called "*Flatland 2: Sphereland*" was released in 2012.

In "*The Fourth Dimension: Toward a Geometry of Higher Reality*" (1984), Rudy Rucker delves into the nature of the fourth dimension and its historical significance to philosophers. The book includes numerous puzzles, challenges, and over 200 images.

Another notable publication is "*Beyond the Third Dimension: Geometry, Computer Graphics, and Higher Dimensions*" by T. Banchoff (1990). It offers in-depth explanations, intuitive visualizations, and explores the history, implications, visualization techniques, and applications of this theory.

2.3. Four-dimensional spaces in video games

2.3.1. Miegakure

Miegakure is a puzzle-platform video game by Marc ten Bosch, currently under development, since 2009, that explores the four-dimensional world in an isometric view and you explore different buildings where you have to use the 4D movement to your advantage. Miegakure was one of the first video games about four-dimensional spaces, and the approach that the developer takes is one that many others have used. Marc ten Bosch changes the "3D slice" that the game can render by turning 90 degrees in one axis, for example, the player sees a closed structure in X, Y, Z but if he rotates the world into X, Y, W the structure is now open because there is no wall in the W axis.

The game contains a short explanation of the four-dimensional spaces, similar to the one seen in "Flatland, romance of many dimensions" (Bosch, 2009).

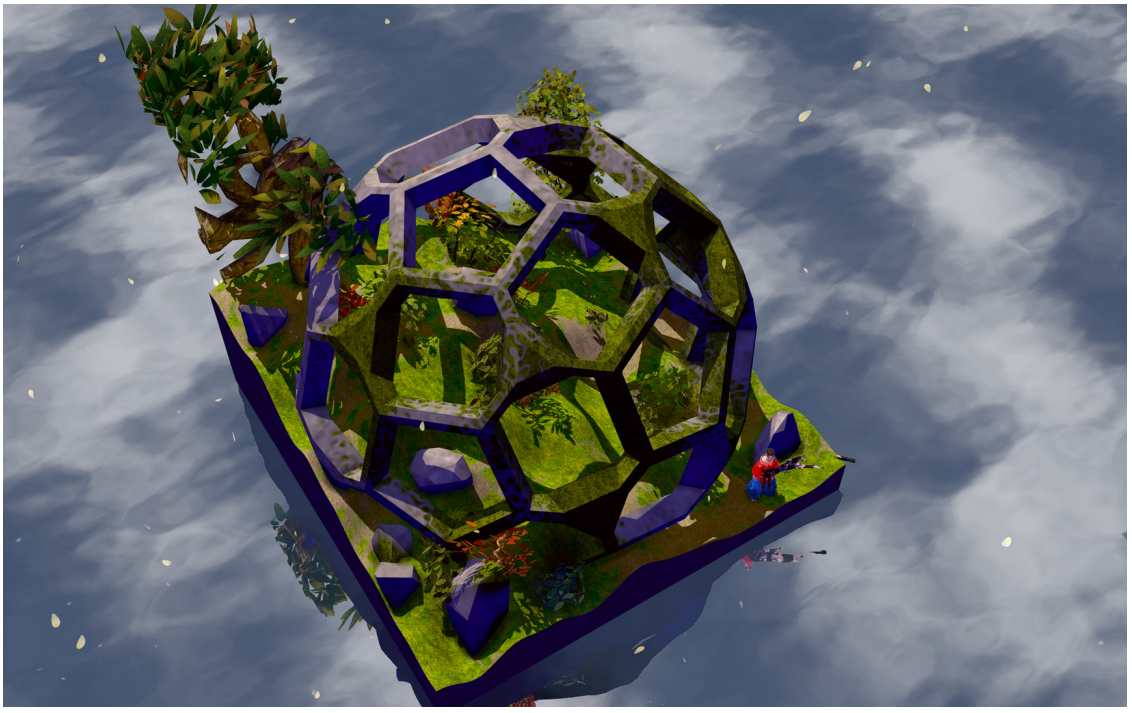

Figure 6: Miegakure by Marc ten Bosch, 2009

Design analysis

The player has to explore a world set in Japan in the 14th century. It has to solve multiple puzzles with the objects in the environment, like aligning some rocks in a formation, but these items are usually in multiple places of the fourth dimension.

Core Game Pillars: Exploration, Platforming, Puzzle-Solving

Game Mechanics: Player movement, Camera rotation, 4D Slice movement (W Slider)

Camera: Isometric, has 4 fixed positions.

Art Style: Low poly with pixel shader

UI: Non existent

2.3.2. 4D Toys

4D Toys is a sandbox video game by Marc ten Bosch, released in 2017. The game places the user in a box of four-dimensional objects that allow him to explore the interaction and physics the system has. It has a detailed explanation of the four-dimensional environment for those who have not interacted with this type of geometry, it also uses the analogy seen in "Flatland, romance of many dimensions" (Bosch, 2017).

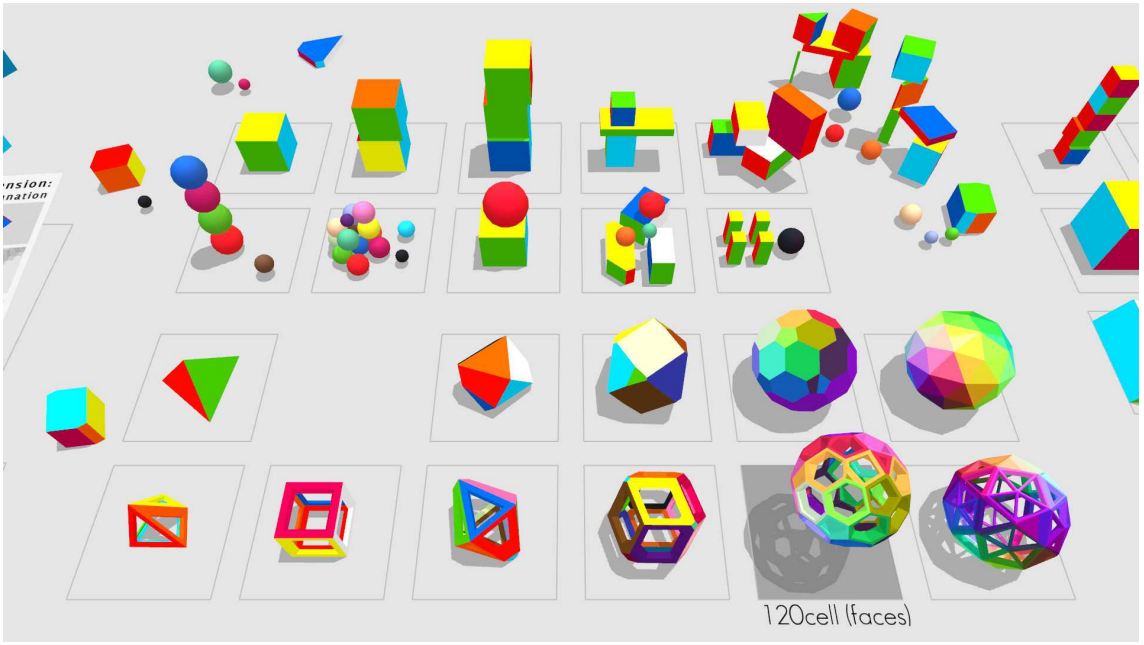

Figure 7: 4D Toys by Marc ten Bosch, 2017

Design analysis

The player has complete freedom to interact with the 4D objects and see how they behave, there is not an objective to achieve, just have fun understanding how this world works.

Core Game Pillars: Playground, Physics-based mechanics, Simulations

Game Mechanics: Drag and Move objects, 4D slice slider (W Slider)

Camera: Fixed in place

Art Style: Primitive Geometry with Flat Shading

UI: Basic Settings, W Slider

2.3.3 4D Miner

4D Miner is a survival sandbox video game by Mashpoe, currently under development, but it has a free playable demo on Steam Platform. It is greatly inspired by the hit game Minecraft, by Mojang, but 4D Miner differentiates a lot from the competence with the use of Hypercubes, the 4D geometric analogue to a 3D cube. The player explores a four-dimensional procedural random world where can extract resources, build constructions and fight enemies, with the extra that events can happen in another 3D slice of your world, so resources can be hidden because you are not looking at the "right" 3D slice or an enemy could attack you and you could not see it since you are situated in a different 3D slice. He solves the problem of new players introduced to 4D by having a live visualization of the 4D environment and using an in-game item that allows you to see all the entities no matter what 3D slice they are in (Mashpoe, n.d.).

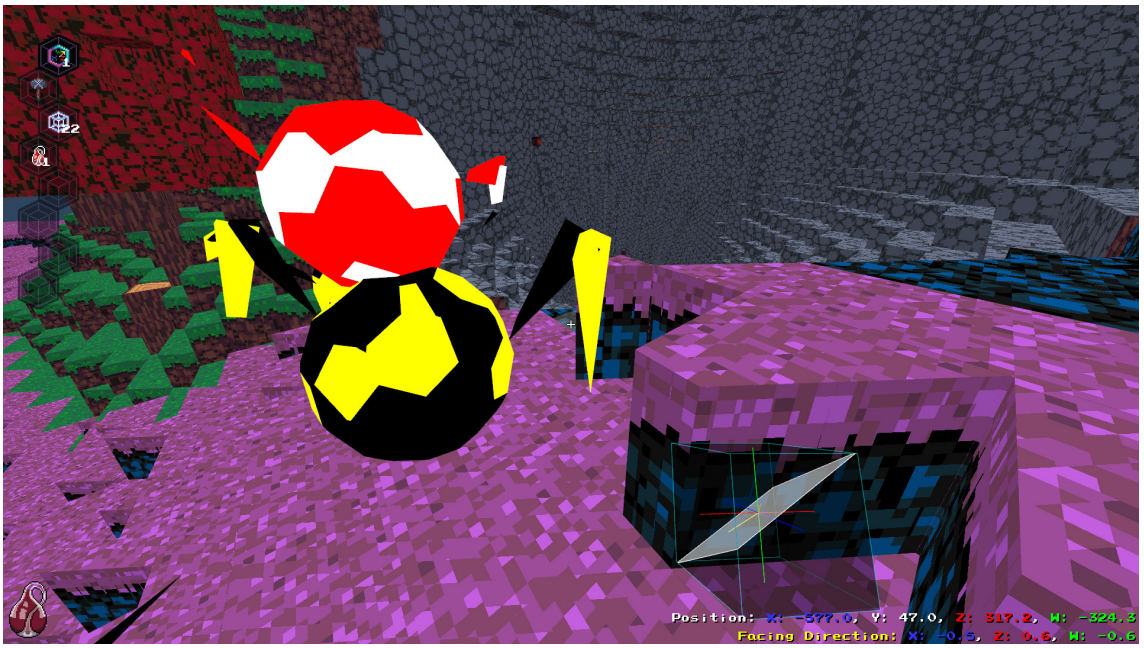

Figure 8: 4D Miner by Mashpoe

Design analysis

The player is placed in a world where it can explore the world and build whatever it wants. The main game mode is Survival, where the player has to gather resources by exploring multiple biomes. With the resources it can build multiple items to make the experience easier or it can build with freedom whatever building the player wants. With

this, the player will not have any problem to combat the enemy spiders that appear around the world.

Core Game Pillars: Exploration, Survival, Open-world sandbox

Game Mechanics: Exploring, Crafting, Building, Mining and Combat

Camera: First Person POV

Art Style: Blocky with pixel art textures.

UI: Inventory system, Player Stats, 4D Slice Display,

2.3.4 4D Golf

4D Golf is a mini-golf simulator video game by CodeParade, currently under development. The player explores higher-dimensions by playing mini-golf and other game modes in up to 50 tracks with multiple obstacles. It is one of the most polished titles and it helps the user to understand the four-dimensional space with a visualizer of the world orientation, similar to the one in 4D Miner, but it also has an outline of the objects that are not currently visible in your view (CodeParade, n.d.).

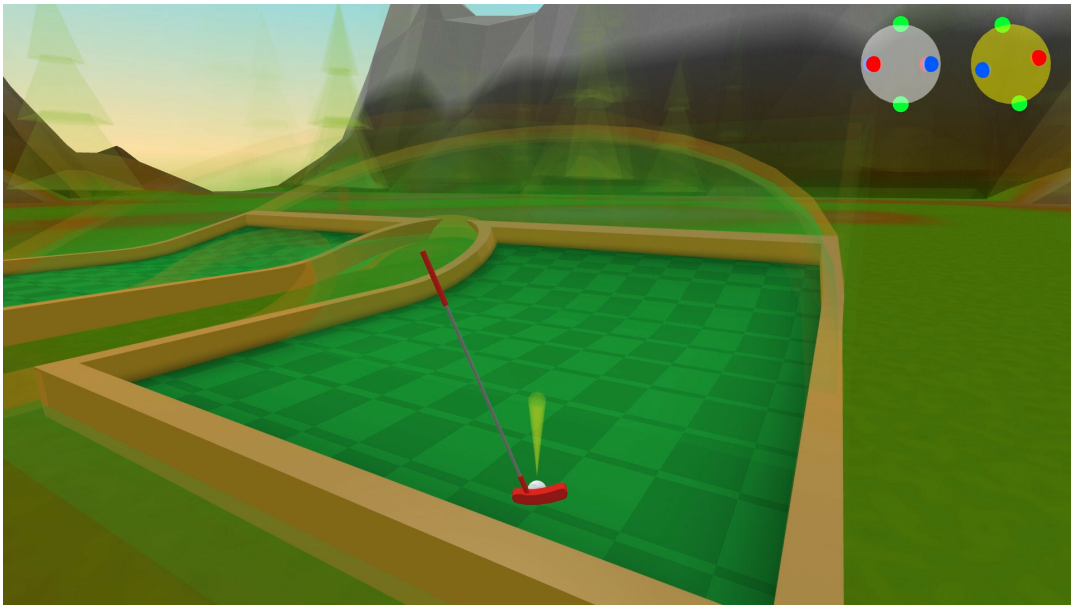

Figure 9: 4D Golf by CodeParade

Design analysis

The player is placed in a world where it can play a game of minigolf in multiple through multiple courses. The game uses the 4D to expand the idea of a minigolf, where the holes have obstacles and traps to complicate the experience.

Core Game Pillars: Sports, Physics-based mechanics, Puzzle-Solving

Game Mechanics: Golf putting system, avoid the obstacles, change the rotation of the 4D world

Camera: Third person, focusing on the ball

Art Style: Low poly with flat shading.

UI: Strength and direction of the ball, orientation of the 4D world display

2.3.5 Cake 4D

Cake 4D is a platformer-puzzle video game with pixel art graphics by TAP OK G, released in 2022. Where you play as Alla, a girl who finds herself in front of a castle holding a cake, while her girlfriend runs inside. The player has to explore through the four-dimensional castle while trying to find what happened and to give the cake to Ren (Tap Ok G, 2022).

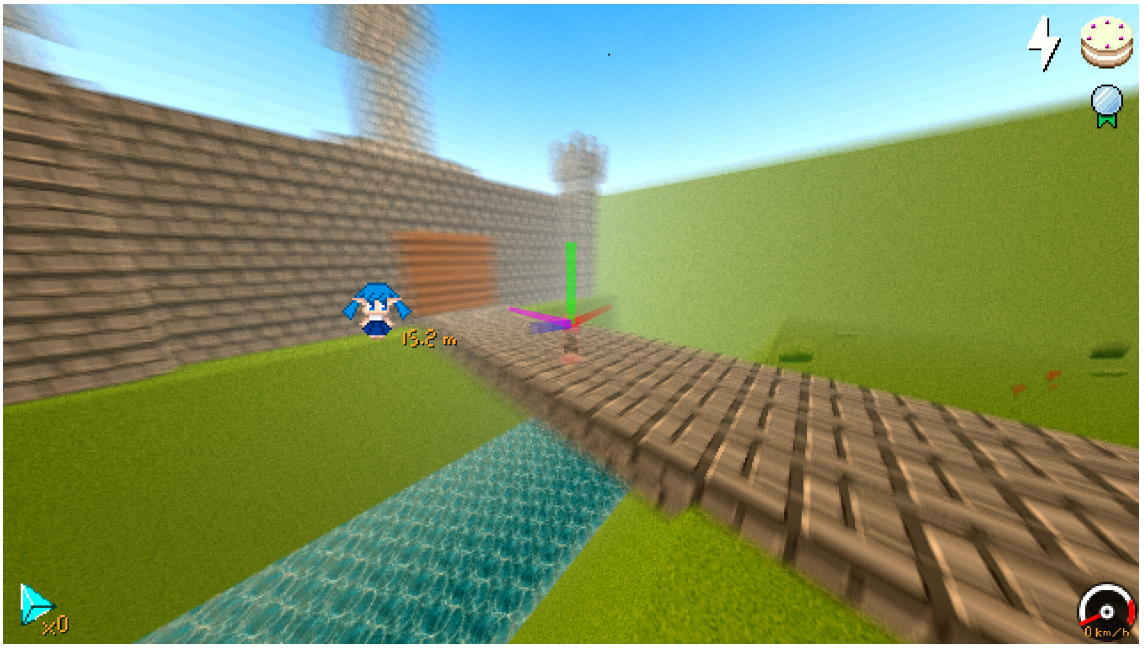

Figure 10: Cake 4D by TAP OK G, 2022

Design analysis

The player has to explore a castle that is set in a 4D world while trying to find her girlfriend. With the 4D it discovers new corridors, doors and buttons to achieve the goal.

Core Game Pillars: Puzzle-Solving, Narrative, Exploration

Game Mechanics: Move though the castle, interact with the buttons, solve puzzles

Camera: First person POV

Art Style: Voxels with pixel art textures

UI: Orientation displays, collectibles and objective gizmos

2.4 Non 4D video games mentions

2.4.1 5D Chess With Multiverse Time Travel

It is a chess variant, by Conor Petersen, released in 2020, that uses the time as a fourth dimension allowing the player to ramificate the timeline in multiple parallel dimensions and giving him the chance of escaping or check mating to other chess boards. It is worth mentioning because it is one of the only games that explain correctly and in a simplified manner the other four-dimensional theory, the Spacetime.

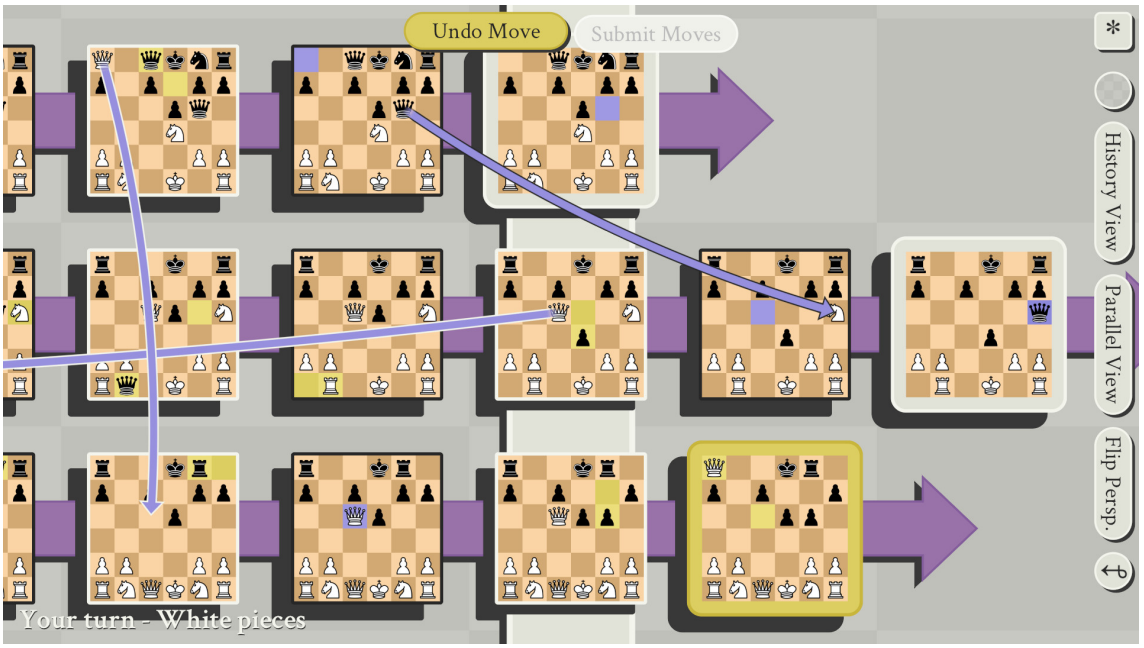

Figure 11: 5D Chess With Multiverse Time Travel by Conor Petersen, 2020

2.4.2 4D Chess

It is a VR chess variant by Ricky Robot, released in 2022, that allows the player to play chess in VR with a 3D board. It does not interact with four-dimensional spaces, but it adds a new dimension to the classical 2D game, so it helps to understand the addition of new dimensions to existing games.

2.4.3 Maze 4D

Maze 4D is a maze puzzle video game by Hunter Tintera released in 2018. The game consists in solving randomly generated puzzles in multiple game modes, but it lacks the aspect of the four-dimensional space, it uses the same principle as 4D Chess, it adds a third dimension to 2D mazes.

3. Project planning

3.1. Procedure

In order to overcome this obstacle caused by the inability to maintain focus on a single topic for an extended period, it is advisable to engage in advance planning. Additionally, regular work and efforts should be made to prevent burnout and excessive workload.

3.1.1 Calendar

To maintain a structured work schedule and ensure tasks stay on track, a calendar in Google Sheets is utilized. This tool enables the establishment of general deadlines and facilitates weekly workflow management. Considering the absence of coordination with multiple departments, the decision was made to forgo the use of a Gantt diagram for project planning purposes.

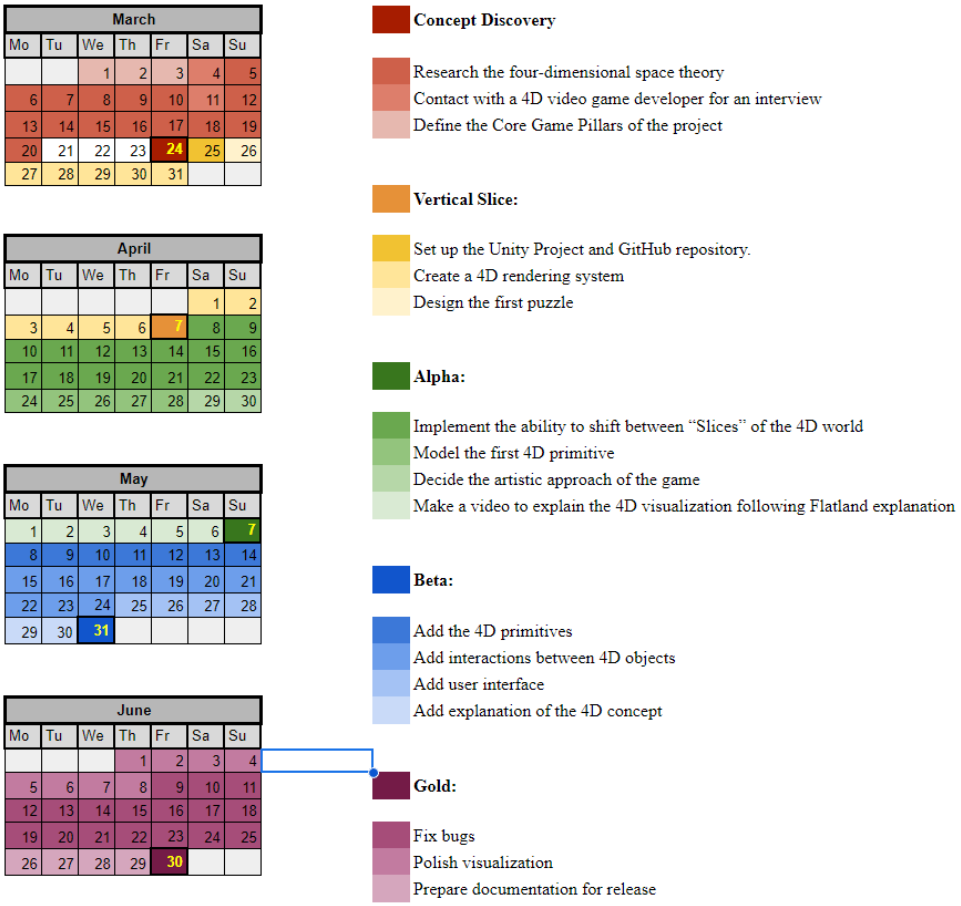

Figure 12: Calendar of the project planning

3.1.2 Kanban

The utilization of the Kanban methodology, derived from Lean thinking, aids in visualizing the progress of work throughout the week. To implement this approach, a whiteboard adorned with post-it notes is employed. This method has been chosen based on prior experience and the recognition that the physical representation of the kanban board promotes a heightened sense of engagement. The board is encountered daily, even when not actively working on the project, which helps to maintain investment and motivation for regular updates.

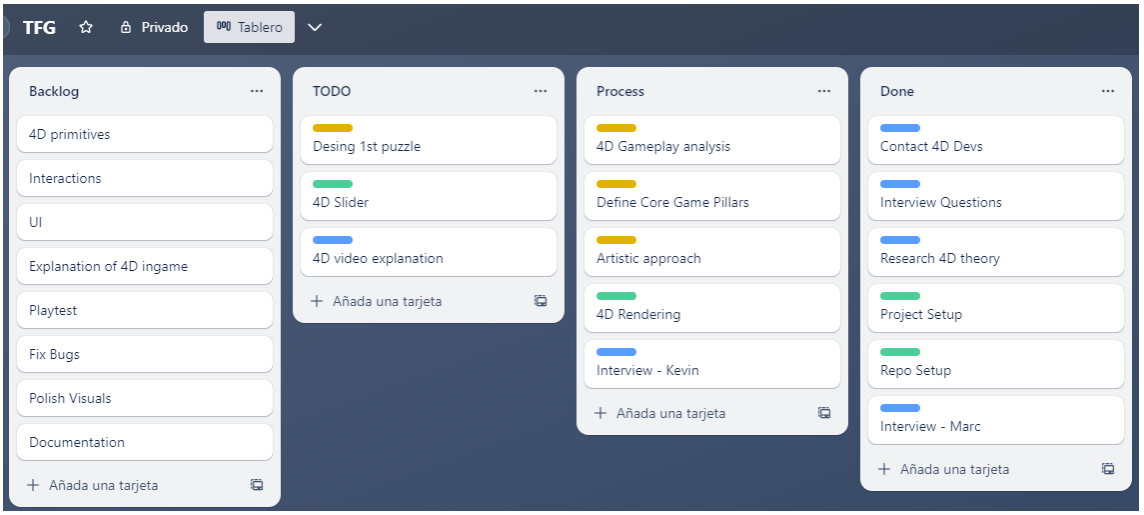

Figure 13: Kanban of the project planning

3.2. Tools and Software

3.2.1 Game Engine

The game engine chosen for the development of this project is Unity. This decision was made based on several factors, including its comprehensive capabilities, extensive documentation, and supportive community. Additionally, the fact that Unity is available free of charge and my prior experience with the engine influenced my choice.

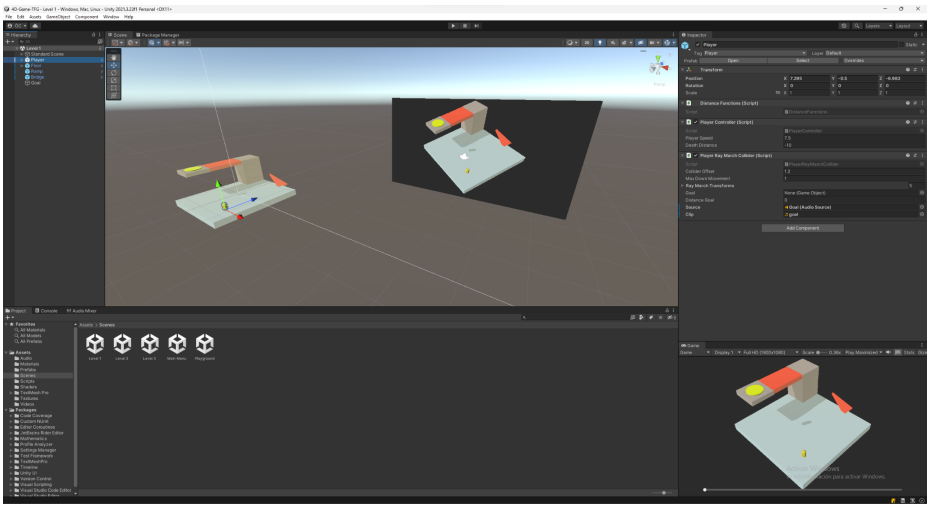

Figure 14: Unity Engine layout

3.2.2 Modeling Software

Blender will be used to model and texture the many objects due to being a free open source software capable of doing 3D models in various styles, it also has a huge community with great tutorials and forums to help new users.

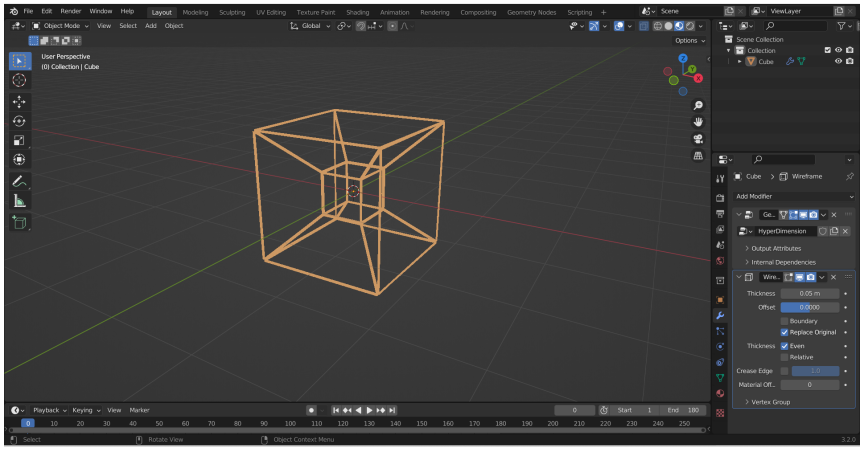

Figure 15: Blender layout

3.2.3 Version Control

The use of GitHub Desktop facilitates the safekeeping and accessibility of the project from multiple machines. It also aids in maintaining organization, thanks to its branching methodology, which enables the creation of parallel development environments when implementing new features.

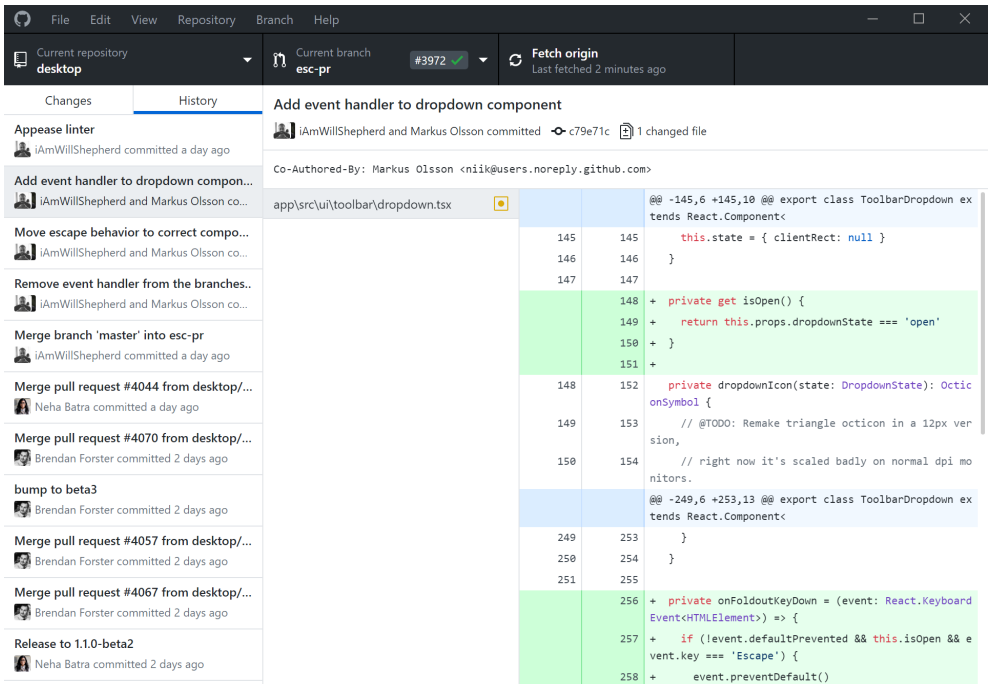

Figure 16: GitHub Desktop layout

3.3. SWOT

	Positives	Negatives
Inner Origin	**Strengths** Complex topic accessible to the broad public Contact with developers that currently work on the topic	**Weaknesses** Hard to program 4D visualization without previous experience Unipersonal team
External Origin	**Opportunities** 4D video game market growth New way to visualize geometry	**Threats** Limited time No interest in the general public

Table 1: SWOT table of the project

3.4. Risks and contingency plan

Risk	Solution
Not having enough time to develop the project	Simplify the project having in mind to not miss the objective
Have trouble with modeling 4D objects	Not model render 3D objects simulating 4D objects
Bugfixing	Avoid them from the beginning and ask for help to mentors
Not being able to contact 4D developers	Research the topic by my own and develop it from scratch

Table 2: Risks and contingency plan table

3.5. Cost analysis

Cost analysis table based on current prices and the necessities for the project.

Category	Item	Description	Cost
Personnel	Salary	Developer's salary for 3 months	7.500 €
			7.500 €
Hardware	Computer	High-performance computer for development	1.500 €
	Monitor	High-quality monitor for development	300 €
	Keyboard & Mouse	Ergonomic keyboard and mouse	150 €
	External Hard Drive	For backup and additional storage	100 €
	Headphones	Noise-cancelling headphones for focus	200 €
			2.250 €
Software	Unity (Personal License)	Video Game Engine	0 €
	Blender	Modeling software	0 €
	GitHub Desktop	Version Control software	0 €
			0 €
Other resources	Internet	Monthly internet connection fees (3 months)	50 €
	Electricity	Electricity cost for 3 months	150 €
	Research materials	Books and articles on 4D geometry	50 €
	Office Supplies	For visualizing and managing tasks using Kanban	100 €
			350,00 €
Total		**Total cost for the 3-month project**	**10.100,00 €**

Table 3: Cost analysis table

4. Methodology

The Agile methodology is employed during the development process due to its widespread usage in the video game development industry. It involves conducting multiple "Sprints," which are small releases with predetermined deadlines. This approach facilitates the visualization of overall progress and allows for testing of each implementation to prevent the accumulation of obstacles in the future.

Figure 17: Agile methodology infographic

The project will be divided into 5 major releases based on previous experience and familiarity with the workflow. This approach serves as a means to further breakdown the Pre-Production, Production, and Post-Production workflow.

Concept Discovery:

- Research the four-dimensional space theory
- Contact with a 4D video game developer for an interview
- Define the Core Game Pillars of the project

Vertical Slice:

- Set up the Unity Project and GitHub repository.
- Create a 4D rendering system
- Design the first puzzle

Alpha:

- Implement the ability to shift between “Slices” of the 4D world
- Model the first 4D primitive
- Decide the artistic approach of the game
- Make a video to explain the 4D visualization following Flatland explanation

Beta:

- Add the 4D primitives
- Add interactions between 4D objects
- Add user interface
- Add explanation of the 4D concept

Gold:

- Fix bugs
- Polish visualization
- Prepare documentation for release

5. Project development

5.1 Investigation

A general understanding of the concept of four-dimensional spaces served as the starting point for the development of this game. However, a deeper comprehension was necessary to acquire the required capabilities.

When visualizing the four-dimensional world on a screen, two primary mathematical techniques are employed: Projection and Slicing. Projection involves mapping higher-dimensional objects onto lower-dimensional spaces, while Slicing entails cutting higher-dimensional objects with lower-dimensional subspaces.

Recommendations from experienced video game developers who have worked on 4D games emphasized focusing on the Slicing technique. This approach was preferred as it simplifies the user's understanding by presenting a 3D world with unconventional shapes, even if the interactions remain unfamiliar.

For visualization purposes, the ray marching rendering technique was adopted. This technique involves emitting a ray from the camera and checking for collisions within a specific radius, allowing the representation of 4D objects as functions and their display as 3D objects in the scene.

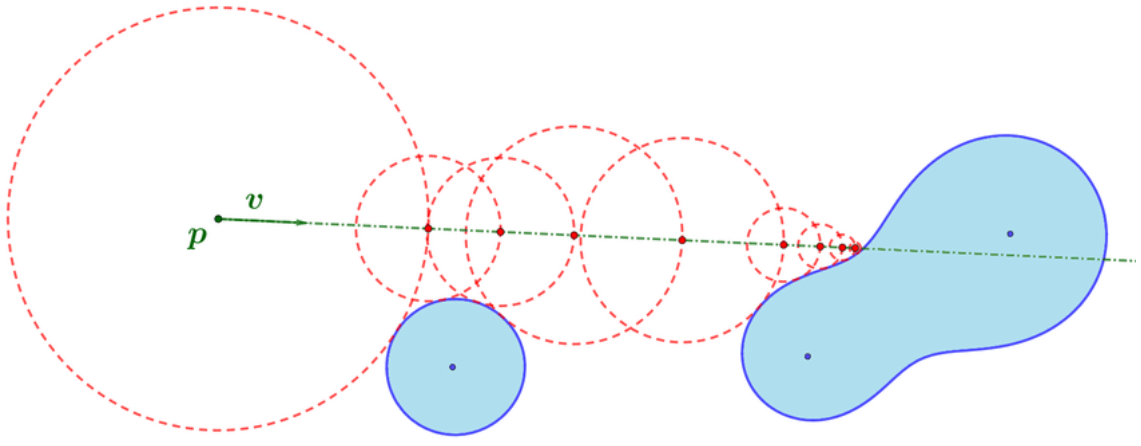

Figure 18: Raymarching representation

5.2 Case Analysis

The market and community of 4D video games have displayed considerable activity. There has been a noticeable increase in general interest in this topic, as evidenced by records from Google Trends. Searches related to 4D, fourth dimension, and higher dimensions have exhibited a steady rise since 2010.

Figure 19: Google Trends, 4D searches worldwide (2004 - today)

The growing public curiosity surrounding this theory has resulted in a rapid increase in the number of video games on the market that incorporate 4D elements. However, the complexity associated with this concept may limit the appeal of such video games to a niche audience.

Name	Developer	Publisher	Platform	Price
4D Toys	MTB Design Works, Inc.	MTB Design Works, Inc.	Windows (VR compatible)	14,99€
Miegakure	MTB Design Works, Inc.	MTB Design Works, Inc.	Windows	Unreleased
4D Minesweeper	Julian Schlüntz	Julian Schlüntz	Windows/Mac/SteamOs	Free
4D Miner	Mashpoe	Mashpoe	Windows	Unreleased
4D Golf	CodeParade	CodeParade	Windows	Unreleased
4D Chess	Ricky Robot	Ricky Robot	Windows (only VR)	3.99€
Cake 4D	TAP OK G	TAP OK G	Windows/Mac	4.99€
Maze 4D	Hunter Tintera	Hunter Tintera	Windows	1,59€

Table 4: Table of 4D video games in the market

The development of all these video games is primarily undertaken by indie developers. This indicates that while there has been a noticeable rise in general interest surrounding the topic, the appeal of video games exploring this theory may not be substantial enough to attract significant investment from larger publishers and developers. Many developers express their motivation to create 4D games out of passion for video games and a particular interest in exploring mathematical concepts.

Another interesting observation from the table is that these games are exclusively released on PC, primarily on Windows systems. This choice is driven by the ease of video game development on the Windows platform, as well as the broader market availability for a variety of games.

In terms of pricing, it is evident that the games target a limited audience. They are priced at a lower range to attract a new audience seeking new experiences. This approach acknowledges that individuals may be hesitant to invest a significant amount of money in something they are uncertain about, and thus, a lower price point is more appealing.

5.3 Interviews to Developers

After conducting an analysis of the market and recognizing the scarcity of video games that incorporate four-dimensional geometry, an initiative was undertaken to interview game developers who have experience working with this mathematical concept in video games.

The first step involved contacting developers who have demonstrated active involvement in the field over the past year. The objective was to maximize the likelihood of securing interviews. Polite and professional communication was established to present the purpose of the interview and to coordinate suitable meeting times, considering the time differences across various time zones.

To ensure consistency and facilitate comparative analysis, a standardized script was utilized for each interview. This approach allowed for the identification of both commonalities and distinctions among the experiences shared by multiple developers.

The interview questions revolved around three main themes: providing an introduction to the developer and their current video game projects, exploring the sources of inspiration and the thought processes driving their development, and gathering insights on their perspectives regarding the future of this concept in video games.

5.3.1 Interview Questions

The questions for the interviews are the following:

1. Who are you, and what game are you developing using the concept of the four spatial dimensions?
2. How would you describe your game?
3. What software did you use for this development? (Engine, modeling, version management)
4. What inspired you to create a video game that incorporates four spatial dimensions?
5. How does the addition of a fourth spatial dimension change the gameplay experience for players?
6. Are there any unique challenges that arise when designing and developing a four-dimensional video game?
7. How did you approach designing the game's user interface to accommodate for an additional dimension?
8. Can you walk me through the game mechanics and how they differ from traditional three-dimensional games?
9. How did you create the game's graphics and environments to visually represent four spatial dimensions?
10. Are there any specific mathematical concepts or theories that influenced the game's development?
11. How did you balance accessibility for players with the added complexity of a fourth dimension?
12. Can you describe any playtesting or feedback you received during the development process and how it influenced the game's design?
13. Do you see the development of four-dimensional video games as a potential trend in the industry, and if so, how do you think it could impact the future of game development?
14. Do you have any tips for my development of a 4D game?

5.3.2 Interview Results

Based on the provided interview responses (see Appendix A to the answers of the interviews), here are some conclusions that can be drawn:

5.3.2.1 Background and Development:

- Both Marc ten Bosch and Kevin from Code Parade are indie game developers.
- Marc has been working on Miegakure since 2013 and 4D Toys since 2017. He has a team helping him with the art and audio for Miegakure.
- Kevin has been doing full-time game development since the launch of Hyperbolica and is currently developing 4D Golf.
- Both developers have a background in computer science and engineering, with self-taught knowledge in mathematical concepts related to four spatial dimensions.
- Marc developed a custom engine that works with 4D and adapted his existing 3D engine to incorporate 4D math.
- Kevin uses Unity as the game engine for 4D Golf and combines procedural mesh generation with Miratope, a 4D software, for object modeling.

5.3.2.2 Game Descriptions:

- Miegakure is described as a puzzle adventure game inspired by Sokoban, where players manipulate the fourth dimension to solve puzzles. The art style is realistic, set in feudal Japan.
- 4D Toys is described as an interactive playground where players experiment with the environment.
- 4D Golf is a minigolf game set in a 4D world, allowing players to control all four dimensions and featuring new challenges and interactions.

5.3.2.3 Gameplay and Mechanics:

- The addition of a fourth spatial dimension is the core aspect of both Miegakure and 4D Golf, fundamentally changing the gameplay experience.
- Understanding and utilizing the fourth dimension is a key challenge for players in both games.
- Marc compares the importance of the fourth dimension in Miegakure to the significance of portals in Portal, highlighting its central role.
- Kevin emphasizes that thinking differently and understanding the concepts of 4D are crucial for players to navigate and succeed in the game.

5.3.2.4 Design and Development Challenges:

- Designing and developing four-dimensional video games present unique challenges.
- Marc highlights the difficulty of making the game visually appealing and understandable while representing the 4D world.
- Kevin mentions challenges in level design, teaching players the controls, and striking a balance between complexity and accessibility.
- Both developers mention the need to break down complex tasks into simpler steps and iterate on designs and UI elements.

5.3.2.5 Mathematical Concepts and Influences:

- Both developers draw inspiration from mathematical concepts related to four spatial dimensions.
- Marc mentions being influenced by the theory of 4D space and the visualization of slicing from the novel Flatland.
- Kevin highlights understanding different visualization methods for the 4D world and applying them in his game's development.

5.3.2.6 Playtesting and Feedback:

- Both developers have conducted playtesting and received feedback during the development process.
- Marc focuses on ensuring the game is enjoyable for players with varying levels of math background and gaming experience.
- Kevin's playtesting sessions were in the early stages, and feedback aligned with features he was already working on.

5.3.2.7 Future Trends and Recommendations:

- While both developers acknowledge the potential of four-dimensional video games, they have different perspectives on its future.
- Marc sees the potential for more games exploring mathematical concepts beyond 4D and believes there will be a growing community interested in playing and making 4D games.
- Kevin is uncertain about the trend's evolution, suggesting challenges in integrating 4D mechanics into certain game genres but speculating that it may find traction in the VR market.
- Kevin advises leveraging existing commercial engines and community resources when developing a 4D game, to avoid unnecessary frustration.
- Please note that these conclusions are based solely on the provided interview responses and may not encompass the entirety of the developers' perspectives or the intricacies of their respective games.

5.4 Project Setup

The setup process for the initial deliveries involved the configuration of various software components. Version control was established using Github, where a repository was created with the MIT License and a customized configuration tailored to Unity to prevent potential issues. During the setup of the repository with the Unity project, certain errors were encountered due to oversized files for Github. However, this obstacle was overcome by deleting and rebuilding the project, effectively resolving the problem.

For the game engine, Unity was selected as the preferred choice. A basic 3D scene was set up, featuring a Capsule game object to serve as the player's control avatar. Implementing movement mechanics was a straightforward task, leveraging previous experience. The newly developed script enabled the player to control the Capsule using either a keyboard or controller input, as the specific control scheme had not yet been determined. Collision handling was also configured, marking the completion of the primary project setup.

Exploring projection techniques for representing four-dimensional geometry in a three-dimensional engine led to the identification of raymarching as the most suitable approach for this project. Raymarching involves calculating the distance to scene surfaces as part of the rendering process. It entails dividing each ray into smaller segments and efficiently sampling a function at each step. By integrating this technique with a shader, objects can be selectively shown or hidden based on their distance from the camera, thus achieving the desired 4D visualization effect.

5.5 Game Design of a 4D Video Game

After analyzing the main titles in the market that incorporate 4D geometry, it becomes apparent that the majority of them adhere to one of two approaches when discussing the Core game pillars: Puzzle solving or Sandbox freedom. Upon recognizing this, the available options for the project are assessed, and a decision is made to create a game with puzzle-like elements utilizing the 4-dimensional world. This choice not only allows for the demonstration of acquired game design skills obtained over the course of four years of studying at CITM but also offers the potential for multiple advantages in case there are limitations in the programming section.

The decision is made to adopt the Game Design template that has been employed to research and analyze other games that utilize 4D elements. Following the same template, the design for the project is structured.

The project will entail the development of a puzzle game in which players are tasked with exploring multiple levels containing obstacles that can only be overcome by strategically utilizing the fourth dimension.

In terms of scope, a preference is expressed for a concise and refined game that leaves players desiring more, suggesting a limit of no more than 3 or 4 levels.

Core Game Pillars: Puzzle-Solving, Platforming, Exploration

Game Mechanics: Player movement, 4D slice slider (W Slider), rotatable camera, environmental puzzles, limited mobility (no jumping)

Camera: Fixed isometric perspective, there are multiple camera lock points.

Art Style: Low poly

UI: Minimal, W Slider

5.5.1 Playground

Due to the limited familiarity of the general population with the concept of 4D, the most effective approach for introducing this mechanic is through a designated playground or level 0. This level serves as an environment where players can freely interact with the new mechanics without facing any penalties or constraints.

Considering its role as an introductory level to the 4D mechanics, Level 0 deviates slightly from the minimalistic approach employed in the other levels. This deviation is necessary to ensure that players can focus solely on understanding the behavior of 4D shapes and their interactions. Consequently, Level 0 incorporates more user interface elements compared to subsequent levels.

Initially, the concept revolved around a simple floor as a consistent visual element throughout the levels, accompanied by three 4D shapes. However, during testing, it became evident that presenting such a significant amount of information at once was overwhelming for players encountering the concept for the first time. As a result, the decision was made to feature one 4D shape at a time, with the option to switch between shapes using a drop-down selector.

To enhance the playground's ability to showcase the distinctive behavior of 4D shapes in comparison to 3D shapes, buttons were implemented to facilitate rotation of the shape along the W axis. This addition injects a sense of interest and dynamism into the experience.

In the event that players "lose" sight of the shape during its rotation, as it may reside in a different 3D slice from the one currently visible, a button was incorporated to reset all values to their default state, providing a means to reorient and reestablish visual contact with the shape.

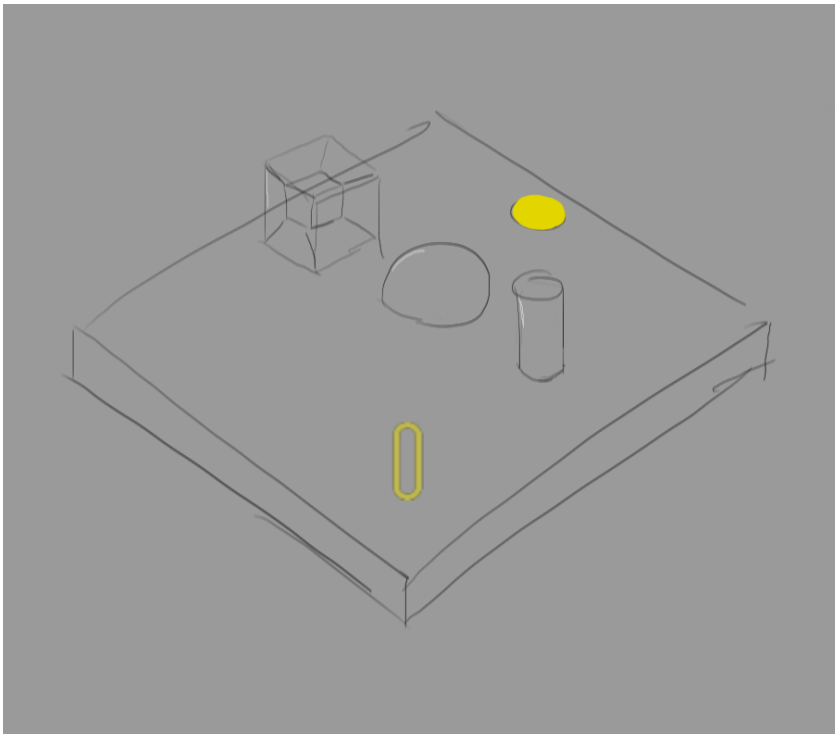

Figure 20: Drawing of the concept for the playground level

5.5.2 Level 1

The primary challenge in designing a 4D video game lies in creating level designs that require players to adopt a new way of thinking in order to overcome obstacles and reach their goals.

Based on discussions with a developer experienced in creating games with 4D mechanics, it became clear that the difficulty progression should be gradual. Additionally, the developer emphasized the importance of allowing players to discover and experiment with the 4D mechanics on their own, as this tends to foster better understanding compared to presenting information through text or tutorials.

For the first level, the objective was to provide a familiar experience to players while introducing the 4D implementation without overwhelming them. The concept involved a scenario where the player must reach an inaccessible goal from their starting position.

To guide the player's attention towards the objective, a yellow platform floating in the air is presented. Elevated positions are commonly associated with strategic advantages in various contexts such as battles, sports games, or negotiations. This visual cue enhances the attraction towards the goal.

The use of color theory further reinforces the player's focus on the intended target. By employing a bright color, such as yellow, the player's attention is drawn to the goal or treasure they need to reach. The player's character is also given a paler yellow color to establish a visual connection between the player and the goal.

In the level design, a pillar resembling the floating platform is visible, and the two are connected by an object functioning as a bridge. The bridge is colored red, which traditionally signifies something negative to be avoided, but in this case, it indicates interactivity with a specific object.

The player observes the presence of a triangular red shape, which shares the same color as the bridge, establishing a visual association between the two. This serves as a hint to convey the idea that certain elements can be concealed from plain sight.

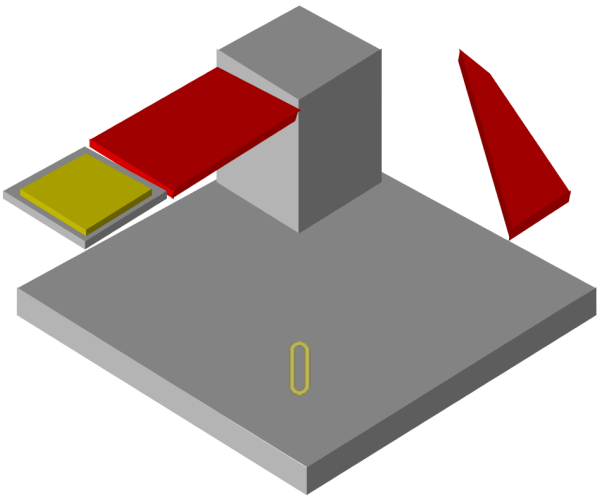

Figure 21: Level 1 concept, as the level starts

At this stage, the player has the ability to move around but is unable to progress further in the level. After exploring the surroundings, the only option remaining is to interact with the W Slider and observe its effects.

Adjusting the slider triggers peculiar movements in the two red shapes, going beyond mere translation or rotation. They undergo complete transformations, causing the bridge to vanish and the triangular shape to morph into a rectangular prism. In a particular range of the W Slider, the prism resembles a ramp that can be utilized to access the pillar. Therefore, if the player positions the slider correctly, they can utilize the shape as a means to advance in the level.

Upon reaching the top of the pillar, the player encounters an obstacle blocking their path. However, having observed the presence of something in that location previously, they understand that progress may require retracing their steps. By returning the W Slider to its previous position when the bridge was visible, a clear pathway to the goal emerges, allowing the player to complete the first level.

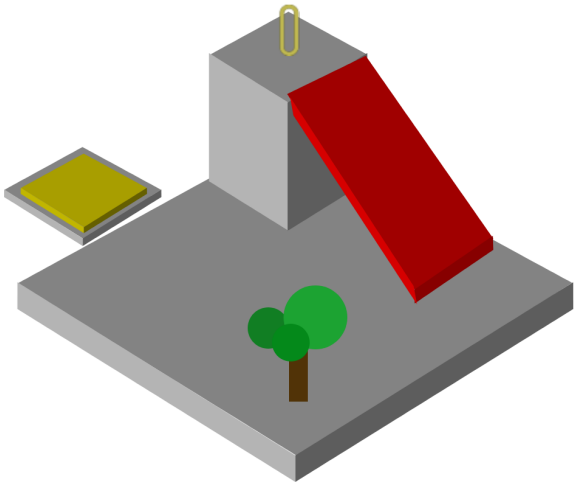

Figure 22: Level 1 concept, when the player has moved the W Slider

In the game, alongside the functional scenery that serves as puzzles, there is a collection of shapes arranged in the form of a tree. This ensemble comprises three hyperspheres and a duocylinder, which serve as analogues to the 3D sphere and cylinder, respectively. The purpose of including this tree-like structure is to provide the player with an opportunity to observe the behavior of other 4D shapes as they navigate the W slider. By familiarizing the player with these shapes in advance, they are introduced to them in a preliminary manner, preparing them for their utilization in future levels.

5.5.3 Level 2

In this level, the main objectives were to demonstrate the utilization of mesh boolean operations, specifically Subtraction, for creating holes in walls and floors. The focus was on showcasing how 4D shapes can be used to overcome obstacles and smoothly navigate the environment.

To begin, the exploration of different camera angles accessible with the Q and E keys was desired. An obstacle was introduced, physically and visually blocking the path to the goal. The player was required to move backward initially, as their character started on a lower level compared to the goal. Without the ability to jump, finding a way to ascend became necessary. At the starting position, a ramp was visible, which could assist in climbing. However, a blocking wall prompted the player to change the camera angle for better visibility.

Upon reaching the same height as the goal, another obstacle appeared in the form of a gray wall. Initially, a 4D hypersphere was used to perform a subtraction operation, creating a circular hole in the wall. This allowed the player to cross the obstacle. Additionally, a ramp was included to illustrate the importance of descending from higher locations to reach the goal.

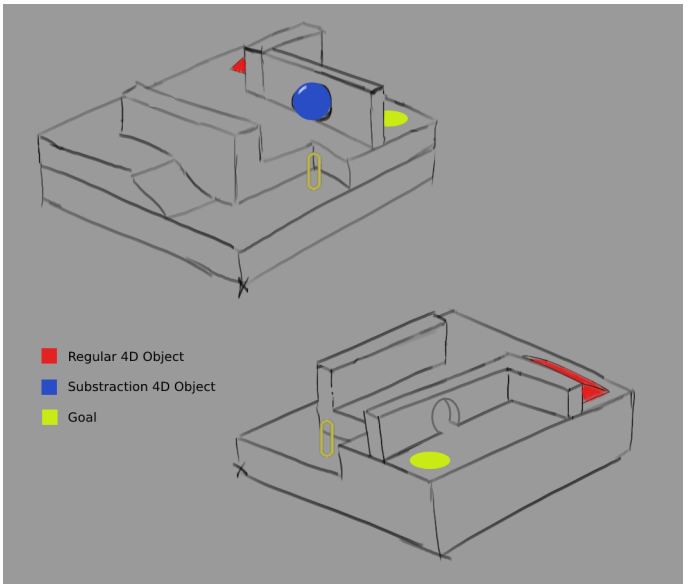

Figure 23: First iteration of level 2

To address the linear progression and emphasize the objective of using 4D shapes to move the character, a modification was made to the level design. The ramp was replaced with an "elevator" constructed with hypercubes in that location. This alteration allowed for a more dynamic experience and showcased the potential of 4D shapes for character movement.

With the player now positioned on a higher floor than the goal, they had the opportunity to descend through a hole created using a 4D subtraction shape. This implementation added an element of strategic navigation and further emphasized the utilization of 4D mechanics within the game.

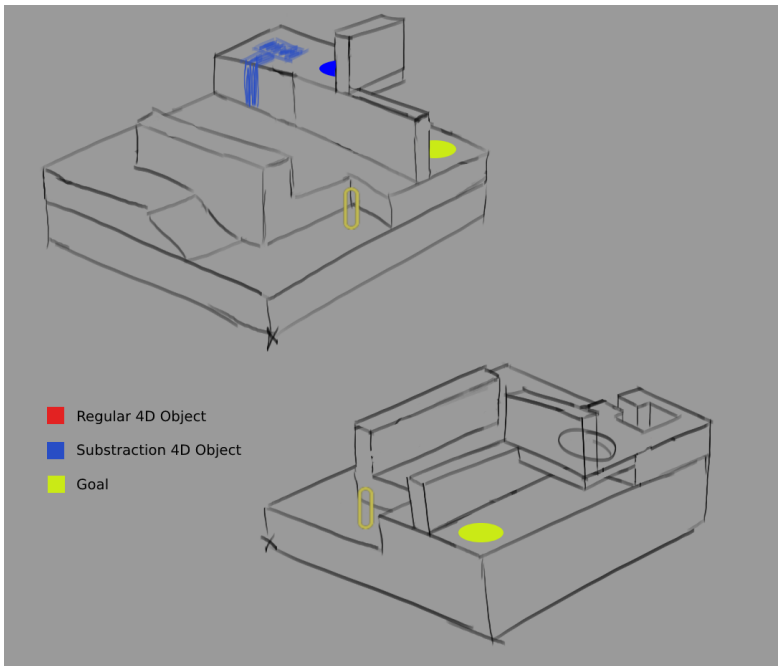

Figure 24: Final concept of level 2

5.5.4 Level 3

The objective for level 3 was to create a climactic ending for the game, resembling a boss level, where players could apply the knowledge and skills acquired throughout the previous levels.

In this level, players are required to navigate across bridges that serve as solutions for various gaps in the environment.

One bridge is similar to the bridge encountered in level 1, but this time it is not fully constructed at any specific point along the W axis. As a result, players must move and adjust the W slider simultaneously to change the 3D slice in which their character resides.

To reach the goal and complete the game, the final challenge involves removing a bridge by adjusting the W value while the character is positioned directly above the goal. This action allows the character to land on the goal and successfully conclude the game.

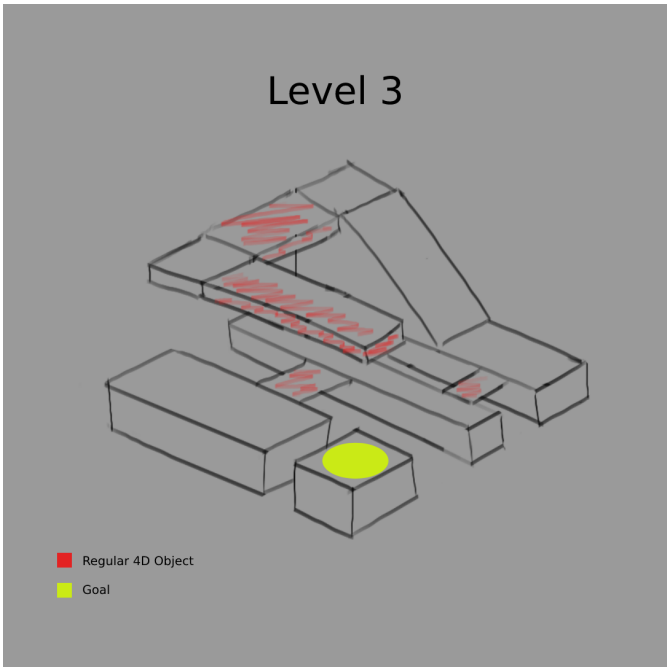

Figure 25: Concept drawing of level 3

5.6 Game Development of a 4D Video Game

5.6.1 Alpha (v0.1)

Due to the main objective of the project, it was decided to begin by utilizing a project template to streamline the game design process. The template was later adapted for personal use in game development.

The project includes pre-existing scripts that employ the ray marching technique for rendering the 4D shapes. Additionally, a collision script is implemented to handle player interactions with the 4D objects within the scene.

The base project served as a proof of concept to evaluate the effectiveness of the design. While there was a desire to enhance the 4D engine, such improvements were not feasible for the current delivery.

Furthermore, a simple menu system was programmed, which will be utilized in the final release of the game.

Working with 4D shapes initially presented challenges, particularly regarding the rotation and positioning along the W axis. Through trial and error, a basic representation of the first puzzle level, as designed, was achieved.

One minor issue encountered in the first level relates to the teleportation of the player to the next level upon reaching the goal. As there is currently only one level, the intended functionality would be to return the player to the main menu. However, due to the collision system's reliance on ray marching, implementing a OnTriggerEnter function to load the next scene is not a straightforward process.

In preparation for the Alpha release, the game was shared with three friends for testing. Minor issues, such as menu typos and visual anomalies, were identified. The playtest also provided valuable insights into the level design's comprehensibility and its ability to equip players with the necessary knowledge to successfully complete the game. Overall, it serves as a suitable introductory level.

5.6.2 Beta (v0.5)

For the second release, the focus shifted towards developing a comprehensive version of the game to facilitate early playtesting. This approach allowed ample time to address any encountered bugs or issues promptly.

Once the initial level was completed, the process of constructing subsequent levels followed a similar trajectory. Overcoming the main challenge faced during the Alpha phase, which involved navigating the unfamiliar terrain of working with 4D shapes in the Unity engine, proved to be a significant breakthrough.

Moreover, a substantial amount of time was dedicated to self-testing the level designs during their construction. This iterative testing process unveiled a noticeable disparity in the game feel of level 2 when compared to the rest of the game. Recognizing this deviation, development efforts were momentarily halted to address the underlying problem.

After investing several days into revising the design of level 2, the implemented changes were assessed to gauge their impact. The resulting outcome yielded a sense of cohesiveness and fulfillment, effectively transforming the game into a more unified experience.

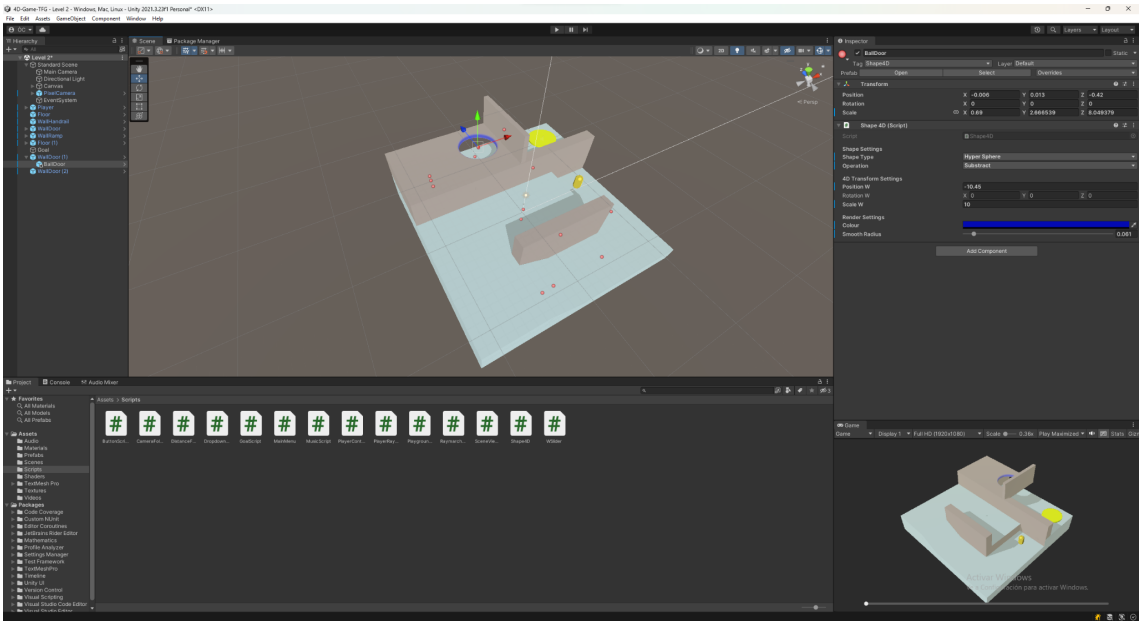

Figure 26: Level 2 development in Unity engine

Incorporating camera movement became a necessary addition to address the discomfort experienced during gameplay in the redesigned second level. Players were occasionally losing sight of the character while attempting to solve puzzles, which posed a hindrance to the overall experience. To mitigate this issue, a script was developed to enable the player to switch between four predefined camera locations using the Q and E keys.

To ensure proper camera orientation, a specific approach was employed. The camera consistently focuses on the coordinates (0, 0, 0), which corresponds to the center of the game environment. However, it was recognized that this approach may pose challenges if future levels involve multiple floors. One potential solution under consideration involves adjusting the camera's Y coordinate based on the player's own Y position, allowing for greater flexibility in capturing the desired perspective.

```
void ChangeCamera()
{
    if (Input.GetKeyDown(KeyCode.E) && !isTransitioning)
    {
        currentPoint++; // Move to the next campoint

        // Check if we have reached the end of the array
        if (currentPoint >= camPoints.Length)
        {
            currentPoint = 0; // Wrap around to the first campoint
        }

        StartCoroutine(TransitionToCameraPoint(camPoints[currentPoint]));
    }
    else if (Input.GetKeyDown(KeyCode.Q) && !isTransitioning)
    {
        currentPoint--; // Move to the previous campoint

        // Check if we have reached the beginning of the array
        if (currentPoint < 0)
        {
            currentPoint = camPoints.Length - 1; // Wrap around to the last campoint
        }

          StartCoroutine(TransitionToCameraPoint(camPoints[currentPoint]));
    }
}
```

```
    void FollowPlayer()
    {
       camera.transform.LookAt(Vector3.zero);
    }
```

To ensure a seamless transition and prevent disorientation, the camera employs a smooth movement when changing positions. This effect is achieved using a linear interpolation, or Lerp, function. The camera smoothly moves from its previous position to the target position over a specified duration, denoted as time T. By implementing this approach, the camera's movement appears fluid and aids in maintaining player orientation throughout the game.

```
    IEnumerator TransitionToCameraPoint(Vector3 targetPosition)
    {
        isTransitioning = true;

        Vector3 startPosition = camera.transform.position;
        float elapsedTime = 0f;

        while (elapsedTime < transitionDuration)
        {
            elapsedTime += Time.deltaTime;
            float t = Mathf.Clamp01(elapsedTime / transitionDuration);
            camera.transform.position = Vector3.Lerp(startPosition,
targetPosition, t);
            yield return null;
        }

        camera.transform.position = targetPosition;
        isTransitioning = false;
    }
```

The issue encountered in the Alpha version where the character failed to detect the goal button was resolved by implementing a distance-based system. When the player approaches the goal button, the system checks if it is within proximity to determine if the goal has been reached. Upon detection, an audio cue is played, ensuring a seamless transition by allowing one second, plus the length of the audio, for the audio to play completely. Subsequently, the next scene is loaded. However, if the player is in the last level, the game returns to the main menu to maintain the intended progression of the gameplay experience.

```
        void GoalReached()
        {
            distanceGoal =
Vector3.Distance(this.gameObject.transform.position,
goal.transform.position);
            Debug.DrawLine(this.gameObject.transform.position,
goal.transform.position);



            if (distanceGoal <= 1.8)
            {
                Debug.Log("Goal");

                if (!hasPlayed)
                {
                    source.Play();
                    hasPlayed = true;
                }

                isGoalReached = true;
                StartCoroutine(LoadNextSceneDelayed());
            }
        }
```

```
private IEnumerator LoadNextSceneDelayed()
{
    yield return new WaitForSeconds(clip.length + 1f);

    if (isGoalReached)
    {
        int nextScene = SceneManager.GetActiveScene().buildIndex + 1;

        if (nextScene >= SceneManager.sceneCountInBuildSettings)
        {
            nextScene = 0;
            Destroy(GameObject.Find("MusicManager"));
        }

        SceneManager.LoadScene(nextScene);
    }
}
```

In order to facilitate the playtesting process, an introduction to the concept of the 4th Dimension was necessary, as many players approached the game without prior knowledge. To address this, a new button was added to the main menu, which, when clicked, played a video explanation accompanied by a 3D animation (as seen in section 5.7).

One challenge encountered with the Unity video player was the lack of a built-in variable to detect if the video clip had reached its end. To overcome this limitation, a simple checker was implemented to determine if the current frame of the video clip was the last one. By checking the state of the isVideoPlaying variable, it could be assumed whether the video had finished playing.

```
    public void PlayVideo()
    {
        if (isVideoPlaying == false)
        {
            isVideoPlaying = true;
            rawImage.SetActive(true);
            mainMenu.SetActive(false);
            title.SetActive(false);
            audioPlayer.GetComponent<AudioSource>().Pause();

            videoPlayer.Play();
        }
    }

    public void StopVideo()
    {
        if (isVideoPlaying == true && (videoPlayer.frame >=
(long)videoPlayer.frameCount - 1))
        {

            Debug.Log("Video ended");

            isVideoPlaying = false;
            rawImage.SetActive(false);
            mainMenu.SetActive(true);
            title.SetActive(true);

            audioPlayer.GetComponent<AudioSource>().UnPause();

            videoPlayer.Stop();
        }
    }
```

5.6.3 Gold (v1.0)

After reviewing the initial feedback from playtesting and engaging in discussions with players, a significant issue arose involving the W Slider, which serves as the primary mechanic for controlling the 4th Dimension in Realm Paradox. It was crucial to address this issue promptly, as it became the main source of complaints and hindered players' enjoyment of the game and overall experience.

To resolve the problem, thorough testing was conducted to identify the specific circumstances under which the glitch occurred and determine if it could be reliably replicated. It was discovered that the issue arose when players clicked the W Slider to adjust the W axis value and subsequently used the WASD keys for movement, resulting in unintended control over the slider.

To streamline input handling in this project, a decision was made to utilize the GetAxis() function from Unity's Input class. By using this function, various input types such as keyboard (WASD), arrow keys, and controller inputs could be managed under a unified approach, avoiding the need for separate input handling methods for each input type.

```
    void MovePlayer()
    {
        if (Input.GetAxis("Horizontal") != 0 || Input.GetAxis("Vertical") != 0)
        {
            Vector3 cameraForward = Camera.main.transform.forward;
            Vector3 cameraRight = Camera.main.transform.right;

            cameraForward.y = 0f;
            cameraRight.y = 0f;

            cameraForward.Normalize();
            cameraRight.Normalize();

            Vector3 movementDirection = (cameraForward * Input.GetAxis("Vertical")
+ cameraRight * Input.GetAxis("Horizontal")).normalized;
```

```
            transform.Translate(movementDirection * Time.deltaTime * playerSpeed,
Space.World);

            if (movementDirection != Vector3.zero)
            {
                transform.rotation = Quaternion.LookRotation(movementDirection);
            }
        }
    }
```

However, an oversight on my part was not recognizing the existence of the "Navigation" variable within the Slider component. This variable enables users to control the slider using input other than the mouse and is set to "Automatic" by default, encompassing both the "Horizontal" and "Vertical" axes. This default setting was the root cause of the problem experienced by players.

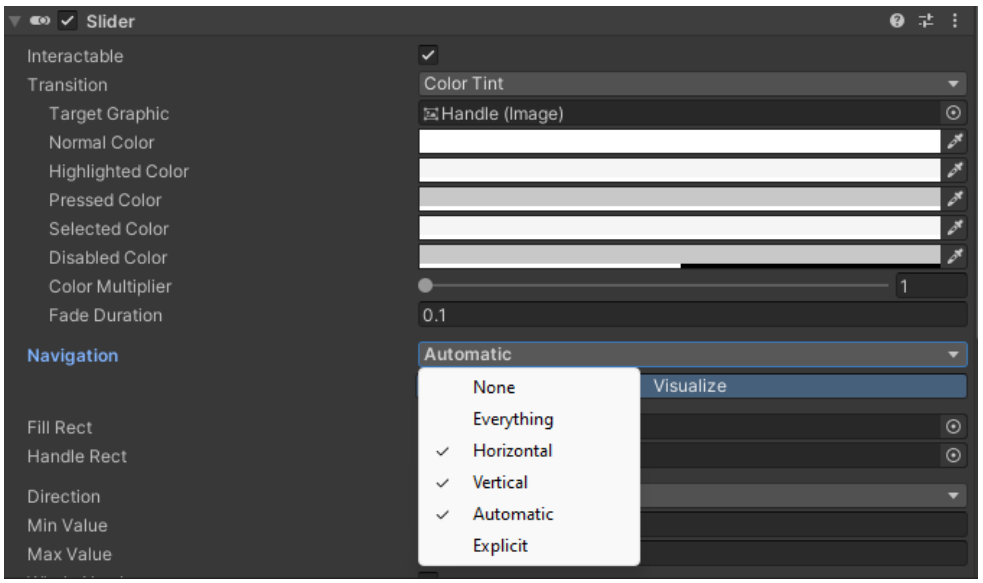

Figure 27: Slider component in Unity with the default Navigation setting

Another issue that was frequently reported by players was the poor performance of the game, particularly in relation to the complexity of the levels. This performance limitation stems from the fact that all calculations involving the 4th Dimension in Unity rely on the raymarching technique, which consumes significant computational resources.

To address the performance concern, a resolution adjustment was implemented for the rendering plane, which integrates the standard 3D objects from Unity (such as the character represented by a default Capsule and the Goal represented by a cylinder) with the raymarched 4D shapes. By reducing the resolution of this rendering plane, the computational requirements of the 4D shape rendering process are reduced. While this may lead to a slightly pixelated visual appearance, it was deemed acceptable since a pixel shader had already been applied to the entire game, resulting in a visual aesthetic where complex shapes appear simplified.

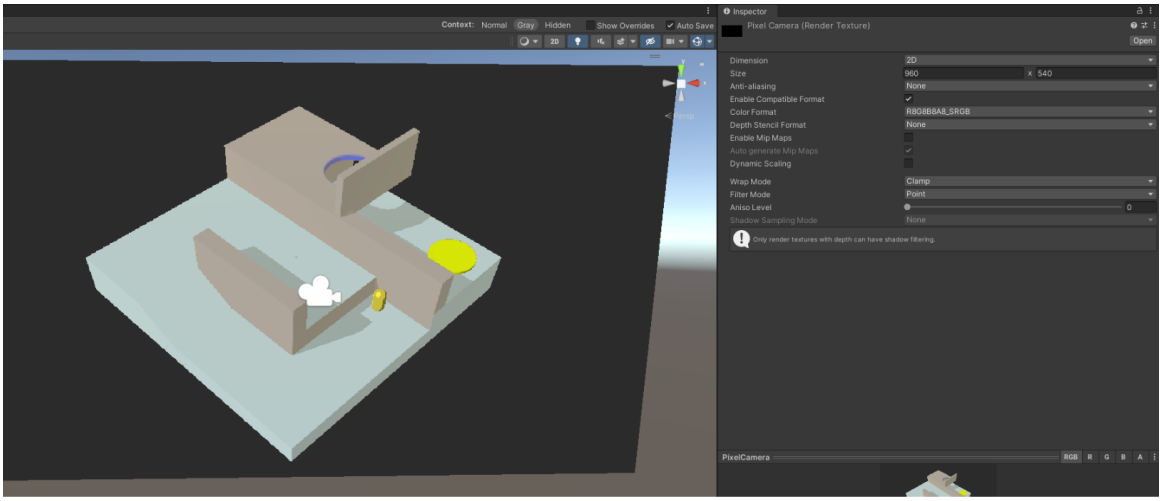

Figure 28: Pixelated Render Texture setted to a smaller resolution to improve performance

After addressing the main issues highlighted during the playtesting phase, the focus of the development shifted towards polishing the game to enhance the overall player experience.

One notable addition was the implementation of an audio system, which incorporated copyright-free music that played throughout the game. Additionally, audio feedback was introduced to provide a sense of accomplishment when reaching the Goal in each level. Furthermore, the main menu was enhanced with audio feedback when pressing and hovering over buttons, improving the overall interactivity.

To encourage players to explore and engage with the various shapes presented in the 4th Dimension, a minor improvement was made to the UI of the Playground level. The dropdown menu now includes clear instructions to guide players on how to change the 4D shape, while the instructions on rotating the shapes in the 4th Dimension were made more explicit, ensuring a better understanding of the mechanics.

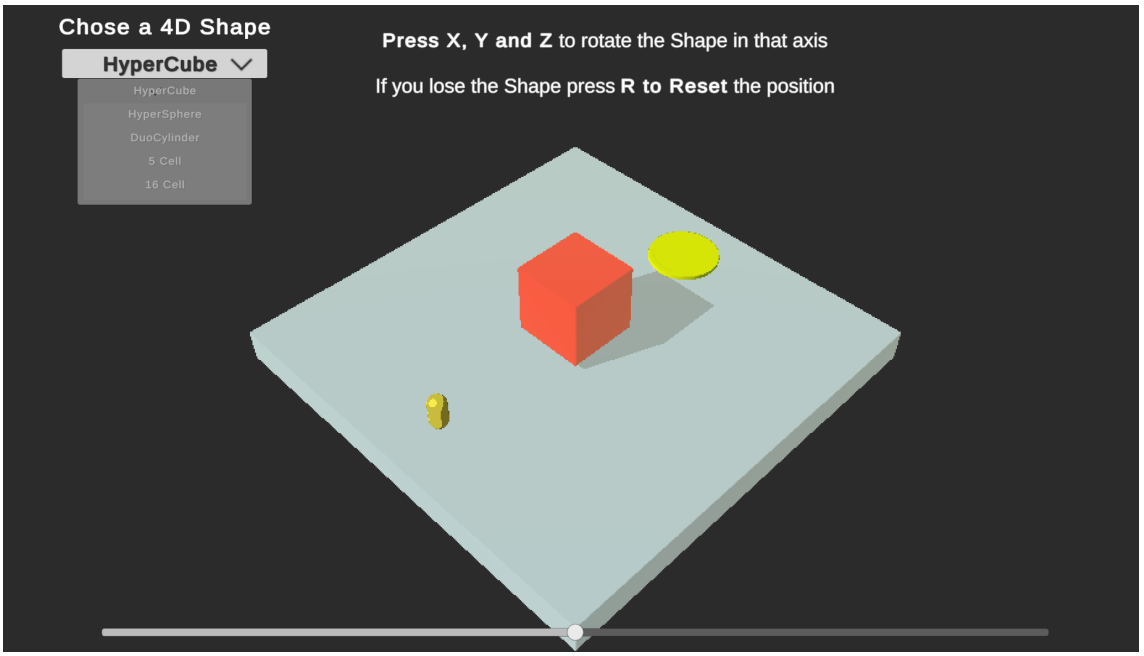

Figure 29: Playground level with improved UI

This is the final version of the game, to play the game refer to the Links section, and for more gameplay images see Appendix B.

5.7 Game Playtesting

After the releasing of the Beta version, a playtesting session was made to mainly see if the objective of the project was being achieved, it also helped to find and identify bugs in the game and problems that the players had when playing.

Before starting to distribute the game, a Google Forms was made. It was divided in two parts, one before and one after playing the game (see Appendix C to the questions of the survey).

In the first section, the testers were questioned about what they understood as the 4th Dimension, and if they had interacted before with it, in a video game or any kind of media.

Considering that the primary objective of the project is to enhance public understanding of the theory of the 4th Dimension, it becomes necessary to ascertain the level of existing knowledge among the general public regarding this topic. This assessment is crucial to determine the extent to which the game fulfills its intended goal.

After playing the game, the testers were questioned about whether their understanding about the 4th dimension had changed. If they had any problem with the 4D shapes and solving the puzzles, and if so, what problem they had.

How natural and non-intrusive they felt about the integration of the 4D.

They were asked to rate the difficulty of the video game from 1 to 5, one being very difficult and 5 being very easy. They also rated the main experience with the game.

And finally, if they had any comment, suggestion or bug they wanted to add to the form.

5.8 4D Explanation Video

To facilitate comprehension of the 4th dimension theory for individuals who prefer not to delve into extensive written material, a decision is made to create a video that explains the concept using the dimensional analogy presented by Edwin Abbott in his book *Flatland* (as referenced in section 2.1). Blender is utilized to develop a simple animation featuring a character named Bob within a 2D space, where he conceals his coins in a chest for safekeeping. A 3D entity manipulates one of the coins along the Z-axis, imperceptible to Bob, resulting in his perception of the coin's disappearance. Transparent planes are then introduced to illustrate the concept that an N-dimensional space can be comprehended as a collection of stacked N-1 dimensional spaces, known as the Cross-Section explanation. Camera movements are incorporated in the animation to enhance the narrative of the explanation.

The 3D models utilized in the animation are sourced from sketchfab.com. Following the completion of the rendering process, captions are added, and Clipchamp software, a free video editor from Microsoft, is employed to showcase a brief preview of the game, Realm Paradox.

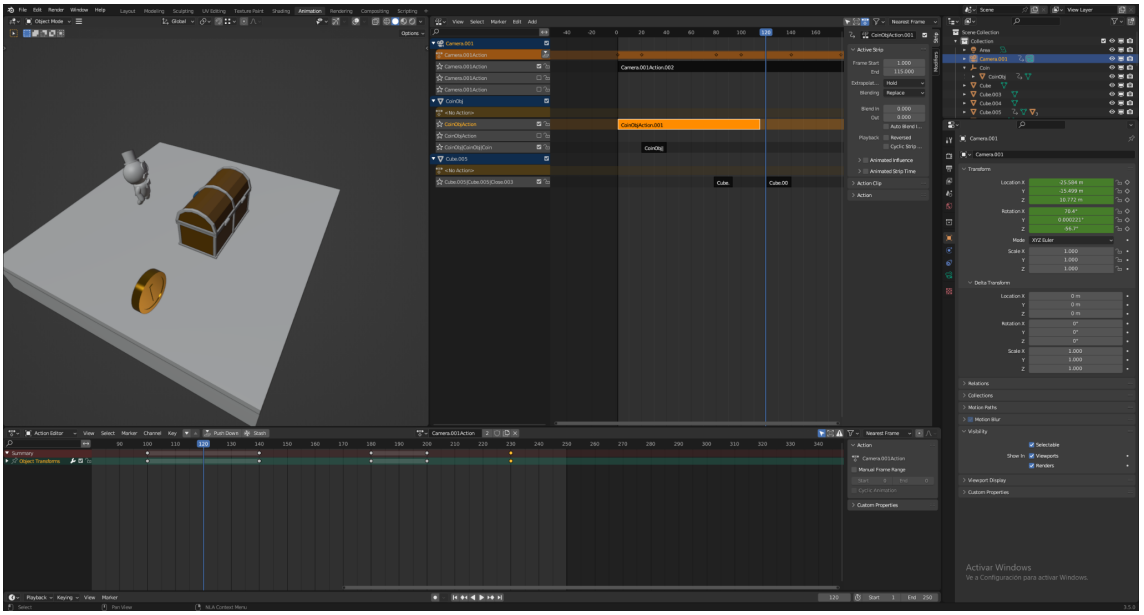

Figure 30: The 3D animation in Blender

6. Project validation

To ensure that the game effectively achieves its objectives and to evaluate its impact on players' understanding of the 4th dimension, a comprehensive validation process was conducted. This involved gathering feedback from participants who took part in playtesting and completing a post-game survey. The purpose of the survey was to determine participants' understanding of the fourth dimension, their familiarity with the game mechanics, and their general opinions. The survey's data collection provides important information on the game's effectiveness and its capacity to reach its intended objectives.

6.1 Playtesting results

The results obtained from the survey showed various aspects that helped to determine if the objectives of the project were archived or not. They also provided some very useful feedback to solve some bugs that interfered with the experience of the players with the game (see Appendix C to the questions of the survey).

Interestingly, the previous knowledge about the 4th Dimension was really diverse, but we can differentiate 3 main groups where the testers could be separated on, those who had no prior knowledge of the theory, those who understood it from the Albert Einstein's Special Relativity theory, the XYZ plus time, and the group that understand it as an expansion of the regular 3-dimensional space with and extra dimension.

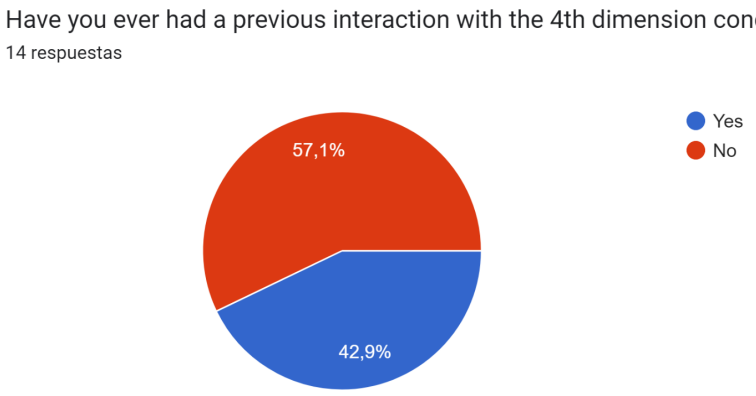

Figure 31: Playtesting question 2

However, after engaging with the game, a significant number reported an enhanced understanding of the concept. This suggests that the game effectively conveyed the intricacies of the 4th dimension to players who were unfamiliar with it.

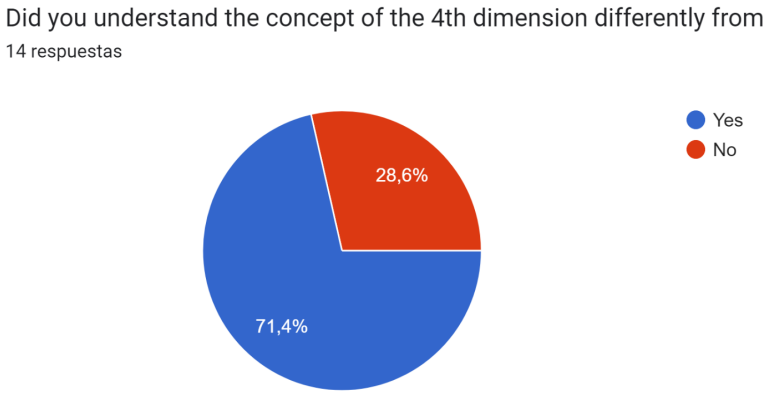

Figure 32: Playtesting question 3

When it comes to the gameplay experience, a few participants encountered challenges related to the 4D shapes and their interaction with the environment, but when looking up close, the problems they described were mainly a glitch that involved the W Slider, which was sometimes moved with the same keys that the player uses to move the character. The other problem some testers found was that the controls for moving in the 4th Dimension, the W Slider, were slightly cumbersome.

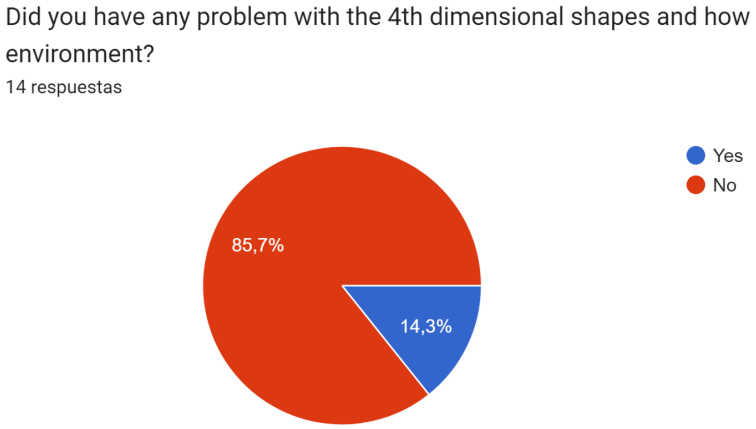

Figure 33: Playtesting question 4

Participants found that the incorporation of the concept felt natural and seamless, contributing to the learning experience. Despite the challenges, they found the integration was generally well received.

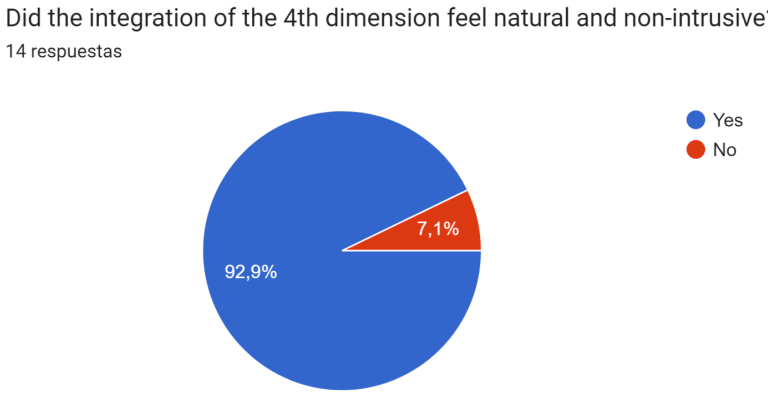

Figure 34: Playtesting question 6

Most of the testers agreed on the difficulty of the levels being easy, which could be explored in future versions of Realm Paradox to achieve better engagement with the playerbase.

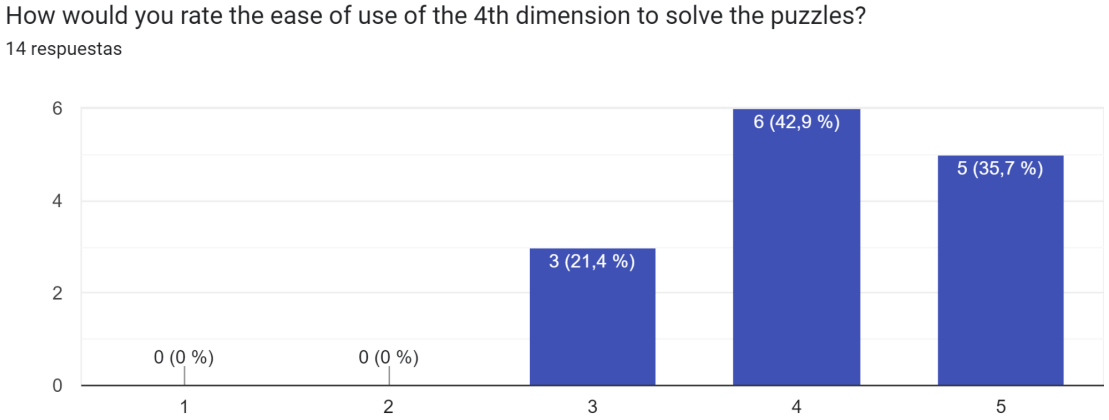

Figure 35: Playtesting question 7

In terms of the overall experience, the participants expressed positive feedback, particularly regarding its educational value and the way it expanded their understanding of the 4th dimension. The main suggestions we can find involve mainly the W Slider bug mentioned earlier. But it is surprising that after the second release that fixed that glitch, the comments focused more on the positive experience they had and the desire for an expansion of levels and enhanced gameplay for future versions.

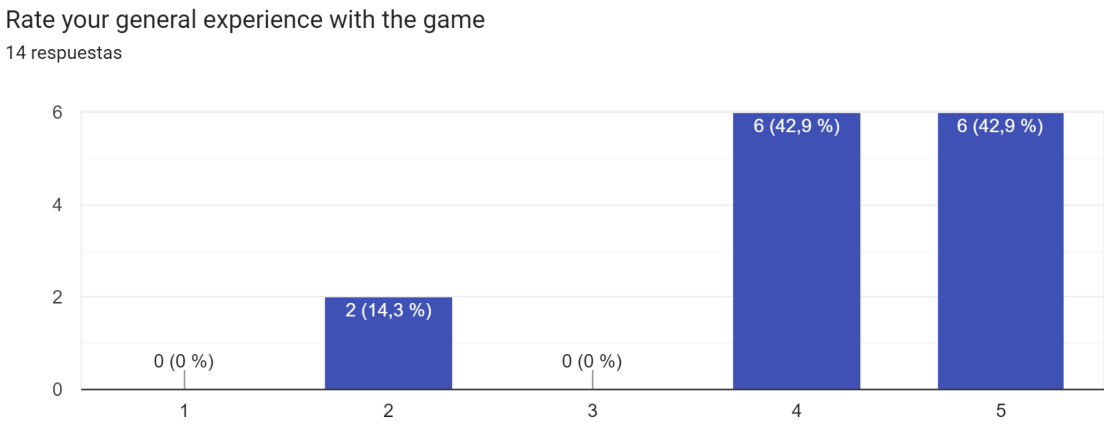

Figure 36: Playtesting question 8

7. Conclusions

The project aimed to develop a video game that would enable players to interact with four-dimensional geometry while making the concept of four-dimensional space more accessible and enjoyable for a broader audience. Let's assess whether the objectives were successfully achieved:

General objectives:

- Develop a video game that allows the player to interact with four-dimensional geometry: **Objective achieved**. The project successfully created a video game, "Realm Paradox," where players can engage with four-dimensional geometry and experience the unique challenges and interactions it offers.
- Make the complex topic of four-dimensional space easier to understand for a broader audience, while making it enjoyable: **Objective achieved**. Through extensive research and game design principles, the project focused on simplifying the understanding of four-dimensional space. The inclusion of puzzles and interactive elements in the game helped players grasp the concepts of 4D space in an engaging and enjoyable manner.

Specific objectives:

- Understand the mathematical concept of four-dimensional space in depth to explain it to others: **Objective achieved**. The project required a comprehensive understanding of the mathematical foundations of four-dimensional space, which enabled the development team to effectively explain and integrate it into the game. This understanding was crucial in designing the puzzles and interactions that challenged players' comprehension of 4D geometry.

- Research how developers have worked with the topic and how game design can be used to explain it: **Objective achieved**. Extensive research was conducted to explore how other developers have approached the topic of four-dimensional space in games. This research included interviews to two of the most important developers of 4D video games. This research informed the game design process, ensuring that the project incorporated effective strategies to convey the concepts of 4D geometry to players.
- Make a short video animation (30 s) to simplify the visualization of 4D space and geometry: **Objective achieved**. A concise and visually engaging video animation was created, utilizing the concept of dimensional analogy to simplify the visualization of 4D space. This animation served as a supplementary tool to enhance the understanding of the topic, particularly for those who prefer visual explanations over textual information.
- Design puzzles that test understanding of 4D space: **Objective achieved**. The game design incorporated a variety of puzzles and challenges that required players to apply their understanding of four-dimensional space. These puzzles aimed to reinforce the comprehension of 4D geometry and provided opportunities for players to explore and manipulate four-dimensional objects in the game world.
- Render 4D objects in a game engine: **Objective partially achieved**. While the project incorporated 4D object rendering, it relied on pre-existing work as a base for this functionality rather than developing it entirely independently.
- Program interaction between multiple 4D objects: **Objective partially achieved**. Similarly, the project utilized pre-existing work as a foundation for programming interactions between multiple four-dimensional objects within the game.

Although objectives 6 and 8 were not fully achieved through independent development, it is important to acknowledge the project's ability to leverage and build upon existing work in the field. By incorporating pre-existing functionalities, the project still succeeded in providing players with the opportunity to experience and interact with four-dimensional geometry.

In conclusion, the project made significant progress in achieving its objectives by developing "Realm Paradox". The project effectively simplified the concept of four-dimensional space and enhanced player understanding through research-informed game design choices and the creation of a visual animation. While the project relied on pre-existing work for the rendering of 4D objects and programming interactions, this utilization of existing functionalities still contributed to an engaging gameplay experience. Overall, the project successfully accomplished its primary goals of creating an accessible and enjoyable video game that introduces players to the intriguing world of four-dimensional geometry.

7.1 Future Plans

The playtesting phase provided valuable insights and feedback from the participants, highlighting areas for improvement and potential avenues for future development. Based on the comments and suggestions received, several future plans have been identified:

Expansion of Levels: Many players expressed a desire for more levels within the game. They enjoyed the puzzles and challenges presented by the four-dimensional space and wanted to explore further. In response to this feedback, future plans involve the development of additional levels that progressively introduce new mechanics and complexities, providing players with an extended and engaging gameplay experience.

Enhanced Gameplay Mechanics: The playtesters' comments highlighted specific areas where gameplay mechanics could be further refined. Some players noted issues with certain controls or interactions, indicating the need for improvements to enhance the overall player experience. Future plans involve addressing these concerns by fine-tuning the controls, optimizing the user interface, and ensuring a smoother and more intuitive gameplay flow.

Community Engagement: The playtesting phase revealed a genuine interest and enthusiasm among players for the concept of four-dimensional space and its integration into video games. Building upon this interest, future plans involve fostering a community around the game. This includes establishing forums for players to share their experiences, strategies, and feedback, as well as engaging with the community through regular updates, contests, and opportunities for players to contribute their own levels or puzzles.

By incorporating these future plans, the project aims to address the suggestions and comments received during playtesting, ultimately improving the game's overall quality and expanding its impact. The goal is to create an immersive and educational gaming experience that captivates players while effectively conveying the intriguing nature of four-dimensional space. With ongoing development and community engagement, the project envisions a future where "Realm Paradox" continues to evolve and inspire curiosity and learning among its players.

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Appendix A: Interview responses

A1 Marc ten Bosch's Interview

1. **Who are you, and what game are you developing using the concept of the four spatial dimensions?**

   I'm an Indie game developer that has been working on Miegakure since 2013 and 4D Toys since 2017. I come from studying computer science, and doing a Masters in computer science and engineering. At the moment I am working on the development of Miegakure with a team, me programming and designing, and a group of people helping me with the art and audio of the game. On 4D Toys I am working on updates alone.

2. **How would you describe your game?**

   Miegakure is a puzzle adventure game inspired by Sokoban. The puzzles consist of playing with the fourth dimension to push blocks which allow you to jump on them to discover new locations. The art is realistic, which is set in feudal Japan. Each level is contained in a region of the world so the player doesn't get lost.

   Whereas, 4D Toys is more like an interactive playground where the player experiments with the environment.

3. **What software did you use for this development? (Engine, modeling, version management)**

   I developed both games with a custom engine that works with 4D, I have developed 3D engines before, so when I discovered the topic I adapted my engine to fit with the 4D math, position having 4 numbers, rotation having 4 numbers, everything just has one more number. Collision detection is also similar to the one in a 3D engine, just check for another dimension where the objects can collide. To render the representation of the 4D world I like to use slicing because it fits much better the videogame application, it's easier to

visualize. For the shapes I don't use any modeling software, it's all done by scripting. If a regular engine divides a mesh in triangles to render the object, I divide the 4D mesh in 3D tetrahedra, depending on the slice the player is, and once I have the new mesh I render it as if it was a regular 3D mesh.

4. **What inspired you to create a video game that incorporates four spatial dimensions?**

   I always wanted to develop games and I saw that my strength wasn't the art, so I started coding. I wanted to use video games as a way to explore new worlds that we could not interact with in real life. I want to make worlds that can be traversed.

   I started thinking about the concept of having more than 3 dimensions, and when the Experimental Gameplay Workshop on the GDC launched I decided to make a game applying the concept of Slicing a 4D world as seen in the book Flatland. That's when Miegakure development started.

5. **How does the addition of a fourth spatial dimension change the gameplay experience for players?**

   It is the Core of the game, it is what makes it special, it is like in Portal, everything is about portals, moving through portals, using portals, solving puzzles with portals. The user goes from a completely new concept to learn what it is, how it works, and how to use it to your advantage. In Miegakure, the player experiences the same learning path but with the concept of 4D.

6. **Are there any unique challenges that arise when designing and developing a four-dimensional video game?**

   The main difficulty when developing 4D games is not the representation of the 4D world in a 3D space, or the math behind all the engine. It is, making the game look pretty and understandable at the same time, finding that balance takes

time and trial and error, because the more understandable the game you want to make, the simpler the art has to be, that's why in 4D Toys everything is a simple geometry and with flat colors, so the player has it easier to understand the 4D world.

7. **How did you approach designing the game's user interface to accommodate for an additional dimension?**

   For Miegakure I wanted the game to be very minimalistic, because the input is a controller, I don't think that there is a need for having a visual UI that displays information to the player.

8. **Can you walk me through the game mechanics and how they differ from traditional three-dimensional games?**

   The player has an extra dimension where it can find blocks to push and solve the puzzle, or enter a closed building because in a certain combination of the dimensions the building isn't closed. Miegakure could just be a puzzle game in 3D but it would be boring without any new mechanics that distinguish the gameplay.

9. **How did you create the game's graphics and environments to visually represent four spatial dimensions?**

   In scripting you divide any 4D shape in the simplest 3D shape there is, a tetrahedra, and having this new mesh we just have to render the triangles of the slice that the player sees from the 3D submesh. It's just adding a new dimension to the process that works for the representation of a 3D shape on a screen.

10. **Are there any specific mathematical concepts or theories that influenced the game's development?**

    Yes, the 4 dimensional space theory, and specifically, the Slicing visualization, it's the one explained in the novel Flatland.

11. **How did you balance accessibility for players with the added complexity of a fourth dimension?**

    You have to start simple and increase the complexity of the topic slowly, if a player gets lost due to the concept being complex and not having acquired the knowledge of how the world works, it will get frustrated and abandon the game. Don't rush the evolution of difficulty.

12. **Can you describe any playtesting or feedback you received during the development process and how it influenced the game's design?**

    People are excited to try a new concept of video game, so they start the playtest with a good opinion to begin with. First they start doing things without understanding what they are doing, then they try to predict how the world will behave to see if they understand how 4D works, in the end once the knowledge is acquired, they start using in their advantage the mechanics of the game with a clear intention.

    It mainly affected the evolution of difficulty. I had to change levels because people got stuck for not understanding the 4D, or had to change the order of levels because how they see the game is really different from the developer view point.

    There are also people that inherently understand the concept of the 4D with ease, I don't know why but there are some cases that with 5 minutes of playing they knew how to use the 4D perfectly.

13. **Do you see the development of four-dimensional video games as a potential trend in the industry, and if so, how do you think it could impact the future of game development?**

    I don't plan to make 4D games for the rest of my life, but I see the community getting bigger, there will be new people interested in playing 4D games and people interested in making them. I just want that Miegakure helps people understand the 4D concept while they have fun solving puzzles. I am not that interested in the evolution of video games that explore specifically the 4D, but I want to see more games exploring mathematical concepts that can only be interacted with in the video game format.

14. **Do you have any tips for my development of a 4D game?**

    Playtest a lot, the main objective is that the player understands how the 4D works so they end up having fun when solving the puzzles because the difficulty should be in the puzzles not in the gameplay.

A2 CodeParade's Interview

1. **Who are you, and what game are you developing using the concept of the four spatial dimensions?**

   I am Kevin and I run the Code Parade youtube challenge. I've done programming and video game development since a young age. My degree is in computer science and electrical engineering, a combined major at UC Berkeley, most of the non conventional math is self taught.

   I was working as a software engineer but now I've been doing full time game development since the launch of Hyperbolica, the game that uses a non-euclidean curved space. I've always been passionate about machine learning, robotics and computer vision, so I decided to open a youtube channel. That helped me to change to full time game development, because with the youtube channel I had free marketing with the devlogs, and a public that was interested in my games.

   Now I'm currently developing 4D Golf, and have some dev logs on my youtube channel where I talk about how it works and interesting things about the game.

2. **How would you describe your game?**

   4D golf is just a video game where you play minigolf in a 4D world, with 4D golf courses. You have full control of the 4 dimensions, you can explore, I am developing some new game modes and also a level editor where you can build your own courses

3. **What software did you use for this development? (Engine, modeling, version management)**

   I use Unity as the game engine for 4D golf because when working with complex topics like this it's better to use the tools that already exist and focus on the new things that you have to develop by yourself. So basically, I use a version of Unity where I overwrite some parts of the engine with my custom tools. For the

modeling of the objects, I combine the generation of procedural meshes by scripting and Miratope, a 4D software that allows you to create regular polytopes and export them in .off file format, then with a custom parser I extract the data from the file and generate the polygons in Unity.

For version control I mainly use Git and Github.

4. **What inspired you to create a video game that incorporates four spatial dimensions?**

   When working on hyperbolic, people told me and I wanted to develop a 4d but it would take me much time, and I spent a week making a demo and I decided to make a game different to the other games. More first person game.

   When I was working on Hyperbolica, people told me to do a 4D game, and I started researching about it, I wanted to develop a video game that used 4D but I knew it would take me a lot of time, so I spent a week making a prototype. My idea was to make something different from all the other games that explore the visualization with the slicing representation, and I wanted the player to feel how a 4D entity would travel through the 4D world. So I combined the Slicing with the Projection visualization method. Also I wanted to make it first person, because there wasn't any 4D first person game at that time. So I found that niche I wanted to fill.

5. **How does the addition of a fourth spatial dimension change the gameplay experience for players?**

   It makes the player think in a different way, trying to understand how 4D works makes you use a different part of your brain. Talking specifically about 4D Golf, it adds fun new challenges and interactions to golf.

6. **Are there any unique challenges that arise when designing and developing a four-dimensional video game?**

   Level design challenge, much more controls for the player, extra keys,

   When developing with 4D feels like working with building blocks, you start doing something, but it's too difficult, so you have to break it down into simpler steps, or even change the order of the tools you are developing, when you develop the tools the game goes on its own.

   In the design section, the most difficult would be the level design, you need to teach the player so many controls, the camera has 2 degrees of freedom more, use more keys to explore the world. And doing so in an intrinsic way, without using a regular tutorial with text boxes it's a great challenge.

7. **How did you approach designing the game's user interface to accommodate for an additional dimension?**

   The UI has gone through many iterations, but I don't think that it's that important. I use it as a compass so the player has a reference point if it gets lost, but I want that the experience is what gives the feedback, not a regular UI. Also, the controls do not differ much from a regular 3D first person experience, it just has two more keys to move in the W axis, two more to rotate, and some keys to reset the orientation if the player gets lost.

8. **Can you walk me through the game mechanics and how they differ from traditional three-dimensional games?**

   If you compare a regular 3D minigolf video game with 4D Golf the player has to use in its advantage, plan and predict how the obstacles will behave and how to move through the environment.

9. **How did you create the game's graphics and environments to visually represent four spatial dimensions?**

   I have parameters and need a track piece and it will give you the piece tha you need,

   It's all done by scripting,

10. **Are there any specific mathematical concepts or theories that influenced the game's development?**

    Of course, the fourth dimensional theory, I would say that understanding both methods of visualization of the 4D world helped me a lot in the development of my game, and making it look pretty at the same time.

11. **How did you balance accessibility for players with the added complexity of a fourth dimension?**

    In golf the player can't lose, so even if a new player doesn't understand how the 4D works, it can progress through the game by trial and error, that's why I think that it's really accessible. And if someone wants to understand the 4D they can use the knowledge to their advantage.

12. **Can you describe any playtesting or feedback you received during the development process and how it influenced the game's design?**

    I've done a very small session of playtest, but I mainly focused on that the game was fun and that was appealing to people that don't have a big math background and do not have much experience with video games. They did give me feedback, but because the playtest was so early in the development process, people told me things that I was already working on, or that I knew I would implement in the future.

13. **Do you see the development of four-dimensional video games as a potential trend in the industry, and if so, how do you think it could impact the future of game development?**

    I don't really know how this trend will evolve, I think it's a unexplored mechanic in games that has much potential, but I think that the main problem is that the 4D doesn't work well with many genres, like a first person shooter, because the complexity that the new controls bring can make very difficult the integration of new people to the game. Maybe it sees more traction in the VR market, because having two controllers with 3 degrees of freedom each and the depth perception with the glasses, I think that many people would prefer a game like that.

14. **Do you have any tips for my development of a 4D game?**

    My tip for you is that if you aren't focusing on developing the engine for making a 4D, take advantage of the existing commercial engines and the tools that the community gives you, because it's already hard enough to develop a 4D game, to do it in an an engine with bad documentation and not many help can be frustrating.

Appendix B: Realm Paradox Screenshots:

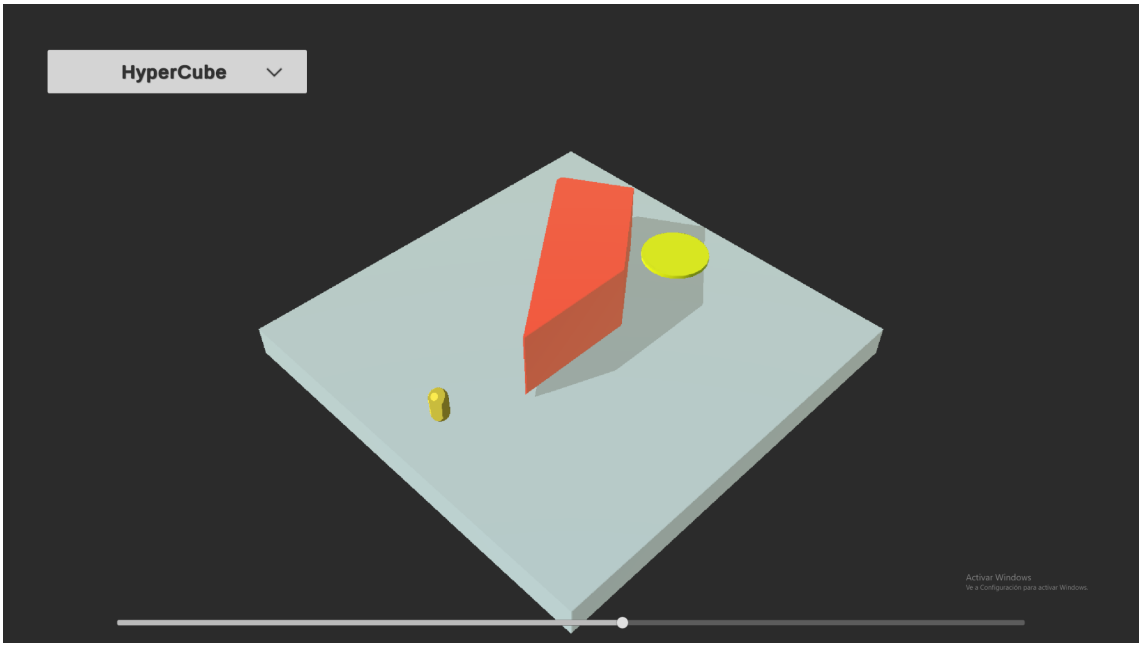

Figure B1: Player playing Playground level

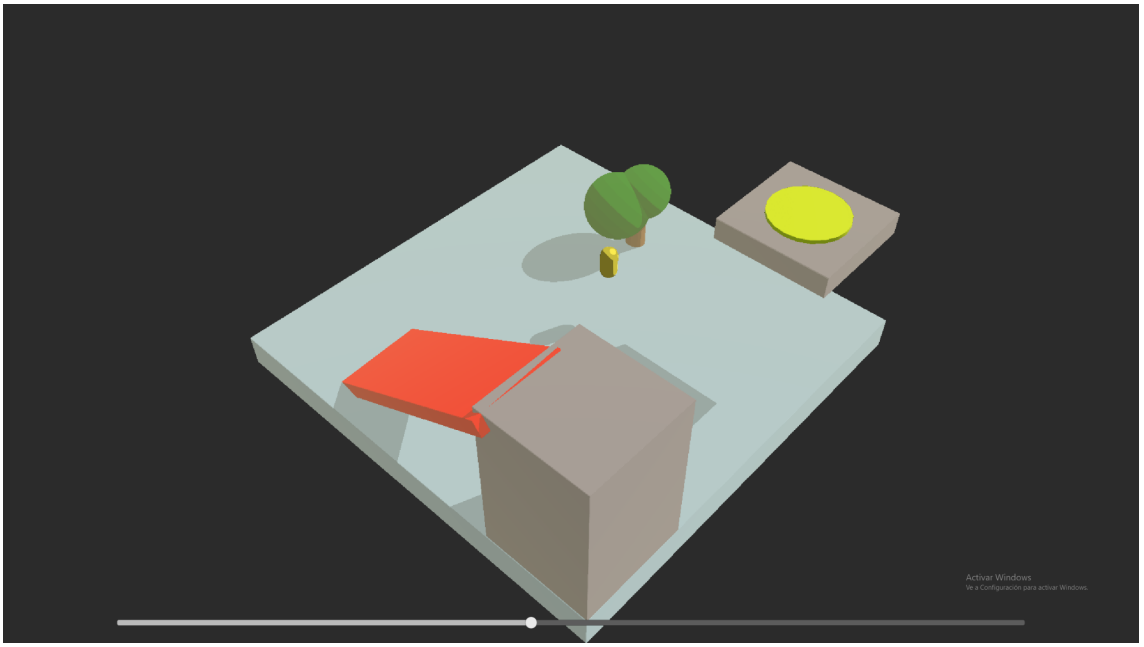

Figure B2: Player playing Level 1

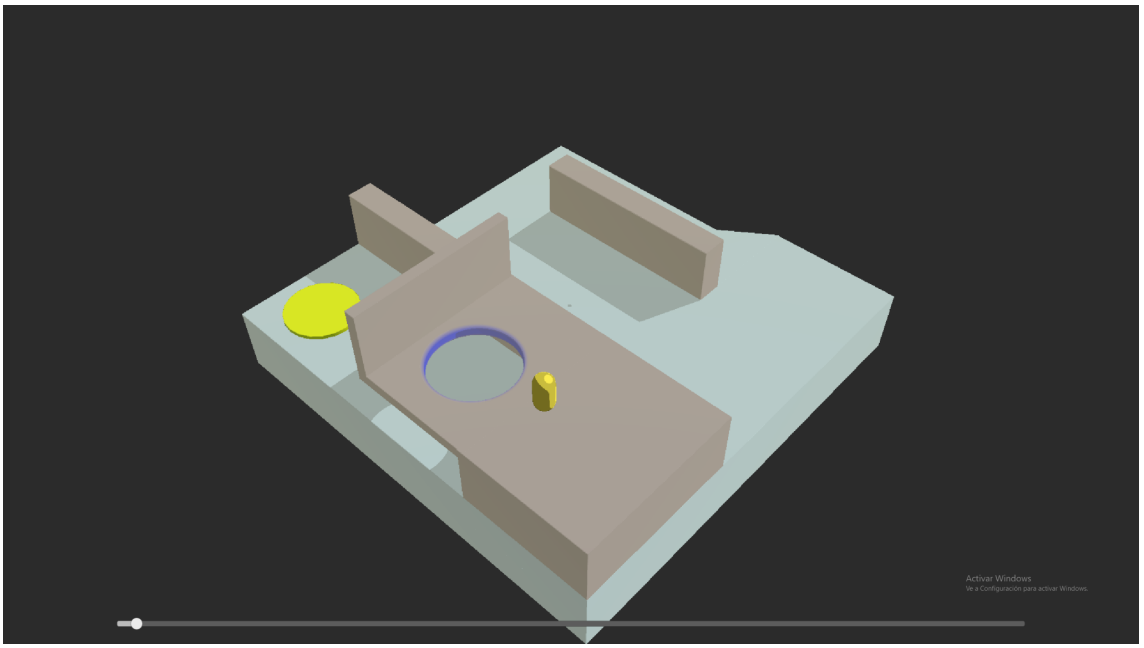

Figure B3: Player playing Level 2

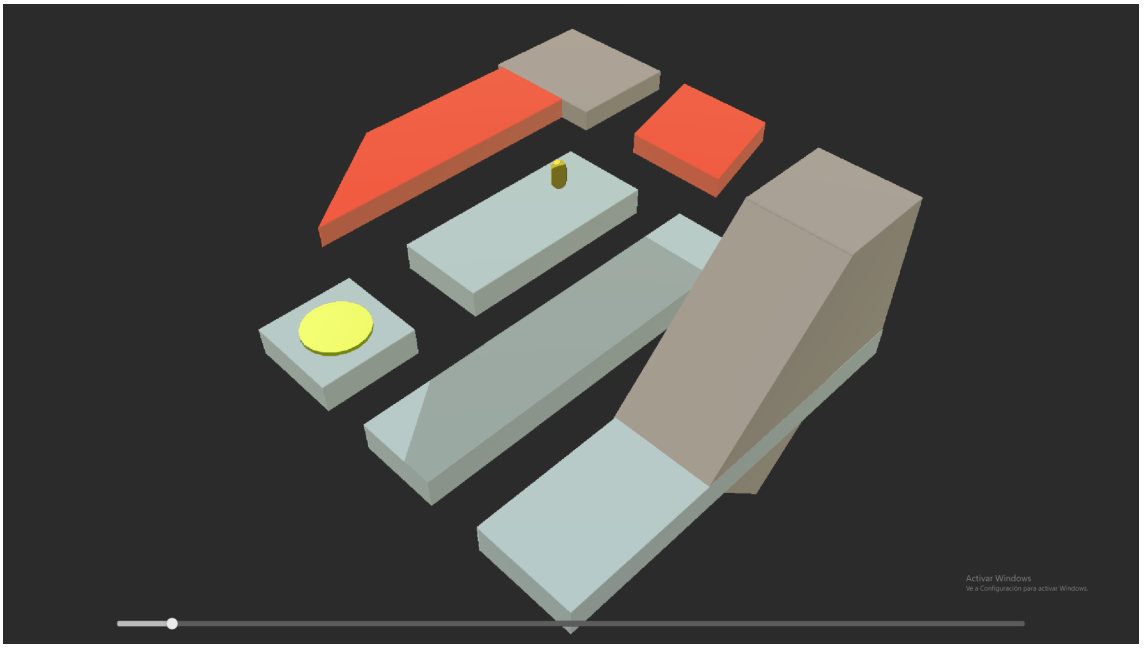

Figure B4: Player playing Level 3

Appendix C: Playtesting survey questions

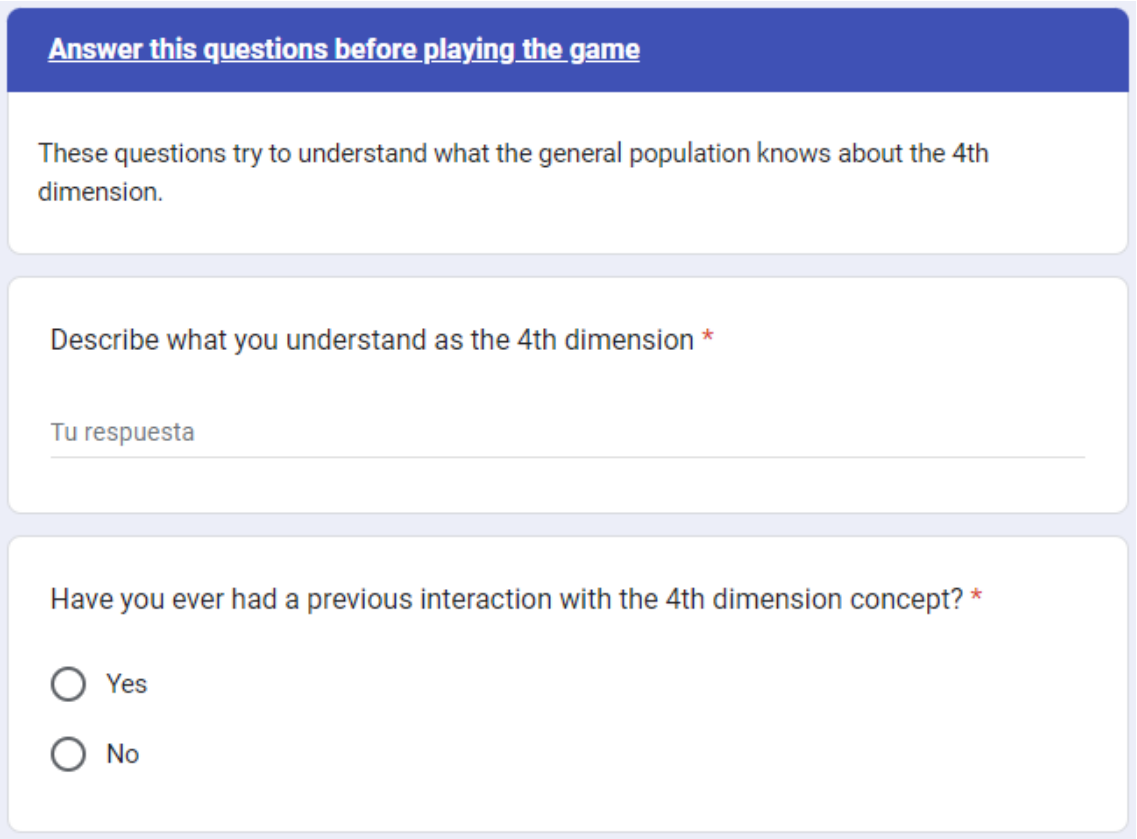

Figure C1: Questions from the playtesting survey #1

Play Realm Paradox and then answer these questions

Execute the Realm Paradox application and enjoy the game session.
For a better understanding of the 4th dimension concept, watch the explanation that is in the menu of the game.
Look up the Controls menu to understand how to play.

Did you understand the concept of the 4th dimension differently from what you previously knew? *

- ◯ Yes
- ◯ No

Did you have any problem with the 4th dimensional shapes and how they interacted with the environment? *

- ◯ Yes
- ◯ No

What problem have you encountered?

Tu respuesta

Did the integration of the 4th dimension feel natural and non-intrusive? *

- ◯ Yes
- ◯ No

Figure C2: Questions from the playtesting survey #2

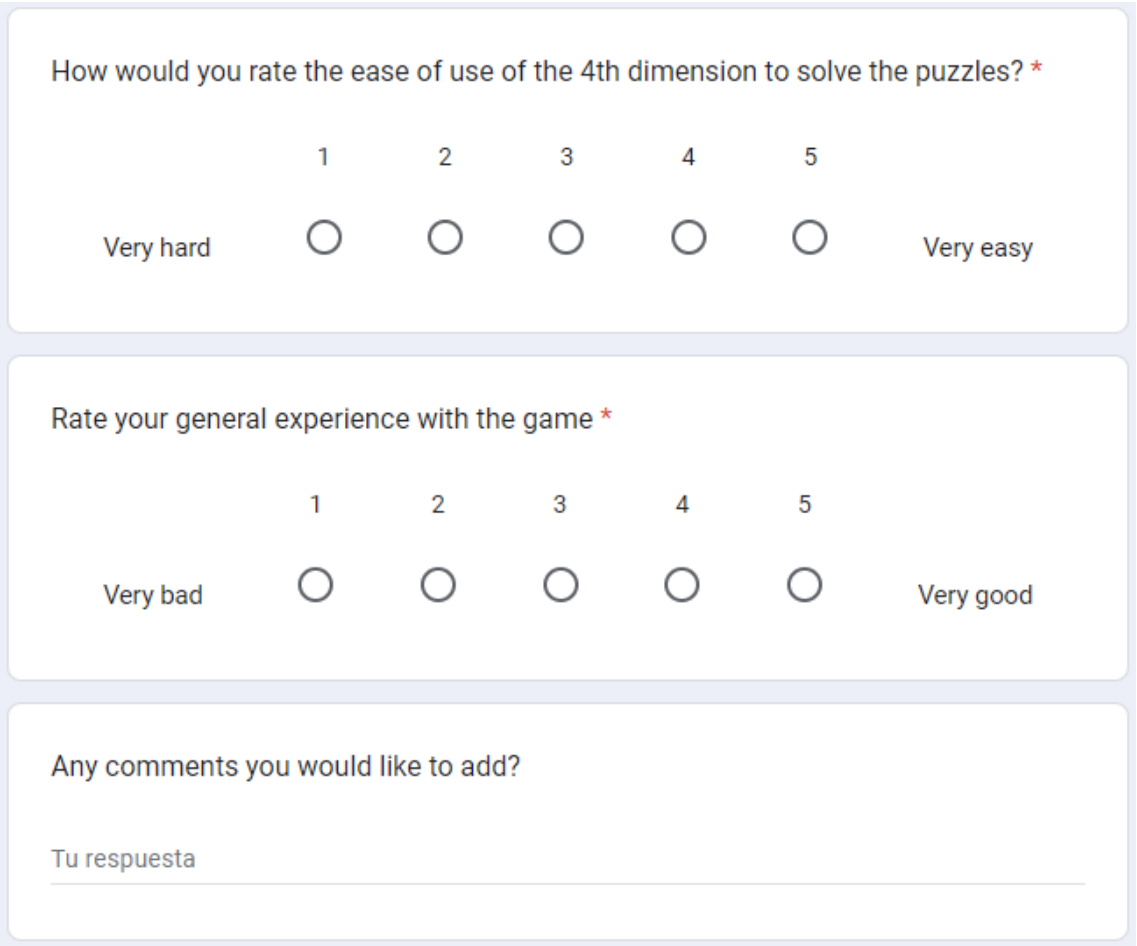

Figure C3: Questions from the playtesting survey #3