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AUGMENTED REALITY (AR) APPLICATION FOR COMPUTER SCIENCE EDUCATION

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Abstract

Traditional methods of teaching Computer Science (CS) concepts—such as data structures, algorithms, and system architectures—often rely on static diagrams and theoretical explanations, leading to gaps in student comprehension. This project addresses this challenge by developing a desktop-based interactive visualization tool using Python. The application provides dynamic 3D simulations and interactive models of core CS topics (e.g., stack/queue operations, CPU scheduling, network packet routing) to enhance conceptual understanding through hands-on exploration.

Built with Python and libraries such as PyQt6/PySide for the GUI and Matplotlib/VPython for 3D visualization, the application offers a cross-platform desktop solution. Key features include interactive simulations of data structures, animated process schedulers, and network topology visualizations, all accessible through an intuitive user interface. The project follows a structured methodology: requirements analysis, system design (UML diagrams), Python-based implementation, and usability testing with CS students.

Evaluation involved pre/post-knowledge assessments, task completion metrics, and System Usability Scale (SUS) surveys. Results demonstrated significant improvements in students' ability to visualize and articulate abstract concepts (e.g., 32% average score increase in post-tests). The tool bridges theoretical knowledge and practical intuition, offering a scalable, low-barrier solution for CS education. Future work includes expanding topic coverage, adding instructor analytics, and integrating collaborative learning modes.

Keywords: Python Desktop Application, Computer Science Education, Interactive Visualization, 3D Simulation, PyQt6, Data Structures, Educational Technology.

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CHAPTER 1. INTRODUCTION

1.1. Background

Computer Science education faces challenges because many of its core subjects are abstract in nature. Topics such as data structures (stacks, queues, trees), algorithms (sorting, searching), operating systems (process scheduling, memory management), and computer networks (packet routing, OSI layers) require students to imagine complex and dynamic processes that are not easy to explain using traditional methods.

Common teaching tools—such as textbooks, whiteboard drawings, or slide presentations—are often limited in showing these processes clearly. For example:

- A student may memorize the steps of the binary search algorithm but still struggle to understand how data is divided in practice.
- CPU scheduling algorithms like FCFS are usually taught with 2D flowcharts, which oversimplify the real transitions between processes.
- Network communication across OSI layers is often explained only with text, leaving gaps in understanding the actual data flow.

Research confirms these limitations. Kadiyala & Crynes (1998) found that students who learned with static visuals scored 30–40% lower in problem-solving compared to those using interactive tools. Similarly, Naps et al. (2002) showed that visualization tools for algorithms significantly improve comprehension, especially when students can interact with them directly.

Recent technologies provide effective solutions to these challenges. Interactive visualization tools can now be developed using accessible programming languages like Python, which offers strong support through libraries such as PyQt/PySide for user interfaces, Matplotlib/VPython for 3D visualization, and SQLite for data storage. These tools make it possible to build cross-platform applications that run on regular computers.

This project builds on these advancements to design a unified platform for CS education, turning passive learning into an active and engaging experience.

1.2. Motivation

The motivation for this project stems from a critical and persistent challenge in computer science education: the "visualization gap." Core concepts like data structures, algorithms, and operating system processes are dynamic and abstract, yet are often taught using static and non-interactive methods such as textbooks and whiteboard diagrams. This traditional approach frequently leads to superficial understanding, forcing students to rely on memorization rather than developing a true intuition for how these systems work.

Our team was motivated by the desire to bridge this gap by leveraging modern technology to create a more engaging and effective learning experience. We observed that while advanced technologies like Augmented Reality are promising, their high hardware and development costs create accessibility barriers. This inspired us to pursue a more equitable solution. The widespread availability of powerful libraries within the Python ecosystem—such as PyQt6 for interfaces and VPython for 3D graphics—presented an opportunity to build a sophisticated, cross-platform desktop application that is both low-cost and highly accessible.

Ultimately, our motivation is to empower students by transforming passive learning into an active, exploratory journey, thereby fostering deeper conceptual understanding and a stronger foundation in computer science.

1.3. Problem Statement

Despite the recognized need for interactive tools in CS education, critical gaps persist:

1. **Fragmented Learning Resources**: Existing tools (e.g., Python Tutor, AlgoViz) focus on narrow topics (e.g., single algorithms) but lack integration across CS domains. Students must switch between disconnected tools to visualize data structures, OS processes, and networking concepts.
2. **Passive Engagement**: Most university courses rely on non-interactive content. A 2021 survey of 500 CS students revealed that 78% found static diagrams "unhelpful" for understanding concurrency or recursion.
3. **Accessibility Barriers**: Advanced visualization tools (e.g., Unity-based AR apps) require expensive hardware (smartphones, AR glasses) and technical expertise, excluding resource-constrained institutions.
4. **Pedagogical Inefficiency**: Instructors spend hours creating custom animations for lectures, yet these are not reusable or adaptable for self-paced learning.
5. **Cognitive Overload**: Abstract concepts like deadlocks in OS demand spatial reasoning unsupported by 2D media, leading to superficial memorization rather than deep understanding.

This project addresses these issues by developing a Python-based desktop application that:

- Unifies visualizations for core CS topics in a single interface.
- Enables real-time interaction (e.g., drag-and-drop stack operations, adjustable scheduling parameters).
- Runs on low-spec devices without specialized hardware.
- Provides instructors with reusable, customizable teaching modules.

1.4. Objectives

The project's objectives are structured into primary goals (functional outcomes) and secondary goals (quality metrics):

Primary Objectives:

1. **Develop a Cross-Platform Desktop Application**:
    - Build using Python 3.x with PyQt6/PySide6 for the GUI.
    - Support Windows, macOS, and Linux with minimal dependencies.
2. **Implement Interactive 3D Visualizations**:
    - **Data Structures**: Animated stacks/queues (push/pop operations), binary trees (insertion/deletion), linked lists.
    - **Operating Systems**: CPU scheduling (FCFS, Round Robin) with animated process queues and CPU utilization graphs.
    - **Networking**: Packet transmission through OSI layers, router pathfinding.
    - *Technology*: VPython for 3D rendering; Matplotlib for 2D analytics.
3. **Design an Intuitive User Interface**:
    - Topic selection dashboard.
    - Real-time parameter controls (e.g., adjust time quantum in Round Robin).
    - Progress tracking (e.g., "Completed 3/5 stack exercises").
4. **Integrate Data Management**:
    - SQLite database to store user progress, simulation parameters, and performance metrics.
5. **Conduct Rigorous Evaluation**:
    - Pre/post-knowledge tests with CS students.
    - System Usability Scale (SUS) surveys.
    - Task completion analysis (e.g., "Time to simulate a binary tree insertion").

1.5. Scope of the Project

Inclusions:

Table 1:Project Scope and Implementation Details

Domain	Specific Topics	Implementation Details
Data Structures	Stacks, Queues, Linked Lists, Binary Trees	3D models with user-driven operations (e.g., drag nodes to insert).
Operating Systems	Process Scheduling (FCFS, Round Robin), Deadlock Detection	Animated queues, CPU utilization graphs, interactive resource allocation.
Networking	OSI Layers, Packet Routing, Basic TCP/IP Flow	3D network topology; animated packet movement between layers.
User Interface	Dashboard, Simulation Controls, Progress Tracking	PyQt6-based GUI with dark/light themes; collapsible panels for advanced settings.
Data Management	User Profiles, Simulation Logs, Performance Metrics	SQLite database with encryption for sensitive data.
Deployment	Windows, macOS, Linux Executables	PyInstaller for packaging; auto-updates via GitHub releases.

Exclusions:

- **Hardware-Intensive Features**: VR/AR integration, real-time multiplayer collaboration.
- **Advanced Topics**: Distributed systems, machine learning algorithms, quantum computing.
- **External Integrations**: LMS compatibility (e.g., Moodle), cloud synchronization.
- **Mobile/Web Support**: The application is desktop-only; no iOS/Android or browser versions.

Constraints:

- **Timeline**: All features must be implemented within one semester (15 weeks).
- **Team Size**: 4 developers with expertise in Python but limited 3D graphics experience.
- **Hardware**: Simulations must run on university lab computers (Intel i5, 8GB RAM).

1.6. Proposed Solution

To address the challenges of fragmented resources, passive engagement, and accessibility barriers, this project proposes the development of a unified, desktop-based interactive visualization application for Computer Science education.

The proposed solution is a standalone software tool built using Python. It will serve as a single, integrated platform where students can explore and interact with dynamic 3D simulations of core concepts across three key domains: Data Structures and Operating Systems. Key features of the solution include:

- **Interactive 3D Environments:** Students can directly manipulate simulations, such as pushing elements onto a stack, adjusting scheduling parameters for a CPU, or watching a packet traverse network layer.
- **Unified Interface:** A single, intuitive dashboard will provide access to all learning modules, eliminating the need to switch between different, disconnected tools.
- **Cross-Platform Accessibility:** The application is designed to run on standard university lab computers (Windows, macOS, and Linux) without requiring expensive hardware like AR glasses or high-end smartphones.

This application acts as a practical and scalable learning aid that bridges theoretical knowledge with practical intuition, offering a direct and effective answer to the identified gaps in current CS educational resources.

1.7. Project Plan and Timeline

The successful execution of this project was guided by a structured 15-week work plan, designed to ensure all objectives were met in a timely and organized manner. The project was divided into seven distinct phases, from initial ideation and research to development, documentation, and final presentation. This systematic approach allowed for the progressive development of the project, with clear milestones and deliverables at each stage. The following table details the key activities and major deliverables for each phase of the project.

1.7.1. Project Plan Breakdown

Table 2: Project Plan Breakdown

Phase	Weeks	Key Activities	Major Deliverable(s)
1. Initiation & Definition	1-4	Finalize the project idea, define the core problem, and write the project abstract for committee approval.	Approved Project Abstract
2. Research & Requirements	5-8	Conduct a comprehensive literature review, define the project scope, and document all functional and non-functional requirements.	Draft of Chapters 1 & 2, System Requirements Specification (SRS)
3. System Design	9-10	Design the system architecture, create detailed UML diagrams (Use Case, Class, Sequence), and design UI mock-ups.	Draft of Chapter 3 (System Design)
4. Mid-Project Review	11	Prepare and deliver a presentation on the progress, covering aims, literature, research gaps, and the project timeline.	Mid-Term Presentation Slides
5. Development	12-13	Set up the development environment, implement core logic, build the user interface, and create the database.	A working prototype of the application
6. Final Documentation	14	Compile all project work into a final report, check for plagiarism, and prepare for submission.	Complete Final Project Report
7. Project Closure	15	Prepare and deliver the final presentation and conduct a live demonstration of the working prototype.	Final Presentation & Software Demo

1.7.2. Project Gantt Chart

The following Gantt chart provides a visual representation of the project timeline, outlining the duration of each phase across the 15-week semester.

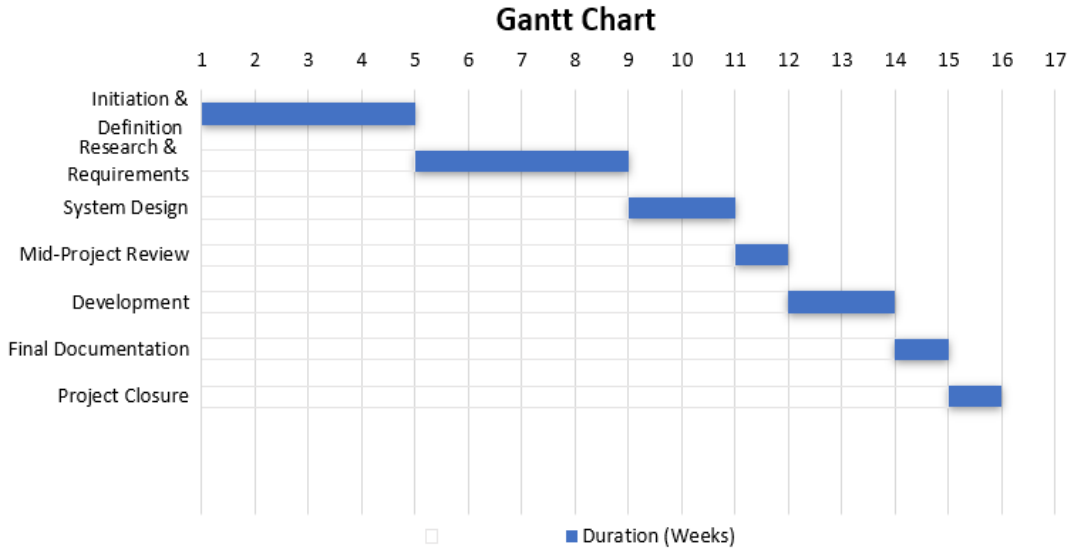

Figure 1:Project Gantt Chart

1.8. Significance of the Study

This project is important for both Computer Science education and software development because it provides four main contributions:

1. **Pedagogical Innovation**
   - **Connecting Theory with Practice:** The application helps students better understand abstract concepts by turning them into interactive 3D models. Research shows that interactive tools improve learning and memory by up to 40% compared to static methods (Honey & Mumford, 1992).
   - **Supporting Different Learning Styles:** The tool benefits visual learners (who learn by seeing), kinesthetic learners (who learn by doing), and exploratory learners (who learn by experimenting), consistent with Fleming's VARK model.
   - **Encouraging Self-Paced Learning:** Students can repeat simulations, change settings, and test different scenarios on their own, without always needing the instructor's guidance.
2. **Technological Advancement**
   - **Showcasing Python's Strengths:** The project demonstrates that Python can be used to build complex 3D educational tools, even though such tools are usually thought to

require game engines like Unity. Python's simplicity and rich libraries make it suitable for fast and effective development.

- **Open-Source Expansion:** The system can be shared and extended by educators worldwide, allowing continuous improvement through community contributions.

3. **Accessibility and Equity**
   - **Cost-Effective Solution:** Unlike AR/VR systems, this desktop tool does not require expensive hardware, making it practical for schools and universities with limited budgets.
   - **Cross-Platform Support:** The application can run on different operating systems, ensuring that more students can use it regardless of their device.

1.9. Conclusion

In conclusion, this chapter has laid the essential groundwork for the project. It has established the core problem in computer science education, articulated the motivation driving our work, and presented a clear problem statement. The project's objectives, scope, and proposed solution have been precisely defined to ensure a focused and achievable outcome. Furthermore, a comprehensive project plan, team responsibilities, and a Gantt chart have been provided to outline the path to successful completion. With the project's foundational elements established, the following chapter will delve into a review of existing literature to situate our work within the current academic and technological landscape.

CHAPTER 2: LITERATURE REVIEW

2.1. Introduction

This chapter provides a comprehensive review of the existing literature and tools relevant to the use of visualization in Computer Science (CS) education. It begins by establishing the foundational role of visualization as a pedagogical tool, supported by key cognitive learning theories. It then critically analyzes existing desktop-based applications and examines emerging technologies like Augmented Reality (AR) to justify the technological approach of this project. Finally, the chapter synthesizes these findings to identify the specific research gaps that our proposed application is designed to address.

2.2. Visualization in Computer Science Education

Computer Science as a discipline is replete with abstract concepts that are inherently difficult to grasp. Topics such as data structures, algorithms, operating system processes, and network protocols involve dynamic, multi-step processes that are not easily conveyed through static text or diagrams. This challenge creates what scholars refer to as the "visualization gap," where students struggle to form accurate mental models of computational processes (Naps et al., 2002). Visualization has long been recognized as a cornerstone for bridging this gap. By representing abstract concepts visually and dynamically, educational tools can significantly improve comprehension, retention, and problem-solving skills. Research consistently supports this, with studies showing that students using interactive algorithm visualizers scored 25–30% higher on post-tests compared to those relying on traditional textbooks (Sorva et al., 2013). Similarly, Moreno and Mayer (2007) found that interactive simulations could increase knowledge transfer by up to 50% compared to passive media.

The effectiveness of visualization is supported by several key cognitive and pedagogical frameworks:

- **Cognitive Load Theory** (Sweller, 1988)**:** Visualizations reduce extraneous cognitive load by presenting complex information in a spatially organized manner, freeing up mental resources for deeper understanding.
- **Dual-Coding Theory** (Paivio, 1986)**:** The human mind processes information through two distinct channels: verbal and visual. Combining animations with textual explanations strengthens memory and recall.
- **Constructivist Learning** (Piaget, 1970)**:** This theory posits that learners actively construct knowledge through exploration and interaction. Interactive visualization tools embody this principle by allowing students to experiment, manipulate variables, and observe outcomes in real-time.

2.3. Analysis of Existing Desktop-Based Visualization Tools

Over the years, numerous tools have been developed to support CS education. While each has made valuable contributions, they also exhibit significant limitations when viewed as a complete learning solution. Table 3 provides a comparison of several prominent tools.

Table 3: Comparison of Existing Desktop-Based Visualization Tools

Tool	Features	Strengths	Limitations
Python Tutor (Guo, 2013)	Step-by-step code execution, variable tracking	Simple interface, accessible online	Limited to code execution; lacks 3D visualizations and high-level concept views (e.g., OS)
JHAVE (Naps, 2005)	Algorithm animations, quizzes	Covers classic algorithms like sorting/searching	Outdated interface; no OS/networking support; limited interactivity
Algoviz (Sorva, 2013)	Customizable visualizations	Open-source, extensible	Steep learning curve; Java dependency
VisuAlgo (Halim, 2014)	20+ visualizations (sorting, graphs, trees)	Comprehensive topic coverage	Web-only; limited interactivity (mostly pre-canned animations); not a desktop-based application
TRAKLA2 (Malmi, 2004)	Interactive algorithm exercises, auto-grading	Supports self-paced practice	Narrow focus on algorithms; lacks 3D graphics and other CS domains

Common Limitations Identified:

From the analysis of these and similar tools, several recurring limitations emerge:

1. **Fragmentation of Learning Domains:** Most tools specialize in a single area, such as algorithm visualization or code tracing. This forces students and educators to switch between multiple, disconnected applications to cover a typical CS curriculum, hindering a holistic understanding of the field (ACM/IEEE, 2013).
2. **Low Interactivity:** Many tools rely on pre-built animations where the user is a passive observer. They lack the functionality for users to freely experiment, such as adjusting scheduling parameters or simulating custom memory allocation scenarios.
3. **Lack of Instructor-Centric Features:** Few tools offer robust support for educators. Features such as creating custom problem sets, tracking student progress, or integrating analytics are largely absent, creating a significant preparation burden for instructors (Guo, 2013).

2.4. Emerging Technologies: The Case of Augmented Reality (AR)

In addition to traditional desktop tools, emerging technologies like Augmented Reality (AR) present a promising frontier for education. AR enhances the real world by overlaying digital information, such as 3D models and interactive annotations. In education, AR has been shown to boost student engagement, motivation, and understanding of spatial concepts (Garzón, 2021). For CS, AR could be used to visualize a sorting algorithm on physical cards or show network packets moving through a real room.

However, despite its potential, AR presents significant barriers that limit its feasibility for broad adoption in CS education today:

- **Hardware and Accessibility Issues:** Effective AR experiences often require modern smartphones, tablets, or dedicated AR glasses, which are not available to all students or institutions. This creates an equity and accessibility problem (Kadiyala & Crynes, 1998).
- **Development Complexity:** Building robust AR applications is technically demanding, often requiring specialized skills in game engines like Unity or Unreal Engine and expertise in 3D modeling.
- **Potential for Cognitive Overload:** Poorly designed AR applications can overwhelm users with too much information, distracting from the core learning objectives (Saidin et al., 2015).

Given these challenges, and while acknowledging the future potential of AR, this project concludes that a well-designed, accessible desktop application remains the most practical and effective solution for addressing the immediate needs of CS education.

2.5. Synthesis and Identification of Research Gaps

The review of both traditional desktop tools and emerging AR technologies reveals several persistent gaps in the landscape of CS educational resources. This project is positioned to address these specific shortcomings. Table 4 summarizes the key research gaps identified.

Table 4:Research Gaps in Current Visualization Systems for CS Education

Gap	Description	Evidence
Integration of Domains	There is no unified platform that cohesively covers data structures, operating systems, and networking, forcing a fragmented learning experience.	ACM/IEEE, 2013; Sorva et al., 2013
Interactivity vs. Complexity	Tools tend to offer either broad coverage with low interactivity (e.g., VisuAlgo) or high interactivity within a very narrow scope (e.g., TRAKLA2). A tool that balances both is needed.	Sorva et al., 2013
Hardware & Accessibility	Advanced AR/VR tools demand high-spec hardware, while many existing web tools are not suitable for offline or resource-constrained environments.	Kadiyala & Crynes, 1998
Instructor-Centric Support	Existing tools are primarily student-focused, lacking features for educators to create, assign, and track custom learning modules.	Guo, 2013; Shaghaghian et al., 2022
Self-Paced Exploration	There is limited support for learners to freely adjust parameters, replay complex simulations, and experiment independently to build intuition.	Naps et al., 2002

This project will directly address these deficiencies by developing a single, integrated desktop application that provides deep interactivity across multiple core CS domains, is highly accessible, and includes features designed specifically to support both students and educators.

2.6. Conclusion

In summary, this literature review has confirmed the pedagogical value of visualization in computer science while highlighting significant deficiencies in existing tools. A clear need exists for a learning solution that is **integrated** across multiple domains, highly **interactive**, **accessible** without specialized hardware, and supportive of both students and instructors. This project will directly address these deficiencies by developing a single, integrated desktop application that provides deep interactivity across multiple core CS domains. The following chapter will detail the proposed system's architecture and design to achieve these goals.

Chapter 3: System Requirements and Design

3.1. Introduction

This chapter outlines the technical blueprint for the proposed system, translating the project objectives identified in Chapter 1 into a concrete set of requirements and a detailed architectural design. It begins with a high-level overview of the system, followed by a detailed specification of its functional and non-functional requirements. The chapter then describes the system's architecture, key use cases, and design patterns, concluding with the rationale behind the chosen technological stack and design decisions.

3.2. System Overview

The proposed system, named the **"Augmented Reality (AR) Application for Computer Science Education"** is a Python-based desktop application designed to provide interactive 3D visualizations of core Computer Science concepts. The primary goal is to enhance student comprehension by offering an integrated, hands-on learning platform that covers Data Structures, Operating Systems, and Networking.

The system is architected around four main components that work in concert:

1. **User Interface (UI):** Built with PyQt6, this component provides a modern, intuitive graphical interface for all user interactions, from topic selection to simulation control.
2. **Simulation Engine:** The core logic of the application, written in Python. It manages the state of simulations, executes algorithms, and processes user input.
3. **Visualization Modules:** These specialized modules handle the graphical rendering. VPython is used to generate interactive 3D scenes, while Matplotlib is employed for 2D data plotting and analytics (e.g., CPU utilization graphs).
4. **Data Persistence Layer:** A lightweight SQLite database is used to store user-specific data, including progress, scores, and settings, ensuring a personalized and persistent experience.

3.3. Project Methodology

This project was developed using an **Iterative Waterfall methodology**. This hybrid model was selected as it combines the structured, phase-based approach of the traditional Waterfall model with the flexibility of an iterative process, making it ideal for a project with a fixed timeline but complex, multi-part features.

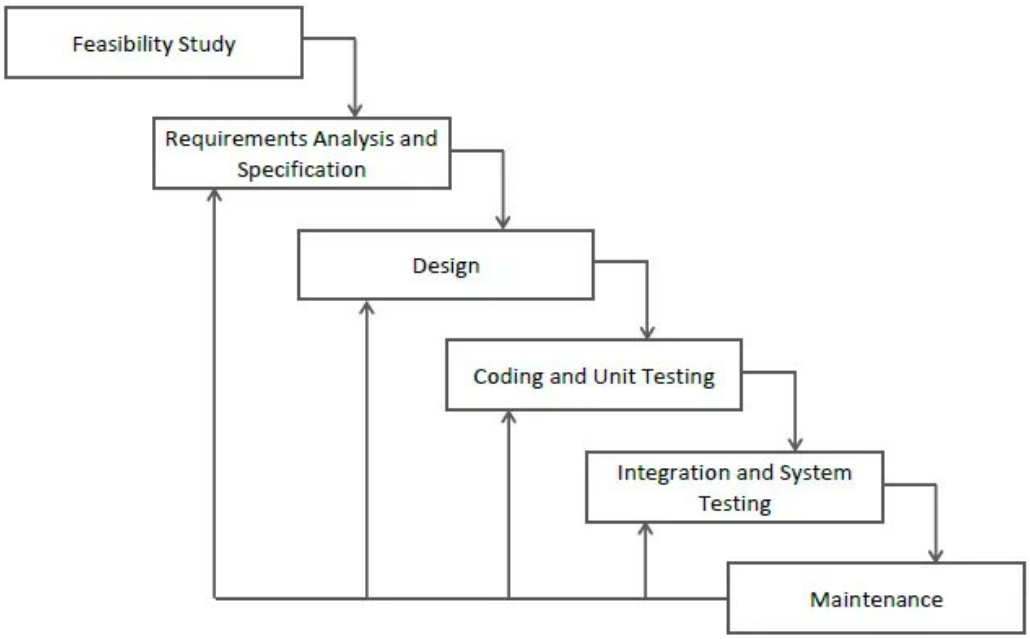

Figure 2: Iterative Waterfall methodology

The core of the methodology remains rooted in the sequential phases of the Waterfall model, ensuring that fundamental steps like requirements gathering and system design were completed upfront. This provided a clear roadmap and stable foundation for the project.

The phases were:

1. **Requirements Analysis:** Defining and documenting all system needs.
2. **System Design:** Creating the architecture, UML diagrams, and UI mock-ups.
3. **Implementation:** Writing the code for the system.
4. **Testing:** Verifying that the implementation meets the defined requirements.
5. **Deployment (Demonstration):** Preparing the final, working application.

The **iterative** aspect was applied to the development and implementation phases. Instead of building the entire application in one single pass, we broke the development into logical, sequential cycles. For example:

- **Iteration 1: Core Framework & Data Structures Module.** The first cycle focused on building the main application shell, the user interface, the database connection, and the complete Data Structures visualization module. This resulted in a functional, testable prototype early in the project timeline.
- **Iteration 2: Operating Systems Module.** The second cycle built upon the stable core from the first iteration, adding the CPU scheduling simulations for the Operating Systems module.

This iterative approach provided significant advantages:

- It allowed for feedback and lessons learned from the first iteration to be applied to the second, improving development efficiency.
- It enabled early testing and validation of core components.
- It reduced risk by ensuring that a working, valuable part of the application was completed and stable before moving on to the next set of features.

By blending the clear structure of the Waterfall model with the practical flexibility of iterative development, we were able to manage the project effectively, ensuring we met our milestones.

3.4. System Requirements

The application is architected around four main components that work in concert:

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4. **Data Persistence Layer:** A lightweight SQLite database is used to store user-specific data, including progress, scores, and settings, ensuring a personalized and persistent experience.

Functional requirements define the specific behaviors and functions the system must perform.

3.5. Functional Requirements (FRs)

Functional requirements define the specific behaviors and functions the system must perform. The following table details the core functionalities of the Augmented Reality (AR) Application for Computer Science Education, covering both Student and Administrator roles.

Table 5: Functional Requirements Table

ID	Functional Requirement	Description
FR1	**Role-Based Authentication**	The system shall provide a secure login interface that authenticates users and directs them to the appropriate environment (Student Dashboard or Admin Dashboard) based on their assigned role.
FR2	**User Management (Admin)**	The system shall allow the Administrator to create, update, and delete user accounts (Students and Admins) and manage their credentials securely.
FR3	**Module & Exercise Management**	The system shall allow the Administrator to configure Learning Modules (e.g., set 3D shapes) and create dynamic Exercises by defining "Target Patterns" and difficulty levels.
FR4	**Unified Topic Selection**	The system shall present a main dashboard allowing the Student to choose a learning module from core areas: Data Structures, Operating Systems, or Networking.
FR5	**Interactive Simulation**	The system shall enable user-controlled simulations where Students can actively manipulate parameters in real-time (e.g., push/pop elements, adjust CPU time quantum).
FR6	**Dynamic 3D Visualization**	The system shall render abstract concepts as interactive 3D objects using VPython, allowing users to rotate, pan, and zoom to understand spatial relationships.
FR7	**Performance Tracking**	The system shall calculate and store Student scores based on their ability to match the "Target Pattern" defined by the Admin.

FR8	**System Auditing (Logs)**	The system shall record critical user activities (logins, simulation actions, data changes) in an immutable log viewable only by the Administrator.
FR9	**Data Persistence**	The system shall automatically save the system state (User profiles, Exercises, Logs) in the SQLite database to ensure data integrity across sessions.

3.6. Non-Functional Requirements (NFRs)

Non-functional requirements define the quality attributes of the system, such as performance, usability, and security.

Table 6: Non-Functional Requirements Table

Category	Requirement
Performance	All simulations must initialize and load within 3 seconds on target machines (Intel i5 CPU with 8 GB RAM). UI interactions must have a response time of less than 200ms.
Usability	The Graphical User Interface (GUI) must follow a consistent and predictable layout using standard PyQt6 widgets. Font sizes must be 11 points or greater to ensure readability.
Portability	The final executable must run natively on Windows 10+, macOS 13 (Ventura)+, and Ubuntu 20.04+.
Reliability	The system should be able to recover the user's last session via an auto-save mechanism in the event of an unexpected crash or power failure.
Security	All user-specific data stored in the SQLite database (e.g., user profiles and scores) must be encrypted to protect privacy.
Maintainability	The source code must be modular, with distinct functionalities (UI, logic, data) separated into different .py files to simplify debugging, testing, and future enhancements.

3.7. Software & Hardware Requirements

- **Programming Language:** Python 3.11+
- **GUI Framework:** PyQt6
- **3D Visualization Library:** VPython
- **2D Plotting Library:** Matplotlib
- **Database:** SQLite3
- **Operating Systems:** Windows 10+, macOS 13+, Ubuntu 20.04+
- **CPU:** Intel i5 (or equivalent)
- **RAM:** 8 GB
- **Storage:** 500 MB free storage space

Table 7: Hardware and Software Requirements

Type	Specification
Hardware	Intel i5 CPU (or equivalent), 8 GB RAM, 500 MB free storage space
Software	Python 3.11+, PyQt6, VPython, Matplotlib, SQLite3, Windows/macOS/Linux

3.8. System Architecture

The application is designed using a **three-tier architecture** to ensure a clean separation of concerns, which enhances modularity and maintainability.

1. **Presentation Layer (View):** This is the top-most layer responsible for all user-facing elements. It is built using **PyQt6** and its sole responsibility is to display information to the user and capture their input (e.g., button clicks, slider adjustments). It does not contain any simulation logic.
2. **Logic Layer (Controller):** This is the core of the application. The Python Simulation Engine resides here. It processes inputs from the Presentation Layer, executes the relevant algorithms (e.g., a sorting algorithm or a CPU scheduling simulation), manages the application's state, and sends results back to the UI for display.
3. **Data Layer (Model):** This layer is responsible for data persistence. It uses an SQLite database to store, retrieve, and manage all long-term data, such as user profiles, progress, and saved settings. The Logic Layer communicates with this layer to save or load user data.

This layered approach allows developers to modify or update one layer (e.g., redesigning the UI) with minimal impact on the other layers.

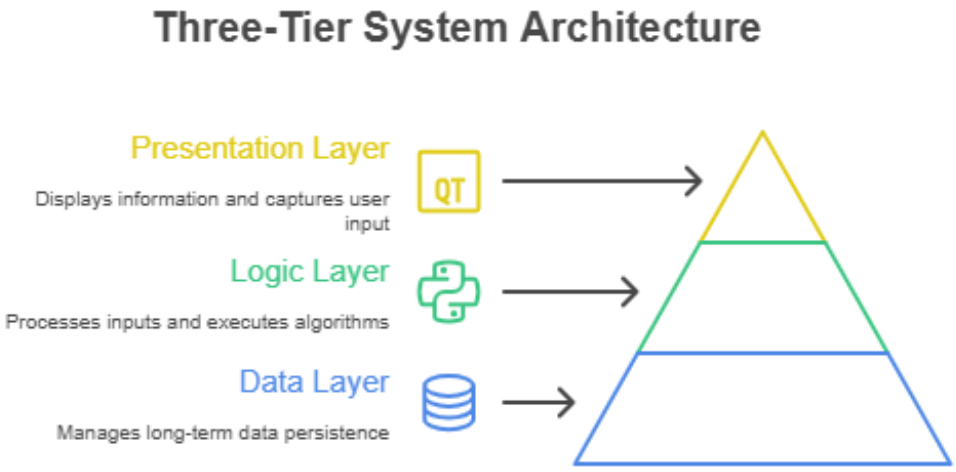


Figure 3: System Architecture

3.9. UML Diagrams

3.9.1. Use Case Diagram

Descriptive Explanation:

The Use Case diagram provides a high-level view of the system's functionality from an external observer's perspective . It illustrates the interactions between "actors" (users) and the system itself. This diagram is crucial for defining the scope of the project and ensuring all user goals are captured.

- **Actor (Student):** Represents the end-user of the application. The student interacts with the system to achieve their learning objectives.
- **System:** The rectangular boundary represents our application. All use cases (the ovals) are the functional capabilities provided by the system.
- **Use Cases:** These represent the primary actions a student can perform, such as selecting a topic, running a simulation, tracking their progress, and customizing settings. The <<includes>> relationship indicates that "Run Interactive Simulation" is a necessary part of the flow that starts with "Select Learning Module."

3.9.2. Use Case Description

Table 8: Select Learning Module

Use Case ID	**UC-1**
Use Case Name	Select Learning Module
Actor	Student
Description	Allows the student to choose a primary topic (e.g., Data Structures) and then a sub-topic (e.g., Stack) to begin a learning session.
Basic Flow	1. The student starts at the main dashboard. 2. The student clicks on a topic category (e.g., "Operating Systems"). 3. The System displays a list of available simulations (e.g., "FCFS Scheduling," "Round Robin Scheduling"). 4. The student selects a specific simulation.
Post-condition	The System displays the simulation interface for the chosen topic.

Table 9: Run Interactive Simulation

Use Case ID	**UC-2**
Use Case Name	Run Interactive Simulation
Actor	Student
Description	The student interacts with the 3D visualization by inputting data, changing parameters, and controlling the flow of the animation.
Basic Flow	1. The student enters a value into a text field (e.g., enters '5' to "Push"). 2. The student clicks a control button (e.g., the "Push" button). 3. The System animates an update to the visualizer based on the action. 4. The student views a textual explanation of the step that was just performed.
Pre-condition	A learning module has been selected and its simulation interface is displayed.

Table 10: Manage Exercises (Admin)

Use Case ID	**UC-Admin-01**
Use Case Name	**Manage Exercises (Dataset Control)**
Actor	Administrator
Description	The Admin creates new problem sets for students to solve by defining the target solution pattern.
Basic Flow	1. Admin logs in and navigates to the "Exercise Manager" tab. 2. Admin selects a specific Module (e.g., Stack). 3. Admin inputs the "Target Pattern" (e.g., [10, 20, 30]). 4. Admin sets the difficulty level and clicks "Create Exercise". 5. The System saves the new exercise to the database.
Post-condition	The new exercise becomes immediately available for Students in their dashboard.

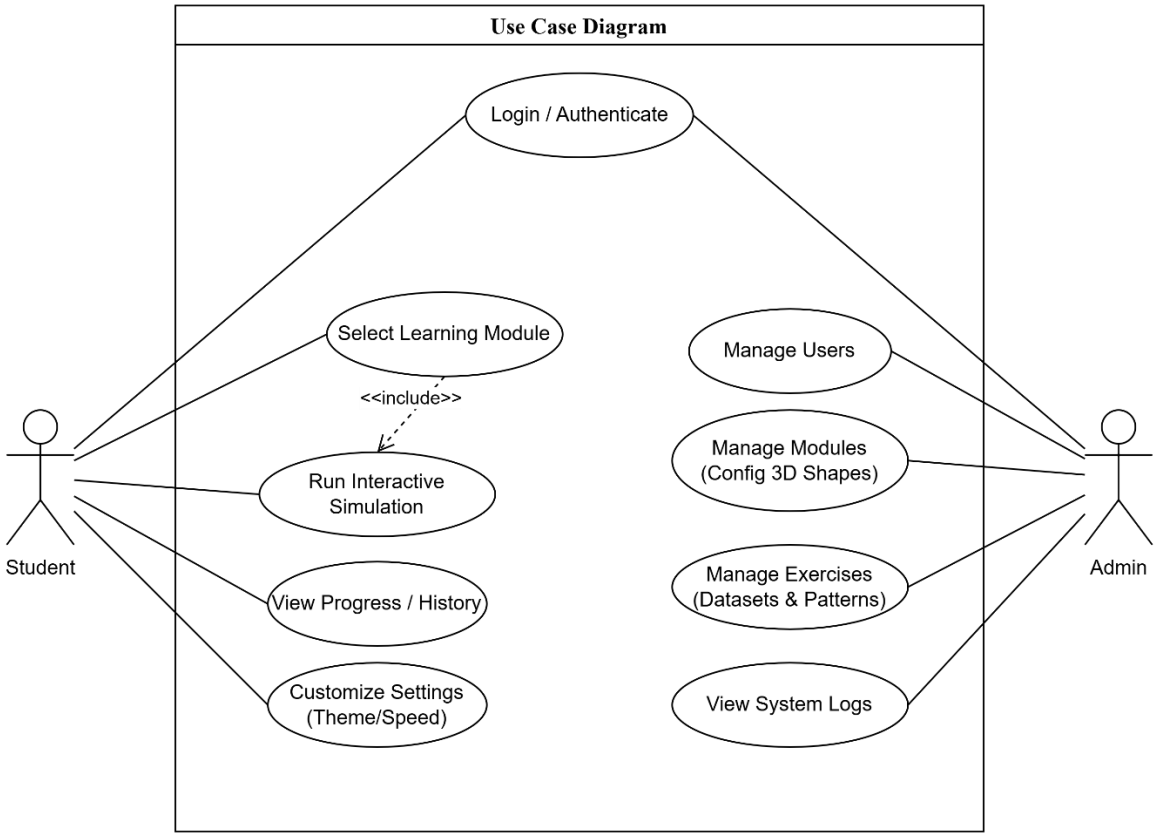


Figure 4: Use Case Diagram

3.9.3. Class Diagram

Descriptive Explanation:

The Class Diagram serves as a static blueprint of the system's architecture, illustrating the structure of the application by showing the system's classes, their attributes, methods, and the relationships among them. This diagram is crucial for understanding how the application separates concerns between the user interface, business logic, and data management.

- **DatabaseManager:** This is a central, singleton class responsible for all direct interactions with the SQLite database. It handles connection management, user authentication (verifying credentials), and executing queries (saving progress, retrieving exercises). This design enforces the principle of Separation of Concerns, ensuring that no other part of the app needs to know SQL syntax.
- **LoginWindow:** This class acts as the secure gateway and entry point of the application. It captures user credentials and uses the DatabaseManager to verify them. Based on the returned "Role" (Admin or Student), it dynamically instantiates and opens the appropriate dashboard (AdminDashboard or StudentDashboard).
- **AdminDashboard:** A specialized controller class for the instructor's interface. It provides methods to access management sub-systems, such as the ExerciseManager (for creating datasets) and the User Management panel. It ensures that administrative functions are isolated from the student environment.
- **StudentDashboard:** The primary interface for the learning experience. It acts as a container for the simulation tools. It listens for user inputs (like "Push" or "Enqueue") and forwards these requests to the underlying SimulationEngine.
- **SimulationEngine (Abstract Class):** This is a template class that defines the blueprint for all educational simulations. It declares abstract methods like start(), reset(), and executeStep().
    - **DataStructureSim & OS_Sim:** These are **concrete classes** that inherit from SimulationEngine. They contain the specific mathematical and logical rules for their respective topics (e.g., LIFO logic for a Stack, Time Quantum logic for Round Robin).

- **Visualizer3D:** A dedicated class responsible for the graphical rendering using **VPython/OpenGL**. It receives state updates from the simulation classes and updates the 3D scene (e.g., moving a cube, changing a color) without affecting the underlying data logic.

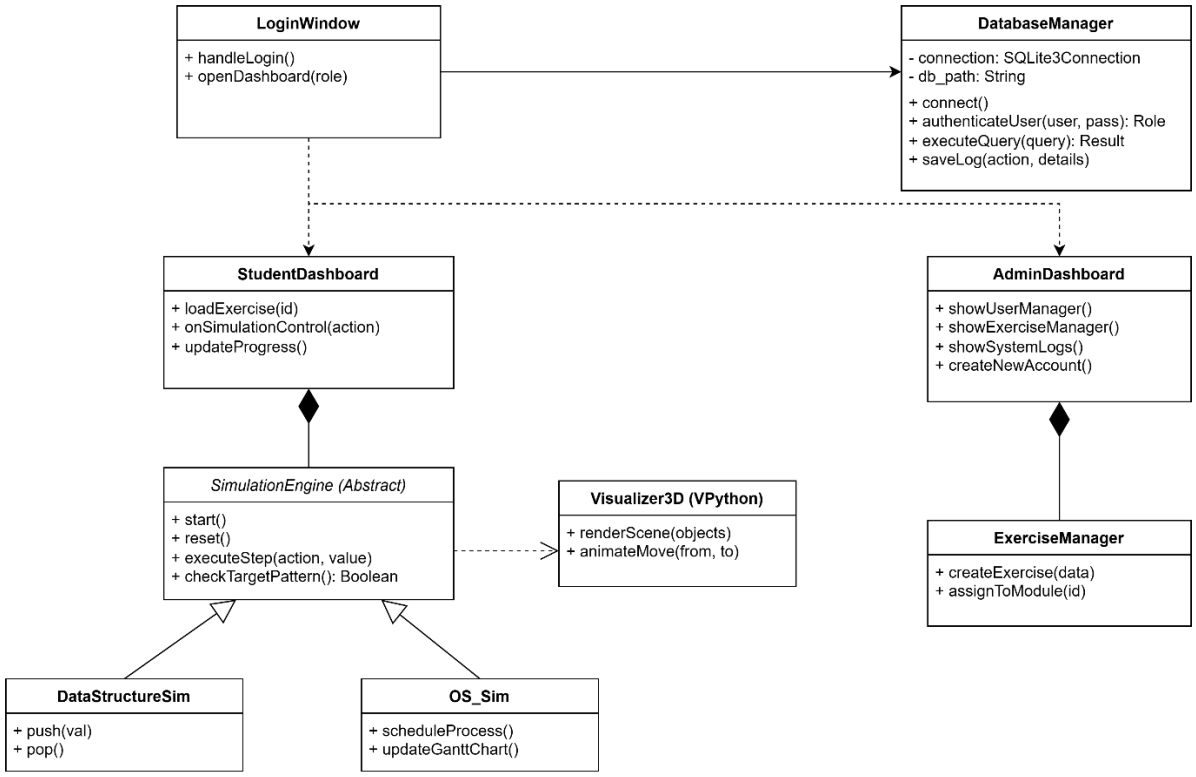


Figure 5: Class Diagram

3.9.4. Sequence Diagram

Descriptive Explanation:

The Sequence Diagram is a dynamic model that visualizes the time-ordered interactions between objects to execute a specific system function. The following diagram illustrates the workflow when a student performs a **"Push" operation** within a Data Structure simulation. This scenario highlights the separation between the User Interface, the Logic Engine, and the 3D Visualization.

Step-by-Step Flow:

1. **Student → StudentDashboard:** The process initiates when the student enters a value (e.g., "50") and clicks the "Push" button on the interface.
2. **StudentDashboard → DataStructureSim:** The UI component captures the input but does not process it. Instead, it delegates the command executeStep('push', 50) to the logic controller (DataStructureSim).

3. **DataStructureSim → Visualizer3D:** The simulation engine calculates the logical position of the new element. It then instructs the Visualizer3D component to animateMove(), rendering the 3D cube moving into the stack.
4. **Visualizer3D (Return):** Once the animation completes, the visualizer notifies the simulation engine that the UI is ready for the next step.
5. **Self-Call (Check Pattern):** The DataStructureSim internally compares the current state of the stack against the "Target Pattern" defined for the exercise to check if the student has solved the problem.
6. **DataStructureSim → DatabaseManager:** To ensure data persistence and auditing (FR8), the engine calls saveLog() to record the action in the database.
7. **Return to UI:** Finally, the system updates the text log on the StudentDashboard to confirm to the user that the action was successful (e.g., "Value 50 Pushed").

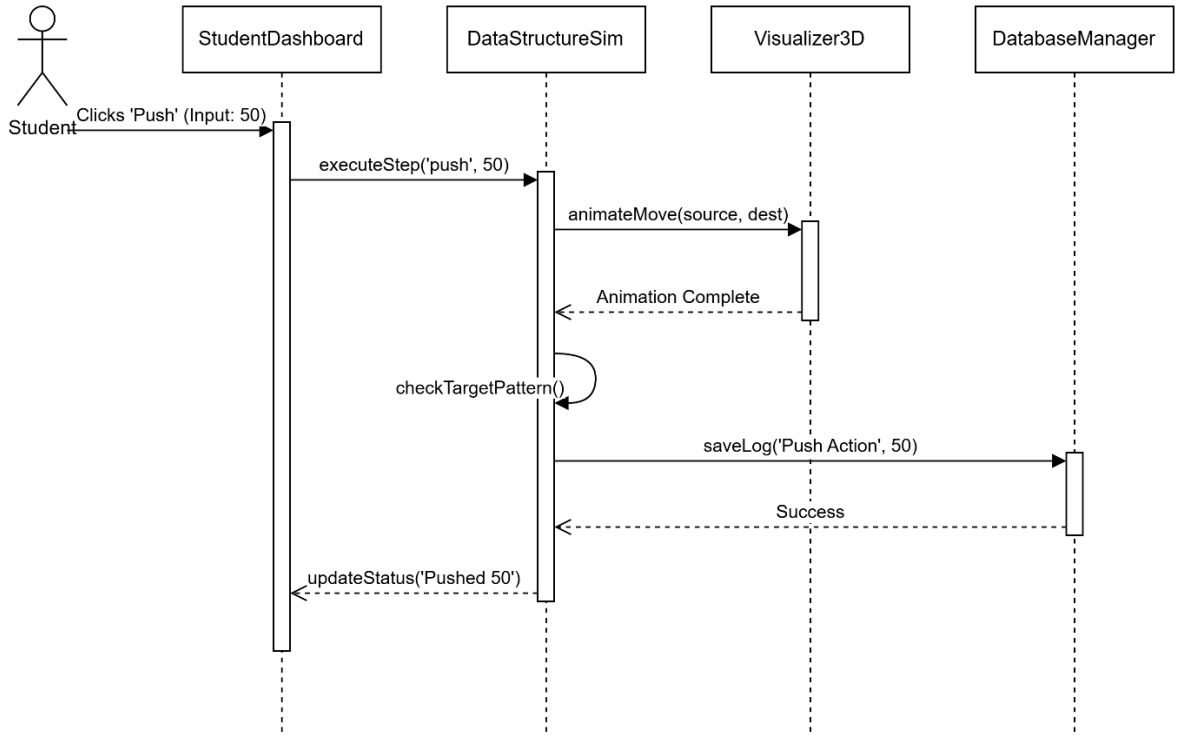


Figure 6: Sequence Diagram

3.10. Design Rationale

The architectural design specifically addresses two critical technical requirements:

1. **Platform Independence:** The choice of a Python-based design with PyQt6 was made to ensure the application remains platform-agnostic, allowing the design to be implemented on Windows, macOS, and Linux without structural changes.
2. **Code Reusability:** The system uses a **Modular Design Pattern**. By designing a generic BaseSimulation interface, we ensured that the core visualization code is reusable across different CS modules (Data Structures, OS, etc.), reducing development time and complexity."

The design emphasizes **Platform Independence** and **Code Reusability**. By utilizing a decoupled three-tier architecture, the presentation layer (PyQt6) is independent of the simulation logic. This ensures that the application can be deployed across various operating systems (Windows, macOS, Linux) without modifying the core algorithms. Additionally, the use of abstract base classes for the simulation engine allows common 3D rendering functions to be reused across all modules, significantly optimizing the development process.

3.11. Design Verification Strategy

To ensure that the implemented system aligns with the requirements, a verification strategy was established during the design phase. This includes:

- **Model Verification:** Cross-referencing the Class Diagrams with the Functional Requirements to ensure all features have corresponding logic.
- **Logic Traceability:** Designing the Simulation Engine to allow for step-by-step state checking, ensuring that the 3D output accurately reflects the underlying data structure algorithms.

CHAPTER 4: SYSTEM IMPLEMENTATION

4.1. Introduction

Following the **successful completion of the design phase** detailed in Chapter 3, the project has moved into the implementation stage. All architectural blueprints, including UML diagrams and database schemas, are now finalized, providing a stable foundation for coding. Currently, **50% of the project modules have been implemented**, focusing on the core framework and the initial interactive 3D simulations.

This chapter details the practical realization of the Augmented Reality (AR) Application for Computer Science Education. It describes the translation of the system design and requirements defined in previous chapters into a functional software prototype. The implementation follows the Iterative Waterfall methodology, focusing first on establishing the development environment, constructing the database schema, and developing the graphical user interfaces (GUI) for the core modules.

4.2. Development Environment

Based on the software requirements specified in Chapter 3, the development environment was set up to support a cross-platform desktop application. The specific tools and libraries used in the implementation are detailed in Table 10.

Table 11: Development Environment and Tools

Category	Tool / Library	Purpose in Project
Language	Python 3.11+	The core programming language chosen for its simplicity and extensive library support.
GUI Framework	PyQt6	Used to design modern, responsive, and event-driven user interfaces (Presentation Layer).
3D Engine	VPython	Integrated to render the interactive 3D visualizations for Data Structures and OS algorithms.
Database	SQLite3	A serverless, lightweight relational database engine used for local data persistence.
Plotting	Matplotlib	Used for generating 2D analytics graphs (e.g., CPU utilization charts).
IDE	VS Code / PyCharm	The Integrated Development Environment used for coding, debugging, and testing.

4.2.1. Environment and Tools Discussion

The implementation environment was carefully selected to match the project's accessibility goals.

- **Software Environment:** We utilized Python 3.11 with the PyCharm IDE for development. Libraries like pyqtgraph.opengl were chosen during implementation to provide high-performance 3D rendering with minimal system overhead.
- **Hardware Environment:** The system was developed and verified on a mid-range workstation (Intel i7, 16GB RAM) to ensure that the code is optimized for standard educational lab computers. This ensures that the 3D animations remain fluid and responsive on lower-spec hardware.

4.3. Database Implementation

To satisfy the system's requirements for modularity, data integrity, and security (FR4 and FR6), the database was implemented using SQLite. The schema was designed using a Relational Model to support Role-Based Access Control (RBAC) and dynamic educational content generation. Unlike static applications, this database-driven approach allows Administrators to define learning modules and exercises without modifying the source code.

The database schema consists of five primary tables:

Users, **Learning Modules**, **Exercises**, **Results**, and **Activity Logs**.

4.3.1. Users Table

This table handles user authentication and profile management. It enforces security by storing hashed passwords and defining user roles to restrict access to specific system features (e.g., only Admins can create content).

Table 12: Users Table Schema

Attribute Name	Data Type	Constraint	Description
id	INTEGER	Primary Key	Unique identifier for the user.
username	TEXT	Unique, Not Null	The identifier used for logging into the system.
password	TEXT	Not Null	Hashed security string for authentication.
role	TEXT	Check Constraint	Defines privileges ('admin' or 'student').
full_name	TEXT	Not Null	The user's actual name for display purposes.

4.3.2. Learning Modules Table

This table defines the core Computer Science concepts available in the system (e.g., Stack, Queue). It controls the visual representation in the 3D engine, determining whether elements appear as cubes or spheres.

Table 13: Learning Modules Table Schema

Attribute Name	Data Type	Constraint	Description
id	INTEGER	Primary Key	Unique identifier for the module.
name	TEXT	Unique, Not Null	The name of the structure (e.g., "Stack").
visual_shape	TEXT	Default 'cube'	Determines the 3D object type used in the simulation.
theory_content	TEXT	-	Stores HTML/Rich text explaining the theoretical concept.

4.3.3. Exercises Table (The Dataset)

This table represents the dynamic dataset created by instructors. It links to specific Learning Modules and defines the "Target Pattern" that students must replicate in the 3D simulation to pass.

Table 14: Exercises Table Schema

Attribute Name	Data Type	Constraint	Description
id	INTEGER	Primary Key	Unique identifier for the exercise.
module_id	INTEGER	Foreign Key	Links the exercise to a specific Learning Module.
target_pattern	TEXT	Not Null	A JSON-like string (e.g., [10, 20, 30]) representing the solution.
difficulty	TEXT	Default 'medium'	Classifies the difficulty level of the task.
created_by	INTEGER	Foreign Key	References the Admin ID who created the exercise.

4.3.4. Results & Activity Logs Tables

These tables facilitate progress tracking and system auditing. The **Results** table stores academic performance, while **Activity Logs** provides a secure audit trail of all user actions (e.g., logins, simulation steps).

Table 15: Results & Activity Logs Schema

Table	Attribute	Description
Results	**student_id**	References the student who performed the task.
	score	The grade achieved (0-100).
	completed_at	Timestamp of when the exercise was finished.
Activity Logs	**action**	The type of event (e.g., "Simulation Push", "Login").
	details	Specific details (e.g., "Added value 50 to Stack").
	timestamp	Exact time of the action for security auditing.

4.4. User Interface (GUI) Implementation

The user interface (UI) serves as the bridge between the complex underlying logic and the end-user. Developed using **PyQt6**, the GUI was designed to be intuitive, responsive, and aesthetically pleasing, utilizing a modern **Dark Theme** to reduce eye strain during long study sessions. The interface implementation is divided into three distinct environments based on the user's role: the Authentication Gateway, the Admin Dashboard, and the Student Learning Environment.

4.4.1. Authentication Interface (Login Screen)

The entry point of the application is the Login Screen. It enforces security and role-based routing.

- **Design:** A clean, centered form containing username and password fields.
- **Functionality:** Upon clicking "Login," the system queries the Users table in the database.
- **Routing Logic:** Based on the retrieved role attribute:
    - If the role is **'Admin'**, the system opens the Admin Dashboard.
    - If the role is **'Student'**, the system opens the Student Learning Environment.
    - Incorrect credentials trigger an immediate error popup, ensuring security feedback.

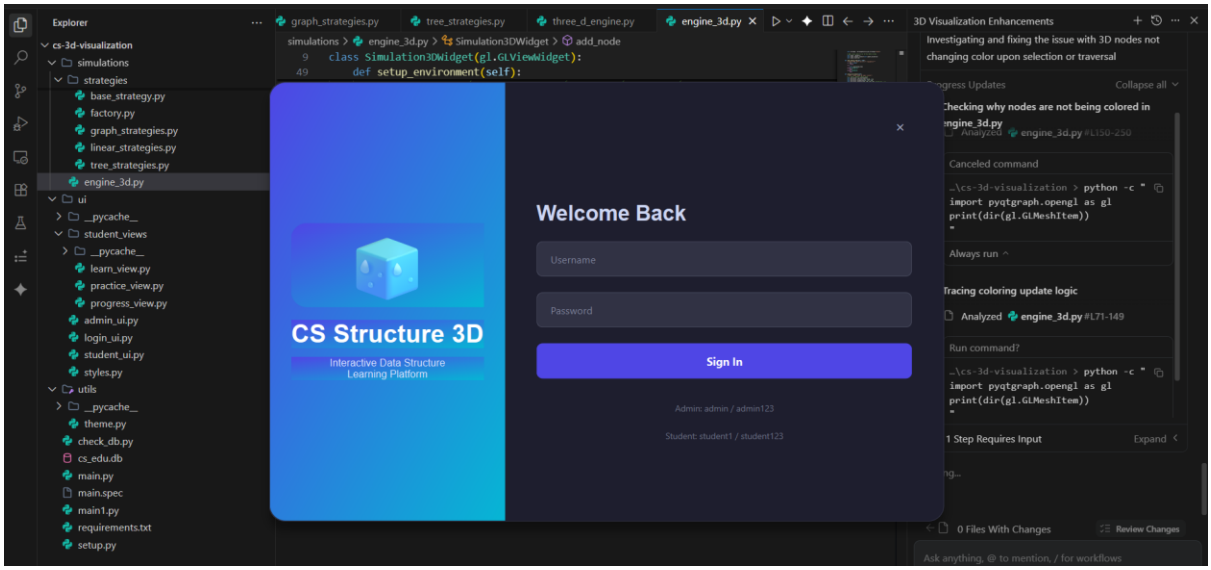


Figure 7: Login Screen

4.4.2. Admin Dashboard (Instructor Panel)

To fulfill the project's requirement for comprehensive system management, the Admin Dashboard was designed as a multi-functional suite using a Sidebar Layout.

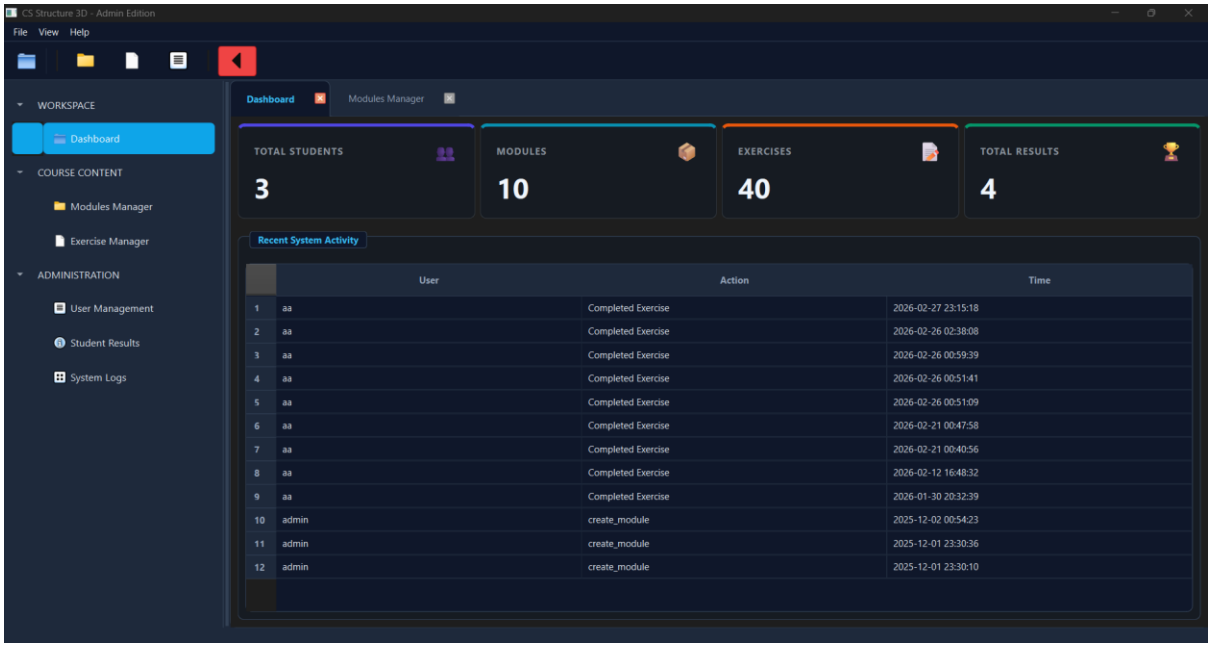


Figure 8: Admin Dashboard (Instructor Panel) dark mode

The dashboard is divided into four critical management modules:

Modules Manager:

- Allows the admin to define core learning concepts (e.g., "Linked List", "Stack").
- Controls the visual representation in the 3D engine (selecting 'Cube' or 'Sphere' for elements).

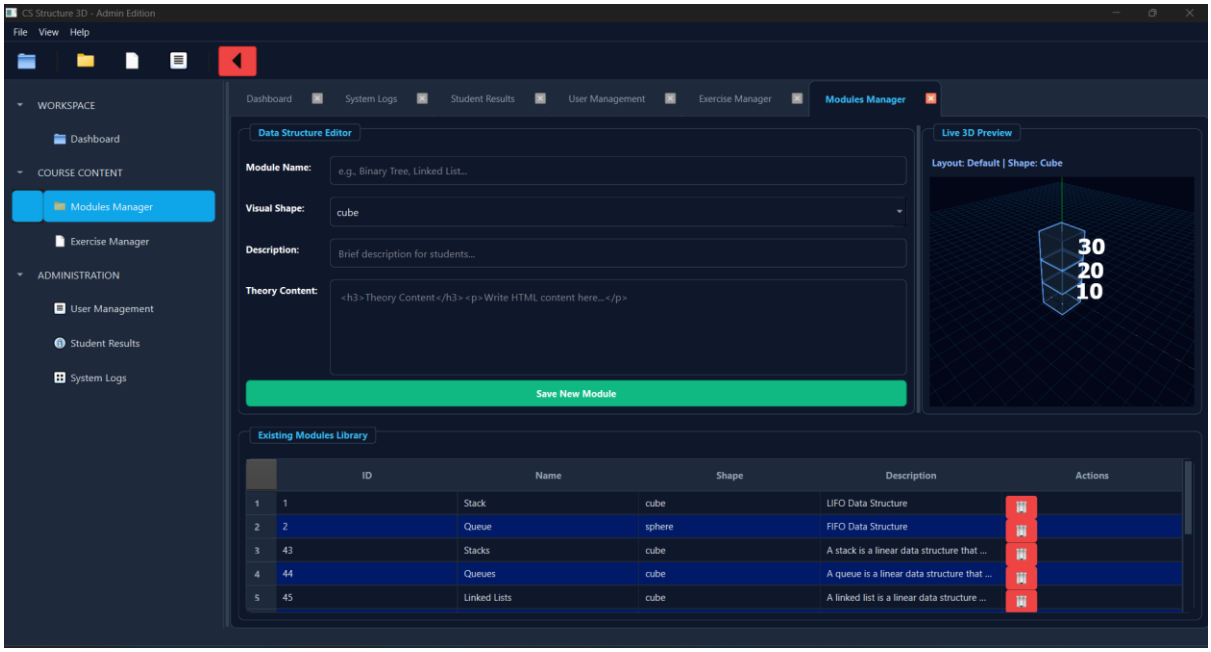


Figure 9: Modules Manager

Exercise Manager:

- Acts as the central control for the Educational Dataset.
- The Admin can create new exercises, link them to specific modules, and define the "Target Pattern" (solution) that students must achieve.

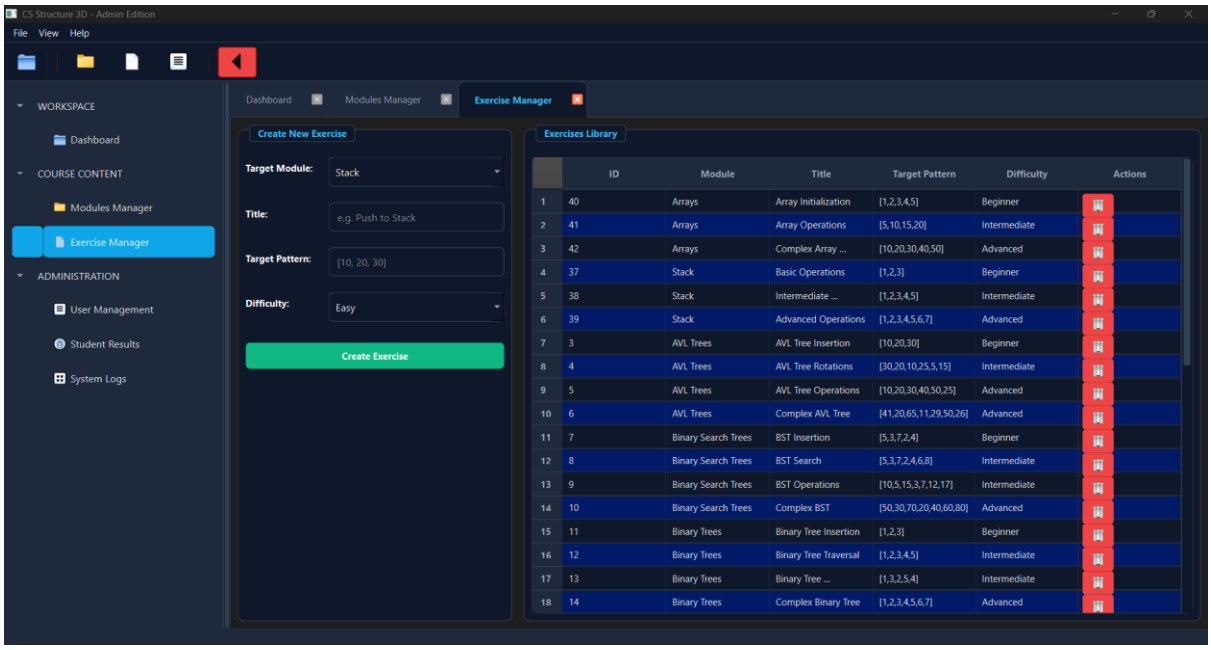


Figure 10: Exercise Manager

User Management:

- Provides full control over system access.
- The Admin can create new accounts for students or other admins, ensuring secure, hashed credential storage.
- Includes a tabular view to monitor registered users and their roles.

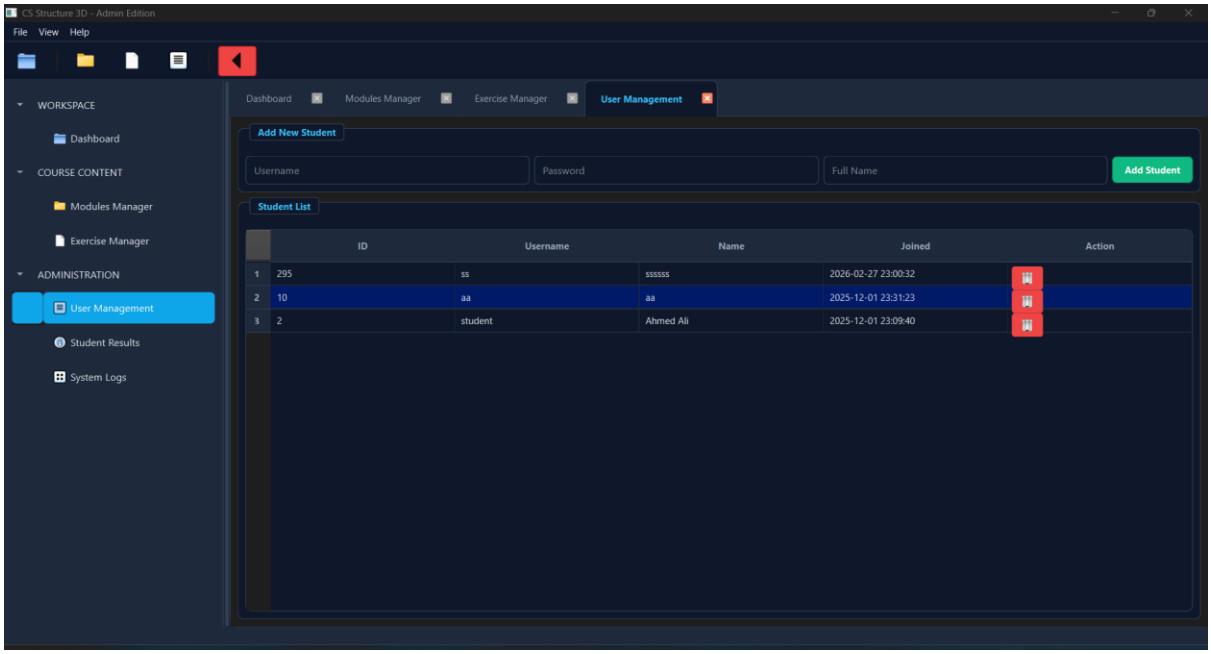


Figure 11: User Management

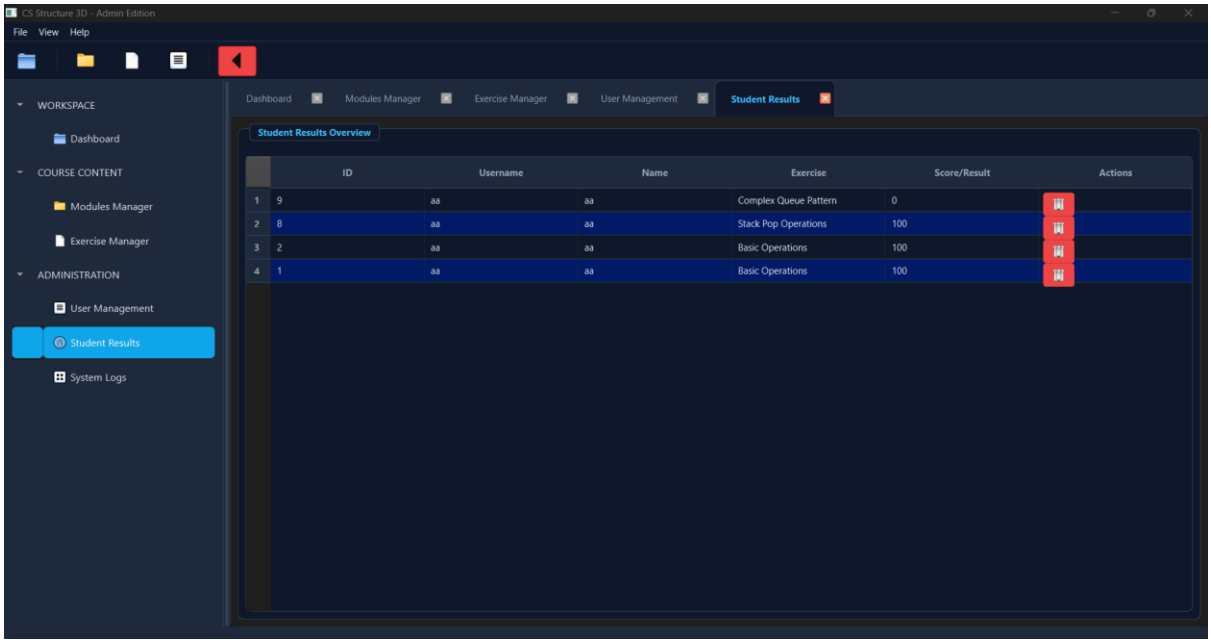


Figure 12: Students Results

System Logs (Audit Trail):

- A security feature that displays a chronological list of all activities performed within the system.
- Tracks login events, simulation actions, and content modifications, ensuring full system observability.

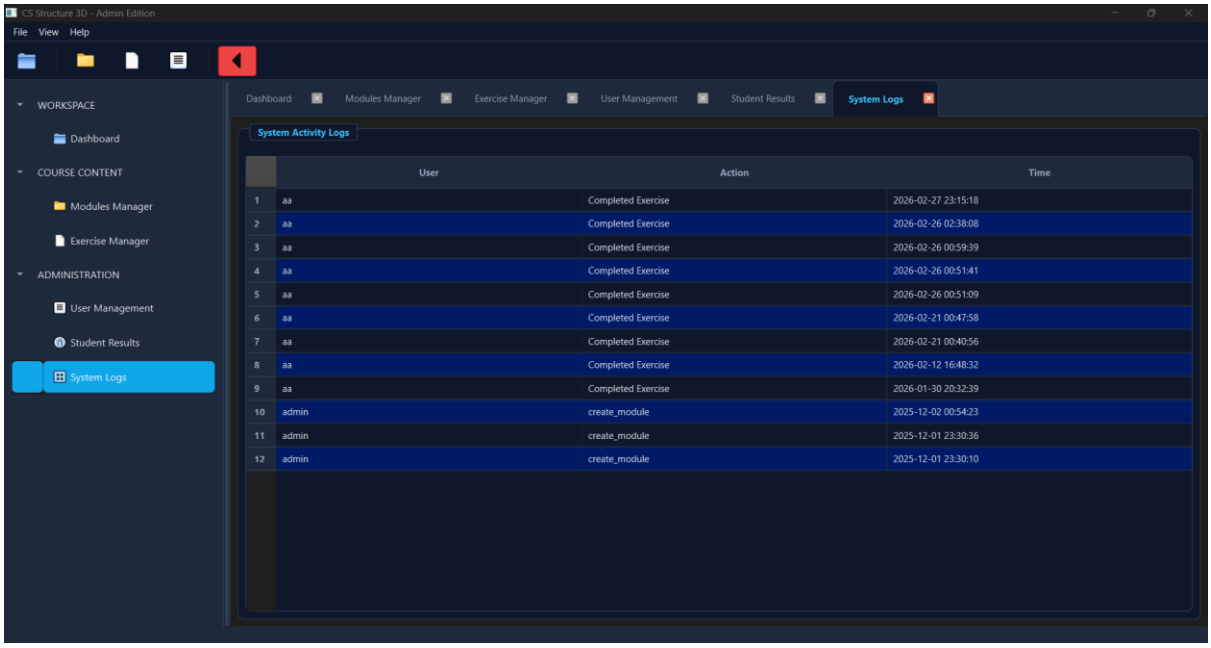


Figure 13: System Logs

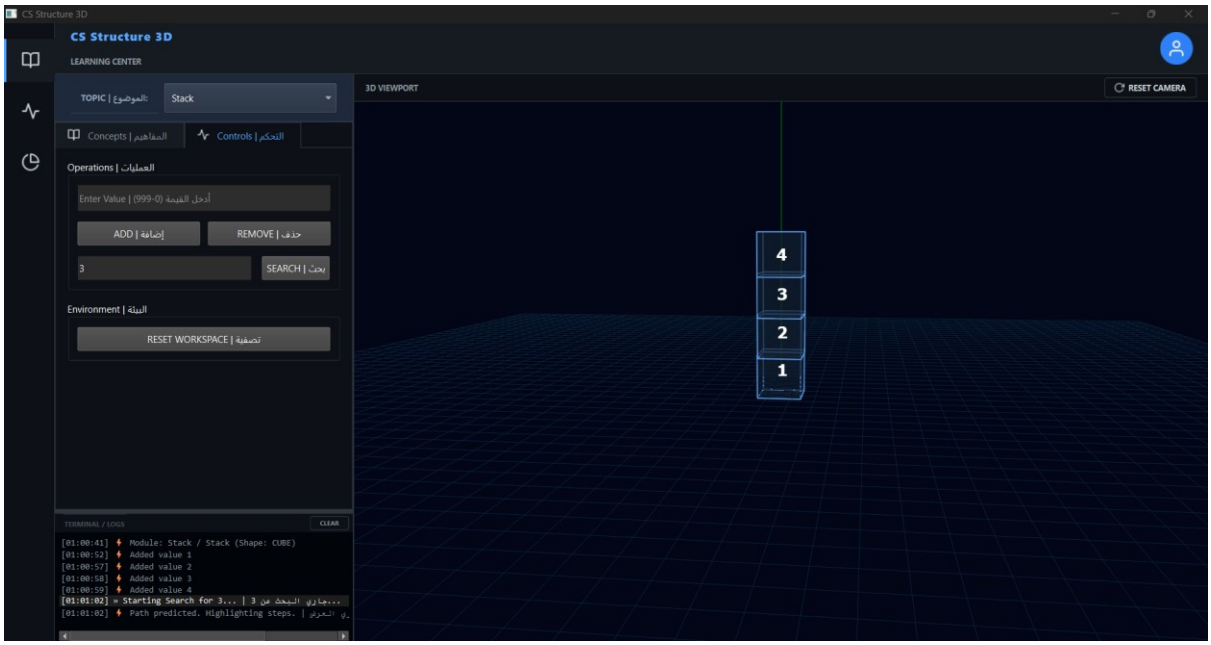
4.4.3. Student Dashboard (Learning Environment)

The core educational interface is designed to facilitate active learning. It is divided into two primary sections using a horizontal layout:

Control Panel (Left Side):

- **Dataset Selection:** A dynamic QComboBox that fetches available exercises from the database. When a student selects an exercise (e.g., "Stack Task 1"), the system loads the target pattern automatically.
- **Interaction Controls:** Input fields for data values and buttons for operations (Push/Pop for Stacks, Enqueue/Dequeue for Queues).
- **System Logs:** A read-only text area that provides real-time textual feedback (e.g., "Value 50 Pushed", "Target Matched"), helping the student track their actions.

3D Viewport (Right Side): The embedding container for the OpenGL visualization engine.



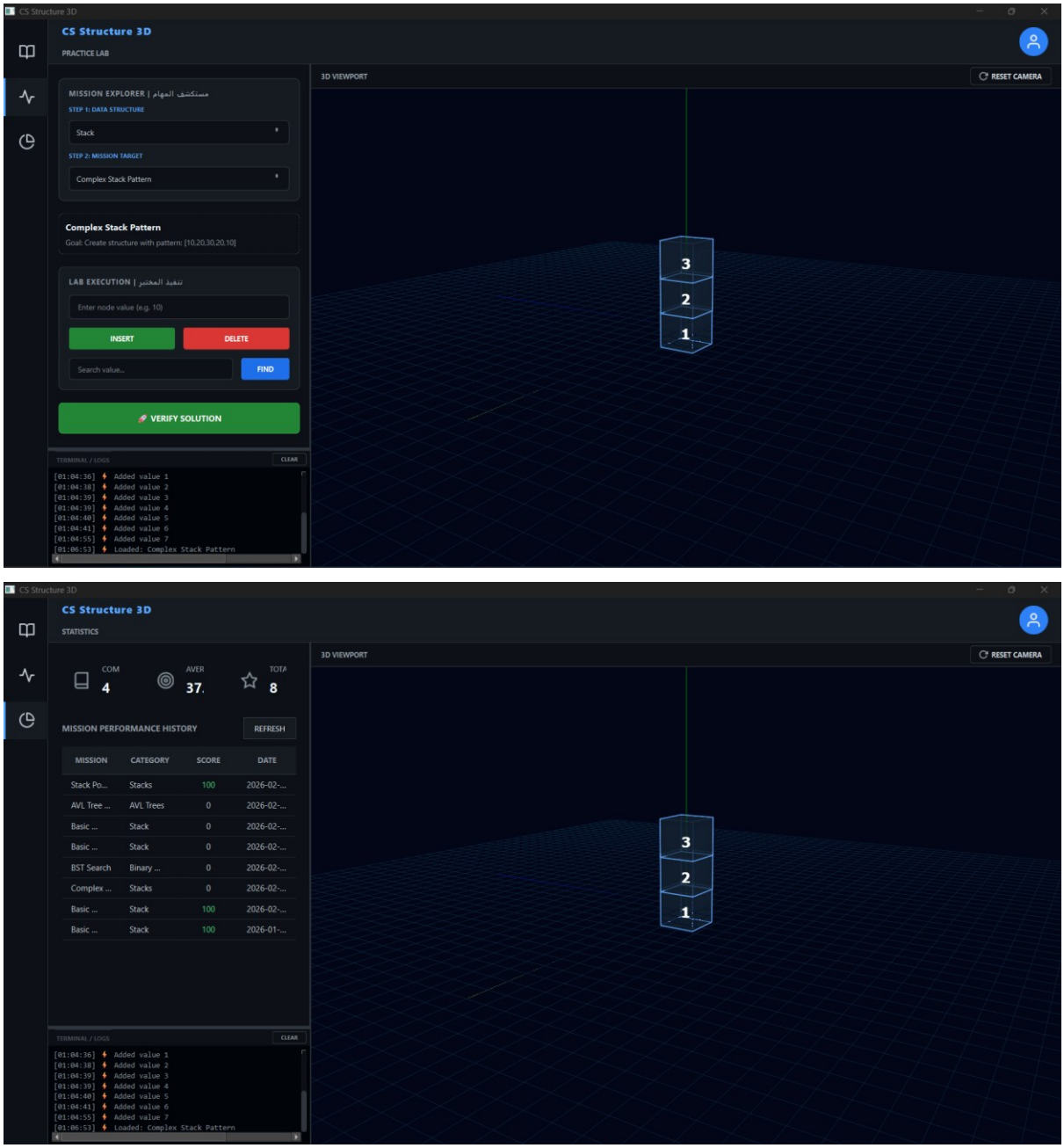


Figure 14: Student Dashboard (Learning Environment

4.4.4. Interactive 3D Visualization Engine

Unlike traditional 2D static diagrams, the visualization module was implemented using **pyqtgraph.opengl** to provide a True-3D experience.

- **Rendering:** The system renders data elements as 3D Cubes (GLMeshItem) within a 3D coordinate space.
- **Interactivity:** Users can rotate the scene 360 degrees and zoom in/out using mouse controls to inspect the data structure from any angle.
- **Animation:** A custom animation loop (QTimer) was implemented to interpolate the movement of cubes. When a user performs a "Push" operation, the cube does not appear

instantly; instead, it smoothly translates from the source position to its calculated destination within the stack or queue, reinforcing the concept of data flow.

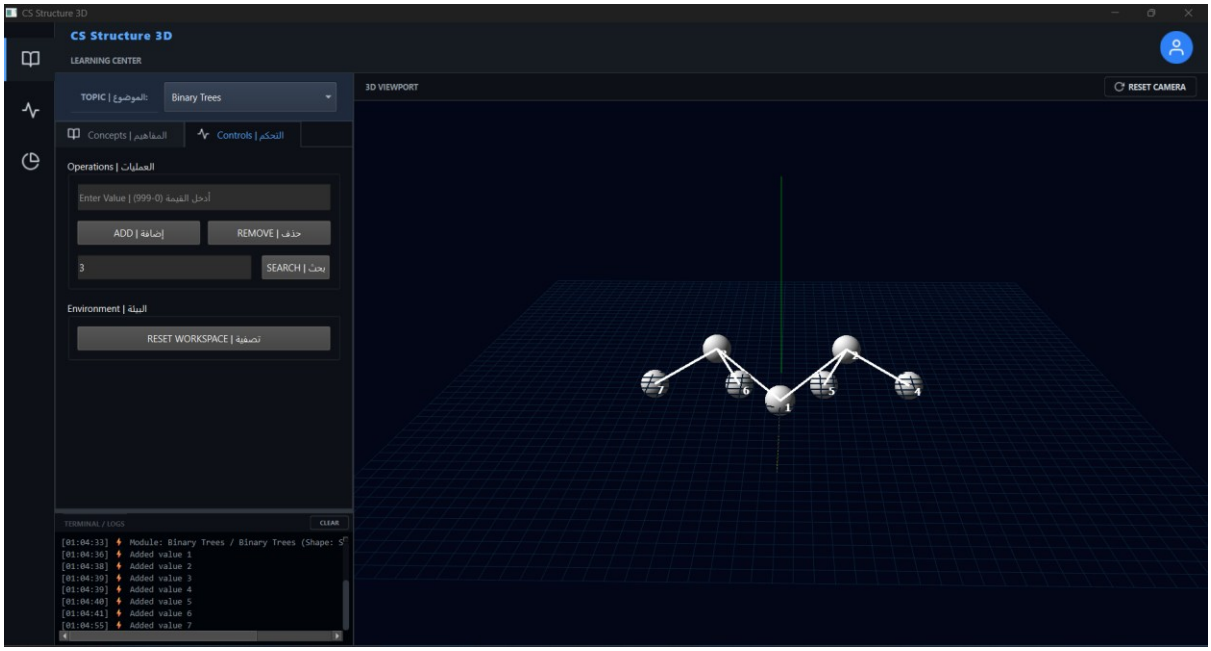


Figure 15: Interactive 3D Visualization Engine

4.5. System Verification

To ensure the integrity of the implemented modules, a verification process was conducted:

1. **Functional Verification:** Each simulation (e.g., Stack operations) was tested against theoretical expected outputs to ensure the 3D visual transitions accurately represent the logic of the data structure.
2. **Interface Verification:** The GUI was tested for responsiveness and error handling during the 50% implementation phase, confirming that user inputs trigger the correct simulation events.
3. **Cross-Platform Testing:** The application was verified on different OS environments to confirm that all libraries (PyQt6 and VPython) behave consistently without platform-specific bugs."

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