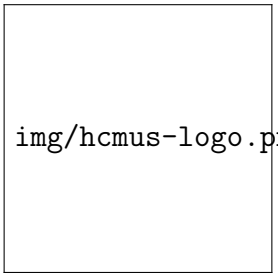

TRƯỜNG ĐẠI HỌC KHOA HỌC TỰ NHIÊN
– ĐẠI HỌC QUỐC GIA THÀNH PHỐ HỒ CHÍ MINH

Khoa Công nghệ Thông tin

CS163 – Data Structures and Algorithms

Interactive Data Structures Visualization using C++ and raylib

Nhóm thực hiện: 11

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Abstract

This project presents a desktop application written entirely in C++ using the raylib graphics library to visualize fundamental data structures. The tool helps students intuitively understand the behaviors of singly linked lists, graphs, hash tables, and AVL trees through animated simulations and interactive controls. While full source code highlighting is only implemented in the Graph module and visualization speed control is not yet available, the application provides undo functionality for all insert and delete operations. Future enhancements include user-defined visual customization and step-by-step control for all structures.

1. Introduction

Understanding data structures is foundational to algorithm design and software development. However, the abstract nature of linked lists, trees, hash tables and graphs makes them difficult for beginners to grasp. This project offers an interactive visualization platform to demystify these core structures, enabling learners to observe their operations graphically and in real time.

2. Group Information

Our team worked modularly: Lộc developed the main framework (‘main.cpp‘) to serve as a base for integrating submodules, Khôi chose the color scheme and handled final integration, while each member contributed equally to development and testing. Below is our role breakdown.

Name	**Role(s)**	**Contribution Description**	**%**
Nguyễn Đình Thiên Lộc	UI Logic, Report Writer& SLL Dev	Developed ‘main.cpp‘ for central control, implemented SLL, tested application, structured report	33.3%
Văn Tuấn Khải	Graph & Hash Table Dev	Implemented Kruskal’s Algorithm, "Courier Bold" Font and HashTable logic	33.3%
Phan Minh Khôi	AVL Dev & Merger	Built AVL Tree module, chose color palette, handled merging and final debugging	33.3%

Table 1: Team members and equal contributions

3. Data Storage

The application stores data in-memory using custom C++ structures. Each data structure maintains its own dynamic memory using pointers or arrays. Visual state transitions are stored as vectors of states, enabling the undo feature for insert/delete actions. File-based input is supported via text path entry (manual input);

4. Project Architecture

- **Language:** C++
- **Graphics:** raylib (cross-platform game graphics library)
- **Key Modules:**
  - `main.cpp` – UI control loop and screen routing
  - `sll/` – Singly Linked List
  - `graph/` – Graph (includes Kruskal's MST algorithm)
  - `hashtable/` – Hash Table with chaining
  - `avltree/` – AVL Tree with rotations
- **Development:** Modular C++ project, built using Makefile or Visual Studio

5. Implementation Details

- **SLL:** Insert, delete, traverse animations. Supports undo and step control.
- **Graph:** Kruskal's MST with edge selection and code highlighting. Step-by-step mode and highlighting implemented.
- **Hash Table:** Insert/delete/search with collision chaining. Supports undo.
- **AVL Tree:** Insert/delete with rotation visualization. Supports undo.
- **Modes:**
  - Step-by-step: Available in all modules
  - Run-at-once: Available in all modules
- **Undo:** Insert/delete undo implemented for all structures
- **Customization:** Speed and color configuration not yet supported
- **Source Code Highlighting:** Available only for Graph (Kruskal)

6. Technical Problems and Solutions

- **Animation timing:** Designed a manual frame-based system for syncing animation states
- **Independent rendering:** Each module uses its own drawing and logic pipeline, coordinated by a central controller
- **Highlighting sync:** Graph module draws code highlights in sync with each algorithm step using pre-parsed state logs

7. Features Demonstration

- Supports insertion, deletion, and traversal in SLL, AVL, Hash Table, and Graph
- Kruskal's algorithm is visualized with edge selection and code highlighting
- Undo functionality for insert/delete across all structures
- Step-by-step and Run-at-once modes
- File loading via text path (manual input), which is implemented using **tinyfiledialogs**

8. Implementation Details

This application was designed using a modular architecture, with each core data structure separated into its own logic, UI, and animation files. Each structure operates independently within a centralized controller.

Main Control Flow (Nguyễn Đình Thiên Lộc, Phan Minh Khôi)

The file `main.cpp` manages the application loop, window lifecycle, and UI routing. User interaction is handled through states and screen enums, and each module draws on top of its own canvas.

Singly Linked List (Nguyễn Đình Thiên Lộc)

- `linked_list_core.cpp` – Structure logic: insert, delete, undo
- `linked_list_animation.cpp` – Transitions and head/tail animations
- `linked_list_drawing.cpp` – Renders node graphics and pointer arrows
- `ui_linked_list.cpp` – Processes input, handles buttons and interaction

Flow Example: When the user clicks "Insert Head," `ui_linked_list.cpp` calls the logic in `linked_list_core.cpp`, pushes the new state to the undo stack, and then triggers visual changes via the animation file.

AVL Tree (Phan Minh Khôi)

- `AVLtree.cpp` – AVL logic: rotations, height balance, insert/delete
- `AVLtreeAnimation.cpp` – Click handling, animated placement
- `initAVLProgram.cpp` – Entry point for AVL visualizer, button router

Each insertion triggers a height update, imbalance check, and the corresponding rotation. These are visualized step-by-step.

Hash Table (Văn Tuấn Khải)

- `HashTable.cpp` – Insertion, deletion, probing, undo/redo stacks
- `hashtable_ui.cpp` – Button states, file input, user interface

Operations such as insertion are deferred until the search animation completes. States are stored before and after changes to enable full undo functionality.

Graph – Kruskal's Algorithm (Văn Tuấn Khải)

- `Graph.cpp` – Edge list, union-find, MST generator
- `ui_Graph.cpp` – Step-wise visualization and Kruskal interface
- `InputBox.cpp` – Graph node/edge input from user

Kruskal's steps are visualized in real-time. This module also includes dynamic source code highlighting to follow each logic branch.

9. User's Manual

This section provides installation, setup, and usage instructions for the Data Structure Visualizer.

9.1. Installation Requirements

- Windows or Linux OS
- C++17 compatible compiler (Visual Studio or g++)
- raylib graphics library (https://www.raylib.com/)
- (Optional) vcpkg for Windows or Makefile/CMake for Linux builds

For detailed raylib + vcpkg setup on Windows, see the guide:
https://www.youtube.com/watch?v=UiZGTIYld1M.

9.2. Building the Application

- **Windows:** Clone the repo, open in Visual Studio, install raylib via vcpkg, then build/run.
- **Linux:** Install raylib (`sudo apt install libraylib-dev`), run `make run` or use provided CMake files.

9.3. Usage Instructions

1. Choose a data structure from the main menu.
2. Enter data manually or load from a '.txt' file by typing the file path.
3. Select visualization mode: step-by-step or run-at-once.
4. Use on-screen or keyboard controls to navigate steps or replay.
5. Observe the visual operation and, for Graph, code highlighting.

9.4. Customization (Planned)

- Color themes are not yet implemented.
- Visualization speed can be changed in Graph module.

9.5. File Format Example

Input file should look like:

```
10 3 8 15 7
```

10. Tables

Feature	Status	Developer
Step-by-step Mode	Implemented	All
Run-at-once Mode	Implemented	All
Undo (Insert/Delete)	Implemented	All
Code Highlighting	Implemented	All
Speed Control	Only in Graph	Tuấn Khải
Font (Courier Bold)	Implemented	Tuấn Khải
History Box	Only in SLL	Thiên Lộc
Color Customization	Not Implemented	–

Table 2: Feature Support Summary

Component	Responsible Member(s)
`main.cpp`, core loop, screen routing	Nguyễn Đình Thiên Lộc
Singly Linked List	Nguyễn Đình Thiên Lộc
Report	Nguyễn Đình Thiên Lộc
Graph: Kruskal's MST, code highlighting	Văn Tuấn Khải
Hash Table logic	Văn Tuấn Khải
Font Incorporation	Văn Tuấn Khải
Color Palette Design (`Color.h`)	Phan Minh Khôi
Overall Integration (modular merge)	Phan Minh Khôi
AVL Tree logic, merger	Phan Minh Khôi

Table 3: Work Allocation by Module

11. Code Snippets

This section presents representative code snippets for each data structure, aligned with the actual implementation logic from the source files.

Singly Linked List – Search with Animation State

```
bool LinkedList::Search(int value) {
    if (!head) return false;

    foundNode = nullptr;
    cur = head;
    curPos = head->position;
    animState = AnimState::SEARCHING;
    animProgress = 0.0f;
    animNode = new Node(value, {0, 0});
    searchAttempted = true;

    return true;
}
```

Listing 1: SLL Search with Animation Setup

Hash Table – Insert with Undo Support

```
void HashTable::Insert(int val, bool isRandom) {
    ResetColors();
    int index = hashFunction(val);
    Node* temp = table[index];

    while (temp) {
        if (temp->val == val) {
            if (!isRandom) searchMessage = TextFormat("%d already exists.", val)
   ;
            return;
        }
        temp = temp->next;
    }

    if (!isRandom) {
        undoStack.push(CopyTable());
        while (!redoStack.empty()) redoStack.pop();
        showCalculation = true;
        insertedNode = nullptr;
    } else {
        showCalculation = false;
        insertedNode = nullptr;
        highlightInsert = -1;
    }
    PerformInsertion(val, isRandom);
}
```

Listing 2: Hash Table Insert with Chaining and Undo

AVL Tree – Deletion with Balance Checks

```
void AVLTree::remove(AVLNode*& node, int value) {
    if (!node) return;

    if (value > node->data) {
        remove(node->right, value);
    } else if (value < node->data) {
        remove(node->left, value);
    } else {
        if (!node->left) {
            AVLNode* temp = node;
            node = node->right;
            delete temp;
        } else if (!node->right) {
            AVLNode* temp = node;
            node = node->left;
            delete temp;
        } else {
            AVLNode* curr = minValueNode(node->right);
            node->data = curr->data;
            remove(node->right, curr->data);
        }
    }

    if (!node) return;

    int bf = getBalanceFactor(node);

    if (bf > 1 && getBalanceFactor(node->left) >= 0) {
        rightRotate(node);
    } else if (bf > 1 && getBalanceFactor(node->left) == -1) {
        leftRotate(node->left);
        rightRotate(node);
    } else if (bf < -1 && getBalanceFactor(node->right) <= 0) {
        leftRotate(node);
    } else if (bf < -1 && getBalanceFactor(node->right) == 1) {
        rightRotate(node->right);
        leftRotate(node);
    }
}
```

Listing 3: AVL Delete with Rotation Cases

Graph – Kruskal Step Animation

```
void Graph::UpdateKruskalStep() {
    if (isPaused) return;
    frameCounter++;

    if (stateOfCode == 1 && !initialDelayComplete) {
        if (frameCounter < 2 * animationSpeed / 3) return;
        dsu.Initialize(nodes.size());
        std::sort(edges.begin(), edges.end(), [](const Edge& a, const Edge& b) {
            return a.w < b.w;
        });
        initialDelayComplete = true;
        frameCounter = 0;
    }

    if (kruskalStep >= edges.size()) {
        stateOfCode = 6;
        message = "MST Complete";
        mstFinished = true;
        return;
    }

    Edge& currentEdge = edges[kruskalStep];
    int rootA = dsu.find_set(currentEdge.a);
    int rootB = dsu.find_set(currentEdge.b);
    if (rootA != rootB) {
        dsu.union_sets(rootA, rootB);
        currentEdge.inMST = true;
    }
    kruskalStep++;
    frameCounter = 0;
}
```

Listing 4: Step-by-Step Kruskal's MST Visualization

References

- Visualization Demo. (2024, Apr 1). *Interactive Data Structures Visualizer using C++ and raylib* [Video]. YouTube. https://www.youtube.com/watch?v=UiZGTIYld1M
- raylib Setup with vcpkg for Visual Studio. (n.d.). GitHub Wiki. https://github.com/raysan5/raylib/wiki/Working-on-Windows#visual-studio-vcpkg

12. Conclusion

The project successfully delivers a visual data structure learning tool built with C++ and raylib. It demonstrates modular programming, interactive animation, and effective state management. The recently added step-by-step mode enhances the educational value by allowing users to follow each algorithmic operation in detail.
Potential improvements include smoother and clearer animations, the addition of sound effects and background music for engagement, support for more advanced data structures, better control flow handling, and a customizable settings panel that allows users to adjust animation speed, themes, and interaction preferences.

Appendix A: Git Commit History

This appendix provides a complete record of the Git commit history for the project, detailing contributions across all branches (e.g., `master`, `dev`, `ui-linkedlist`). The history, generated using `git log -all -pretty=format:"%h - %an, %ad : %s"`, complements Table 3 (Work Allocation by Module) in Section 10 by providing a granular view of individual commits by Nguyễn Đình Thiên Lộc, Văn Tuấn Khải, and Phan Minh Khôi. It documents the development of data structures (Singly Linked List, AVL Tree, Hash Table, Graph) and UI features.

```
commit ed8ff0a5e2433c5c9dc3c7390c3100c20de20492
ed8ff0a | nguyendinhthienloc | 2025-04-26 | index on master: 2091835 Merge branch 'master' of https://github.com/nguyendinhthienloc/cs163
commit 0f01b8625e8060903e085ac8eef5c1a9ebdfe48f
0f01b86 | khoiLearnsToCode | 2025-04-26 | Minor AVL codeBox bug fix
commit f2733e2628603527f42a476aca393a760f98da6b
f2733e2 | nguyendinhthienloc | 2025-04-26 | Fix Deletion and Insertion
commit b2661f6ccc4201d5d7c2ca6467b12fa16a0e7679
b2661f6 | khoiLearnsToCode | 2025-04-26 | Fix bug for search codeBox
commit e5410abf3142bc407d8462cbbae9b96a21e9b2f9
e5410ab | nguyendinhthienloc | 2025-04-26 | Changed my directory and Added fixes to Linked List
commit e2cc43cd4e898028710fd398d400a983cc79a585
e2cc43c | tuankhai2006 | 2025-04-26 | minor change
commit 0f98c57ee881c9c46f60537eee4cc216f9054997
0f98c57 | khoiLearnsToCode | 2025-04-25 | Color modification for ht and AVL codeBox
commit e539f971cfe5cd373b4949a6a795c388017531f5
e539f97 | tuankhai2006 | 2025-04-25 | add update for ht
commit 3e18701301526b493a645a07cbeaae98f64b456f
3e18701 | khoiLearnsToCode | 2025-04-25 | Some new feature for AVL codeBox
commit d5cbda74ae57cea0769368cbd720faa32a1a931c
d5cbda7 | nguyendinhthienloc | 2025-04-25 | LaTeX files for Report
commit bdcae4f49c470769f63a9bd170e25534d3002509
bdcae4f | tuankhai2006 | 2025-04-25 | add codeBox for avl
commit dccf915546a99d889231ff36f218fe6c15adacbd
dccf915 | nguyendinhthienloc | 2025-04-25 | Fix deletion
commit 42814c7bdb6f31d8093f54590d02ca38ab5f0119
42814c7 | tuankhai2006 | 2025-04-25 | better font for avl
commit 3dee6d5499f032bcdca015ea5a04da963b84c187
3dee6d5 | tuankhai2006 | 2025-04-25 | better font for ht
commit 980df3b107a5c3d44aa544517810972b9bf6dea5
980df3b | tuankhai2006 | 2025-04-25 | change graph representation
commit 151b34d75b40172bacf5b598227214716bb258bf
151b34d | tuankhai2006 | 2025-04-24 | add highlight code for hashtable
commit 4e17468269e6de76150b843bc6fab3fe3a1850f0
4e17468 | tuankhai2006 | 2025-04-24 | change button position in hashtable
commit 1356f67508a3dbe53540f2961a33cf96855860f0
1356f67 | khoiLearnsToCode | 2025-04-24 | Fix file locating problem for tinyfiledialog.h
commit d0a3700480d7583e83fc2175c70b12c50367640e
d0a3700 | nguyendinhthienloc | 2025-04-22 | Add Pseudo Code illustration  + Smoother transition
commit 0c21473db59cb5c1925e7229665eb182779b270f
0c21473 | nguyendinhthienloc | 2025-04-21 | Enhance the step-by-step
```

```
commit 25570d21cf7d5bed9efce829d0a9888bdca50d63
25570d2 | nguyendinhthienloc | 2025-04-21 | Added necessary changes to Linked List
commit 992978bc61c85c05e5153e8f8433d92154b0bd31
992978b | khoiLearnsToCode | 2025-04-18 | Minor color fix for hashtable
commit e3c98bbfe7b2903df28e9eb93b7db13293cb5d2a
e3c98bb | tuankhai2006 | 2025-04-18 | add run at once for hashtable
commit 6b042a335f606fb87b7184b7bfd28d343ee9904d
6b042a3 | tuankhai2006 | 2025-04-18 | Add run at once for graph
commit f69aa8bc92eb783dedd6620fe7354167da0c62b9
f69aa8b | nguyendinhthienloc | 2025-04-18 | Update README.MD
commit 5689500c5d94753db1854717b4417cddd448a35c
5689500 | khoiLearnsToCode | 2025-04-17 | Add run-at-once function and fix stack bugs for AVL Tree
commit e0f184f87a14f18515e8f98e3333bca9dda2476f
e0f184f | khoiLearnsToCode | 2025-04-15 | Move exe, ttf and dll files into App folder
commit 6209122d91f91e7b65d3f5d018abea91717f2ce3
6209122 | khoiLearnsToCode | 2025-04-15 | Add exe and ddl files
commit 9ef35adb5e3b64d5a106958d28dea49ba488466e
9ef35ad | khoiLearnsToCode | 2025-04-13 | Delete exe file (not working)
commit 64fd168c8b712a81a657cc9d53b3e525890480fa
64fd168 | khoiLearnsToCode | 2025-04-13 | Need these 2 .ddl file for .exe file to run
commit a787c41bdba19352082ab1955088cff27b48128d
a787c41 | khoiLearnsToCode | 2025-04-13 | Done!
commit 37b7ed68f7d2eef68f02d6c7f8642057f8d0d76e
37b7ed6 | khoiLearnsToCode | 2025-04-12 | Minor bug fix
commit e3786b64e731ebd734ebd639c07b864507cabe19
e3786b6 | khoiLearnsToCode | 2025-04-12 | Upscale buttons and AVLTree, fix color
commit b2d05bd7bbc880bb284d7ddecbe9379cc639b5f3
b2d05bd | khoiLearnsToCode | 2025-04-12 | Erase <iostream> and unnecessary animations
commit 415d6139df62cca19e775e2acae717bd058c5f98
415d613 | khoiLearnsToCode | 2025-04-12 | merge graph successfully
commit 3c37e786c7cc58a76622a540fa1151ea29be634f
3c37e78 | tuankhai2006 | 2025-04-11 | add main function
commit 9fb2f94c8d6b46dd9aae2347b38ece85d4d29041
9fb2f94 | tuankhai2006 | 2025-04-09 | update input box and add instruction table
commit 17e9815ff6f9be8b4a2f1e9d686178556a69ede0
17e9815 | tuankhai2006 | 2025-04-06 | add matrix input
commit 91bba0f5ca0fcb3e745f9cbe4598c703319c33fa
91bba0f | tuankhai2006 | 2025-04-05 | update input box and graph check
commit 12c971be7d42ef73483b7d414ce525397d8143b8
12c971b | tuankhai2006 | 2025-04-05 | update input box
commit 377057d51d6f73eded73531f2e7ff224dc17d868
377057d | tuankhai2006 | 2025-04-05 | add input box
commit ec49060289e9a2ddbaf5047bc41c9786213c601d
ec49060 | khoiLearnsToCode | 2025-04-05 | add and merge hashtable
commit 46f56e7e196c02d2a8db04cc04dc15451d2dab08
46f56e7 | tuankhai2006 | 2025-04-04 | Change screen size with small modification
commit 8cad2853d11be45de9b4d2664d20debdedf6cc22
8cad285 | khoiLearnsToCode | 2025-04-03 | Merge ll and avltree
commit 5ebd7b31e2d135ee204e5b9d1ee6a99d5442e444
5ebd7b3 | khoiLearnsToCode | 2025-04-03 | Done
```

```
commit d15d55a21b4d76521877a02608d37ab6f5d9de08
d15d55a | tuankhai2006 | 2025-04-01 | min spanning tree visualization
commit 3b5594f9673c221aa0e0b987e92646dd8eee492a
3b5594f | tuankhai2006 | 2025-04-01 | clear graph branch
commit ffd7f8d80cfd45960d564bbd98fdc46a0255274c
ffd7f8d | nguyendinhthienloc | 2025-03-28 | Delete src/ui-linkedlist/README.md
commit 555c1b07870046185d9a050e5c0bf5c84cbeddd6
555c1b0 | nguyendinhthienloc | 2025-03-28 | Delete src/ui-linkedlist/main.cpp
commit 96e82cd03589c0a3063abbb48fdcf9ea8aec9902
96e82cd | nguyendinhthienloc | 2025-03-28 | Add Linked List files
commit 04a3ebaf0b0fa1976fffafc6c56cdb311eaf2529
04a3eba | khoiLearnsToCode | 2025-03-28 | add initAVLprogram
commit ca75572066d0347fbc8481ed05f9dfe5ceed9de2
ca75572 | khoiLearnsToCode | 2025-03-28 | small update main.cpp
commit 6d4a2b4352261de0c5063939e1aeebb18de415ea
6d4a2b4 | nguyendinhthienloc | 2025-03-27 | Delete src directory
commit 6319c428751fd0cf8792396305c8ecd525a31182
6319c42 | khoiLearnsToCode | 2025-03-27 | Update gitignore for VS
commit e619ca1a41ae26405fc8b6dcd5421cd9a81ac7ee
e619ca1 | nguyendinhthienloc | 2025-03-26 | Added Insert After feature
commit 79373eba96192673c8f5df82cdbadb489a22d9ad
79373eb | khoiLearnsToCode | 2025-03-26 | Add load file function
commit 7c7a724567ea56b01a834c874748dfdf2630bea1
7c7a724 | khoiLearnsToCode | 2025-03-26 | add color and <load file> button
commit 624daeda10f9727af481687f9a371f5f8879d19a
624daed | nguyendinhthienloc | 2025-03-22 | Delete src/linked_list.cpp
commit 111666c21e161c98a3a553c66ed938ceb4f26e9b
111666c | nguyendinhthienloc | 2025-03-22 | Delete src/ui.cpp
commit c339058769a6dd2dc27e1d961e93b8f6b9f194a5
c339058 | tuankhai2006 | 2025-03-21 | minor change
commit 616c83e686929886a8fa2838eb2b355536bd766d
616c83e | tuankhai2006 | 2025-03-21 | better file organize
commit 20600ce96a4f6424db8ca040c1c854bdfb66fd47
20600ce | nguyendinhthienloc | 2025-03-21 | Deleted files outside src
commit 7cc946cd18b83cf7df5f391a6df9557229bb1eab
7cc946c | nguyendinhthienloc | 2025-03-21 | Reorganize files
commit ee1be5930f340da671b1eecc50dad16117df2406
ee1be59 | nguyendinhthienloc | 2025-03-21 | Remove duplicate Linked List files
    from root directory
commit 8e2fe879d804ce4d12e7aac50f20b1e7b76f2a00
8e2fe87 | nguyendinhthienloc | 2025-03-21 | Divide the UI files into smaller
    files
commit 7101841e23959f106d3fe5fbaef289f0a0bb9087
7101841 | nguyendinhthienloc | 2025-03-21 | Delete .gitignore
commit dd253fb59dceebf456c5cb705fcb0ae20654b980
dd253fb | nguyendinhthienloc | 2025-03-21 | Delete Makefile.mak
commit 229cb977c5d847cfcf46c6f53d6baaaeba2473a6
229cb97 | nguyendinhthienloc | 2025-03-21 | Fixed undo button and make buttons
    more responsive
commit 315346d51cb33ce5baaca2888dde6b9fcd089f48
315346d | nguyendinhthienloc | 2025-03-21 | Delete src directory as we dont need
     it yet
commit e88d9ad14a06fa4238bafcfd3ac6a038dd627737
e88d9ad | nguyendinhthienloc | 2025-03-21 | Delete .gitignore cause its pretty
    useless
```

```
commit d8e5a5e83422aa3826d96ccd2d3fa180767df2dc
d8e5a5e | nguyendinhthienloc | 2025-03-21 | Update README.md
commit df45dd1e21c71626033cb940126ba6ae972a0d9f
df45dd1 | nguyendinhthienloc | 2025-03-20 | Added new features, debugged and completed Linked List =))
commit 4b7b3f4451bd1bd8fe7da8b2a3226b4cf76c265f
4b7b3f4 | nguyendinhthienloc | 2025-03-20 | Delete linked_list.cpp as I have alreadly split
commit cf24772ffa95a054857eccccb11e8a496ddd0c74
cf24772 | nguyendinhthienloc | 2025-03-20 | Split files and optimize further <33
commit a7ad8f8b67acdffbfc1f018a9cb43a51a80b9ef9
a7ad8f8 | nguyendinhthienloc | 2025-03-20 | Add files for Linked List visualization and UI
commit bdb36df08842e5b16541c99caa0c0656edb100d2
bdb36df | nguyendinhthienloc | 2025-03-20 | Switched to Visual Studio and created the sub-program to test LinkedList
commit 0d978dc0d5ff07e910b326a1ee15583d83bd0ca8
0d978dc | tuankhai2006 | 2025-03-20 | minor change in drawing function
commit 5b88e2a9c78e124bd1de84b01397f0d9cdefde0a
5b88e2a | khoiLearnsToCode | 2025-03-20 | Fixed collision, fixed line collision within the node
commit 79f7db9da6918fe396879c500190bf69ab81f578
79f7db9 | tuankhai2006 | 2025-03-19 | update load from file function
commit b906c2ac4efe42201f14f35c1ddae7ed6c189085
b906c2a | khoiLearnsToCode | 2025-03-19 | Insert animation fixed. Added state stacks (undo & redo).
commit 346011b309dd062403f30f03ddeff7597758d5d1
346011b | khoiLearnsToCode | 2025-03-18 | Delete and search animation fixed, but insert animation got bugged. Need rotate animation and state stacks.
commit 21b4d484a4e50943c52c568aa5091358153fb0e3
21b4d48 | tuankhai2006 | 2025-03-18 | add load from file button
commit 939dd8c41e5eff04e07b296188d07ce7548eb255
939dd8c | tuankhai2006 | 2025-03-18 | Updated insertion and deletion animations
commit aa2b80d72b0d71941dd1b153c871bd8a6594ed17
aa2b80d | nguyendinhthienloc | 2025-03-18 | Update .gitignore and add required changes
commit e1dfcdc9c2afb77d296b286b96cae87cfae9ef4b
e1dfcdc | nguyendinhthienloc | 2025-03-18 | Move ui.h and ui.cpp from ui-linkedlist to dev branch
commit f0be45d991df2ef65d64b816e1a00243f4ed6100
f0be45d | nguyendinhthienloc | 2025-03-17 | Removed w64devkit
commit ef58095150d3cec4309e12406016834353431095
ef58095 | nguyendinhthienloc | 2025-03-17 | Removed Makefile.mak from master
commit 571ceb214b285f9ece5afb52930a615fb35b3eb6
571ceb2 | nguyendinhthienloc | 2025-03-17 | Removed w64devkit from dev
commit ba6c37d1f19eca89529a3488558ca28f64859baf
ba6c37d | khoiLearnsToCode | 2025-03-17 | Debug random, delete logic successfully. Need fixing delete animation and add random animation.
commit ef5393edc2006c71609b678989bf90268272abbd
ef5393e | nguyendinhthienloc | 2025-03-17 | Moved Makefile from master to dev
commit 5ed30b7b009746f3b5dbf2929e2b41bf835079a0
5ed30b7 | nguyendinhthienloc | 2025-03-17 | Moved main.cpp to dev branch
commit e8da482a12db3c8ab0efca4968ba06aa6d2fb5c6
e8da482 | nguyendinhthienloc | 2025-03-17 | Initial UI & Linked List Integration : Insert, Delete, Search, Update + UI Transitions
```

```
commit cc33b837845b8b133344d9bdfe34ab3ef63f96dc
cc33b83 | nguyendinhthienloc | 2025-03-17 | Linked List updated with 3 files
commit 0d50aff841d33b4d0e6dd9cacafc4f5352da5213
0d50aff | nguyendinhthienloc | 2025-03-17 | Remove TestAVL folder from ui-linkedlist
commit b594168cff6859bbe9009b366df25bfc1bcb0c54
b594168 | nguyendinhthienloc | 2025-03-17 | Remove UI files from master to keep it clean
commit 446bd11dcc79fec03cd213ecfc03563cfac57c9d
446bd11 | nguyendinhthienloc | 2025-03-17 | Move UI files related to Linked List to ui-linkedlist branch
commit dca3f16a5934d9c209a121d8bfdda72f8c73c2d8
dca3f16 | nguyendinhthienloc | 2025-03-17 | Move Linked List files to ui-linkedlist branch
commit d6fb462e10c827646f296fb8bf6cebb84eae1eff
d6fb462 | nguyendinhthienloc | 2025-03-17 | Remove AVL Tree files from master to keep it clean
commit 81e0f8888b5e818668ea1f39bbd55b1638e66e88
81e0f88 | khoiLearnsToCode | 2025-03-16 | Insert animation almost finished, need rotate animation, fix deletion's and random's bugs.
commit bc90504e3d3cbe2eae98b301b820baa91b5a412f
bc90504 | tuankhai2006 | 2025-03-16 | Minor change
commit 7edc45298a7abc1d40215456e3429e8ac7701de5
7edc452 | tuankhai2006 | 2025-03-15 | Updated hash table implementation
commit 2eb71ecb8100b00e9f703badaa11756eef5b79b6
2eb71ec | nguyendinhthienloc | 2025-03-02 | Initial commit: Cleaned up project structure, added src and README
commit 6d0f3b26e31d00bc27179c5d175e27bc8364038d
6d0f3b2 | nguyendinhthienloc | 2025-03-02 | Removed unnecessary files
commit bbf334a6cf7efc7d4eb3a10dc0abc5e6dbb404c8
bbf334a | nguyendinhthienloc | 2025-03-02 | Updated visuals and fullscreen mode
commit 711764a7e76f8041dfce38dc3009881dbe8ab529
711764a | Loc | 2025-02-17 | Added linked list and main window files
```

Listing 5: Complete Commit History Across All Branches

Appendix B: Repository and Video

- GitHub Repository: https://github.com/nguyendinhthienloc/cs163
- Demo Video (YouTube): https://youtu.be/29hX_Gt-rks