Walk Me Through It: Using Impossible Spaces to Embody Graph Traversal Algorithms

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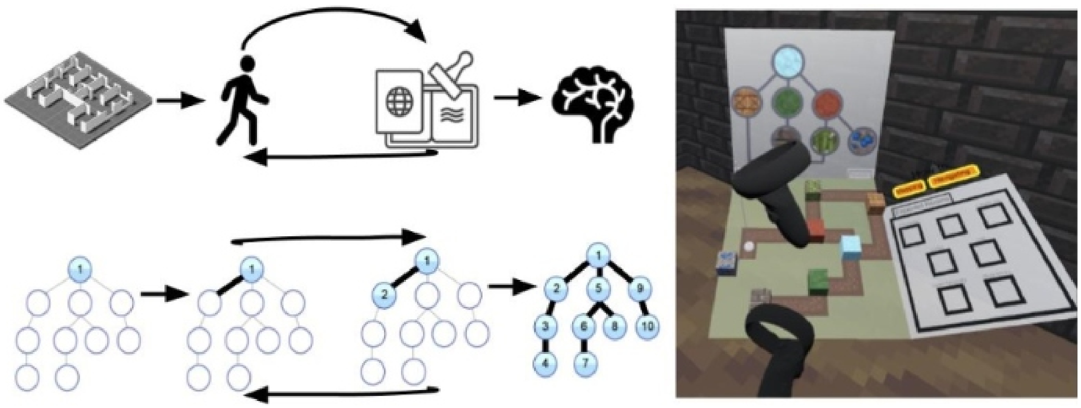

Figure 1: Through this guided walk-through experience, users can ”walk in the shoes” of a graph traversal algorithm by exploring a graph layout designed with Impossible Spaces. Users collect Tokens from each room, like stamps on a passport, in order to construct a map of the layout as a way of enriching their conceptual understanding of graph traversal algorithms.

Abstract

When faced with learning new algorithms, students often struggle with recognizing the details of the algorithm or with understanding the meaning of its intermediate stages and interpreting the results. These difficulties typically stem from the inherent inadequacies of using static representations to describe dynamic systems. We have developed the guided walk-through experience, *Walk Me Through It*, as a way for users to, not only visualize but interact, with every stage of common graph traversal algorithms, Breadth-First Search and Depth-First Search. Users must construct their own map of the room layout and connections between them by collecting room Tokens as they navigate the maze implemented with Flexible Spaces.

Index Terms: Human-centered computing—Human computer interaction (HCI)—Interaction paradigms—Virtual reality;

1 Introduction

Graph Theory, the study of the mathematical structures representing connections between a set of points defined by vertices and edges, is a key topic in any discrete mathematics course. Discrete mathematics provides the mathematical foundation for computing, and is often a compulsory course for anyone pursuing a computer science degree. For instance, graphs have a variety of applications across computing like data mining, image capturing, and path planning in robotics. When learning fundamental graph traversal algorithms, such as Breadth-First Search (BFS) and Depth-First Search (DFS), students are given an image depicting the entire graph. Often, students struggle with recognizing the details of the algorithm or with understanding the meaning of its intermediate stages and interpreting the results [1]. These difficulties typically stem from the inherent inadequacies of using static images to describe dynamic systems.

Virtual reality (VR) systems can transcend these shortcomings by providing an immersive, embodied learning experience. These systems create dynamic experiences by providing visual, auditory, vestibular, and tactile sensory feedback to the user. Thus, users are able to not only observe, but to directly interact with the virtual environment (VE), resulting in higher levels of engagement [2]. Interactivity paired with guided activity presents a powerful tool for supporting user reflection and sustained conceptual understanding by allowing the user to reflect on their actions within the virtual environment [3]. Embodiment can both ground abstract ideas and provoke a more flexible understanding of core concepts [6]. Additionally, embodied VR experiences, where the user has a virtual body mirroring their motion, further amplify learning [4].

The *Walk Me Through It* experience deploys key elements of both interactivity and embodiment to allow users to “walk in the shoes” of a graph traversal algorithm by placing them in a collection of rooms and hallways analogous to a graph. This guided walk-through interactively introduces the concepts and heuristics of BFS and DFS algorithms by tasking the user with collecting Tokens to build a map of its traversal. Through natural walking and redirection with flexible Spaces [7], users explore the graph by walking between the vertices, represented by rooms, and the edges, represented by hallways. The map the user builds tracks the rooms that have been visited and the user’s understanding of their connections to each other. The user collects a token from each new room which represents it on the map, similar to passports receiving a stamp whenever someone enters a new country. Users can keep track of the relationships between the rooms by drawing paths, or connections, between rooms on the map. By comparing the constructed map of explored rooms with the static image of the graph, we aim to enhance users’ understanding of the intermediate stages of BFS and DFS.

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2 Background

When navigating a new environment, whether it be physical or virtual, people often resort to using landmarks to remember their position and orientation. Landmarks are defined as distinctive environmental features that function as reference points for when and where navigational actions should be taken, thus contributing to the development of one's spatial knowledge of the environment [8]. This spatial knowledge forms the cognitive map, a mental model of the spatial layout. However, these models are not perfect representations of the layout due to spatial distortions. Cognitive maps are actually categorical, hierarchical structures that are highly biased by environmental features [9].

Since cognitive maps mostly rely on environmental landmarks, the purpose of the VE does not have to depend on its spatial layout therefore allowing the use of Flexible Spaces, a subset of Impossible Spaces [5]. Impossible Spaces introduced VEs with overlapping architecture to compress larger architectural layouts into smaller physical spaces. Flexible Spaces builds upon this by using procedurally generated corridors that have the user believe that they are walking in a single bidirectional hallway between two rooms when really they navigated to the next room using one route and were able to return using another. By keeping the user's view consistent as they navigate the twisting corridors between rooms, it is possible to manipulate the architecture of the VE to be self-overlapping without the user noticing. While detailed spatial knowledge such as navigational actions are useful, they are not essential. Thus, users need to rely on the relationships of the landmarks themselves, rather than the paths between them. Shifting the responsibility of providing orientation cues to the VE and its landmarks allows the user to focus more attention on the contents of the VE. Our constructible map interface provides the user with a method of remembering spatial orientation information that focuses on the relationships of landmarks, the Flexible Space rooms, to other landmarks by having the user build it for themselves.

3 Implementation

The user enters the experience in the middle of a maze and must find the exit. The maze is laid out according to a developer-specified graph. They must explore the maze in order to gain an understanding of the layout and the many rooms it holds. In order to accomplish this, users must construct a map of the maze by placing the tokens retrieved from each room and charting the connections between them through the Map Interface. Acquiring more tokens causes its room to appear in the Exploration Log, the list of all the rooms that have been explored, allowing the user to easily track what rooms have and have yet to be visited. Users will continue "wandering" the space following the highlighted path until the final room, representing the goal node of the graph search, is reached. In the final room, the user must determine what kind of traversal algorithm was walked and answer the prompt, deciding between BFS and DFS. They must use the map that they have been creating of the maze's rooms and their relationships with each other in order to determine the type of traversal by comparing it with the Overlay, a static image of the complete graph structure

3.1 Map Interface

The bimanual interface places the Map in the user's non-dominant hand (the Map hand) and the cursor to manipulate the objects on the Map in the user's dominant hand (the Cursor hand). The Map's visibility is toggled by holding the trigger on the Map hand. The scaling of the Map can be adjusted by using the joystick on the Map hand and its viewing angle can be adjusted by rotating the Map hand. In addition, the user also sees the Overlay image and the Exploration Log as attachments to the Map.

When the user walks into a new room, the room's Token will float towards them to signal that a new entry in the Exploration Log has been created. The next time the Map is toggled, the user can grab the Token from the Exploration Log and place it on the Map by holding the Cursor trigger. The Token is placed in the desired spot if the spot is unoccupied when the Cursor trigger is released. Users can see a preview of the Token's placement prior to placing it. Draw paths to connect Tokens by holding either button on the Cursor hand and dragging the Cursor in the desired direction. Paths must start and end on a Token in order to be valid, these paths will remain visible upon releasing the Cursor trigger. Users can delete a specific path they had previously made by hovering over it and pressing the Cursor trigger twice. All paths connected to a Token can be deleted at once by picking it up.

3.2 System Specifications

This experience was developed for the Oculus Quest in Godot 4.2.1 using the OpenXR plugin for compatibility with all consumer headsets. It was developed on an HP Omen X with an Intel Core i7-7820HK, an NVIDIA GeForce GTX 1080, and a Windows 10 operating system. The tracking space dimensions were 6m x 6m. The environment textures are from the Pixel Perfection Community Edition Minecraft resource pack originally published by XSSheep and the Xbox360 Pixel Art Controller Icons are from Open Game Art.

4 Conclusion

Leveraging a Flexible Space design, the relationships between landmarks in navigation can be used to create a dynamic explanation of the popular graph traversal algorithms BFS and DFS. The *Walk Me Through It* experience has users create a reference map of the VE's layout as they virtually walk through a graph in search of the goal node. By fully immersing the user in the mechanics of these algorithms through embodiment, we aim to enhance their understanding of the intermediate stage and results of graph traversals.

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