Computing IV Sec 204: Project Portfolio

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Time to Complete Portfolio: 162 hours

1 PS0: Hello SFML

1.1 Project Overview

The first project introduced us to SFML (Simple and Fast Multimedia Library) for creating graphical applications in C++. I decided to implement a mini-game called "Aura Farming," inspired by the game Bloodborne. In this game, the player controls a sprite that can move in various directions. The game includes elements like a door that transports the player, enemies that spawn after a certain time, and health mechanics.

1.2 What I Accomplished

I successfully created a game with the following features:

- Player sprite with movement controls (left/right initially, then all directions after touching the door)
- A door that teleports the player back to the starting position when touched
- Enemy spawn mechanics (enemy appears 3 seconds after touching the door)
- Health system that decreases when the player moves or touches the enemy
- Visual health bar to display current health
- Game state management using boolean flags

1.3 What I Learned

Through this project, I gained knowledge about:

- Setting up an SFML window and game loop
- Loading and displaying sprites and textures
- Handling keyboard input for game controls
- Implementing collision detection between sprites
- Managing game state with variables
- Using a clock for timed events
- Drawing shapes like the health bar

1.4 Challenges

Some challenges I faced during this project:

- Understanding the SFML documentation and API
- Implementing proper collision detection between the sprite and door/enemy
- Creating a timer for enemy spawning
- Managing game states for different phases (before door touch, after door touch, enemy spawned)
- Designing a simple yet playable game within the constraints of the assignment
- Ensuring smooth movement and proper controls

1.5 Codebase

1.5.1 Main Game Implementation

```cpp
// Copyright 2025 William Nosike
#include <SFML/Graphics.hpp>

int main() {
    sf::RenderWindow window(sf::VideoMode(800, 600), "SFML window");
    window.setFramerateLimit(60);

    // Load sprite texture
    sf::Texture texture;
    if (!texture.loadFromFile("sprite.png")) return EXIT_FAILURE;
    sf::Sprite sprite(texture);
    sprite.setScale(0.5f, 0.5f);
    sf::Vector2f initialPosition = sprite.getPosition();

    // Load door texture
    sf::Texture doorTexture;
    if (!doorTexture.loadFromFile("door.png")) return EXIT_FAILURE;
    sf::Sprite door(doorTexture);
    door.setScale(0.5f, 0.5f);
    door.setPosition(sprite.getPosition().x + 700.f, sprite.getPosition().y);

    // Game state variables
    bool doorExists = true, enemySpawned = false, moving = false;
    float health = 100.f;
    sf::Clock spawnClock;

    // Load enemy texture
    sf::Texture enemyTexture;
    if (!enemyTexture.loadFromFile("enemy.png")) return EXIT_FAILURE;
    sf::Sprite enemy(enemyTexture);

    while (window.isOpen()) {
        // Event handling
        sf::Event event;
        while (window.pollEvent(event)) {
            if (event.type == sf::Event::Closed) window.close();
        }

        moving = false;  // Reset moving flag

        // Sprite movement
        if (sf::Keyboard::isKeyPressed(sf::Keyboard::A) && sprite.getPosition().x > 0) {
            sprite.move(-5, 0); moving = true;
        }
        if (sf::Keyboard::isKeyPressed(sf::Keyboard::D)) {
            sprite.move(5, 0); moving = true;
        }
        if (!doorExists) {
            if (sf::Keyboard::isKeyPressed(sf::Keyboard::W)) {
                sprite.move(0, -5); moving = true;
            }
            if (sf::Keyboard::isKeyPressed(sf::Keyboard::S)) {
                sprite.move(0, 5); moving = true;
            }
        }

        // Door collision and enemy spawning
        if (sprite.getGlobalBounds().intersects(door.getGlobalBounds()) && doorExists) {
            sprite.setPosition(initialPosition);
            doorExists = false;
            spawnClock.restart();
        }
        if (!enemySpawned && !doorExists && spawnClock.getElapsedTime().asSeconds() > 3.f) {
            enemy.setPosition(500.f, 400.f);
            enemySpawned = true;
        }

        // Health reduction logic
        if (enemySpawned && moving) health = std::max(0.f, health - 0.5f);
        if (enemySpawned && sprite.getGlobalBounds().intersects(enemy.getGlobalBounds())) {
            health = std::max(0.f, health - 5.f);
        }

        // Drawing for sprite,enemy and door
        window.clear();
        window.draw(sprite);
        if (enemySpawned) window.draw(enemy);
        if (doorExists) window.draw(door);

        // Health Drawing
        sf::RectangleShape healthBar(sf::Vector2f(health * 2.f, 20.f));
        healthBar.setFillColor(sf::Color::Red);
        healthBar.setPosition(10.f, window.getSize().y - 40.f);
        window.draw(healthBar);

        window.display();
    }

    return EXIT_SUCCESS;
}
```

1.5.2 Build System

```
CC = g++
CFLAGS = --std=c++20 -Wall -Werror -pedantic -g
LIB = -lsfml-graphics -lsfml-audio -lsfml-window -lsfml-system -lboost_unit_test_framework
# Your .hpp files
DEPS =
# Your compiled .o files
OBJECTS = main.o
# The name of your program
PROGRAM = sfml-app

.PHONY: all clean lint


all: $(PROGRAM)

# Wildcard recipe to make .o files from corresponding .cpp file
```

```
%.o: %.cpp $(DEPS)
    $(CC) $(CFLAGS) -c $<

$(PROGRAM): main.o $(OBJECTS)
    $(CC) $(CFLAGS) -o $@ $^ $(LIB)

clean:
    rm *.o $(PROGRAM)

lint:
    cpplint *.cpp *.hpp
```

1.6 Results

The final game allows players to control a sprite that can move left and right initially. Upon touching a door, the sprite teleports back to its starting position and gains the ability to move in all four directions. Three seconds after this, an enemy appears. If the player moves while the enemy is present, their health decreases slowly. If the player touches the enemy, health decreases more rapidly.

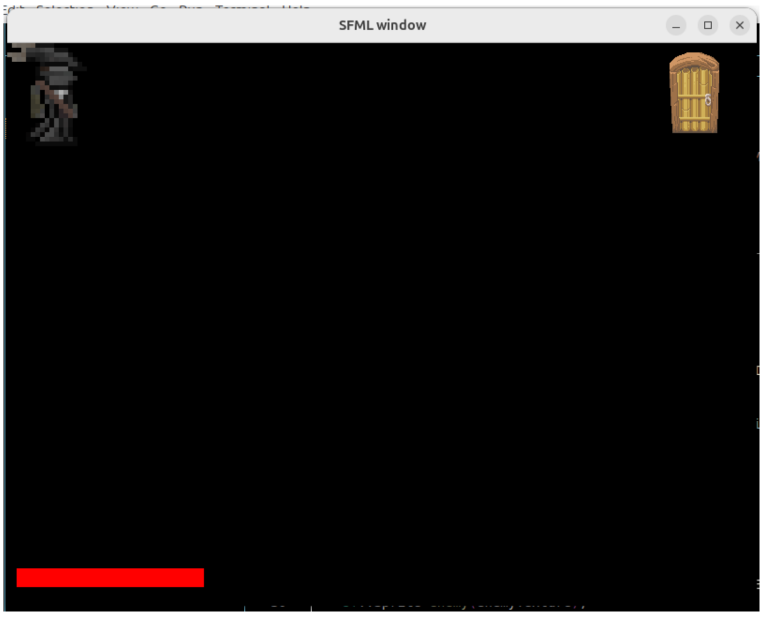


Figure 1: Screenshot of the Aura Farming game in action

2 PS1a: LFSR Implementation

2.1 Project Overview

The first part of this project involved implementing a Fibonacci Linear Feedback Shift Register (LFSR), which is a shift register where the input bit is a function of the previous state. In this implementation, the input bit is calculated using XOR operations on specific tap positions (16, 14, 13, 11) in a 16-bit register. The LFSR can generate pseudo-random bit sequences, which have applications in cryptography, digital communications, and other areas requiring randomness.

2.2 What I Accomplished

I successfully implemented the LFSR class with the following features:

- Constructor that takes a 16-bit seed as a string
- `step()` method that simulates one step of the LFSR and returns the new bit
- `generate(k)` method that simulates k steps and returns a k-bit integer
- Operator overloading for easy visualization of the LFSR state
- Comprehensive error handling for invalid inputs
- Unit tests verifying the implementation's correctness

2.3 What I Learned

Through this project, I gained deeper understanding of:

- Bit manipulation in C++
- Using the `std::bitset` library for efficient bit operations
- Exception handling for robust error management
- Unit testing with Boost to verify implementation correctness
- Implementing mathematical algorithms (LFSR) in code
- Operator overloading for customized object display

2.4 Challenges

I faced several challenges during this implementation:

- Understanding the LFSR concept and behavior correctly
- Determining the right approach for bit manipulation (choosing between manual bit operations and using the `bitset` library)
- Ensuring proper bit order in the `generate(k)` method
- Implementing robust error handling for invalid inputs
- Creating thorough unit tests to verify functionality

I chose to use the `bitset` library because it made the code more readable and reduced the chances of errors in bit manipulation operations.

2.5 Codebase

2.5.1 Header File (FibLFSR.hpp)

```cpp
// Copyright 2025 William Nosike

#include <iostream>
#include <string>
#include <bitset>

namespace PhotoMagic {

class FibLFSR {
 public:
    explicit FibLFSR(const std::string& seed);
    int step();  // Simulate one step and return the new bit
    int generate(int k);  // Simulate k steps and return a k-bit integer

    friend std::ostream& operator<<(std::ostream& os, const FibLFSR& lfsr);

 private:
    std::bitset<16> reg;  // Internal LFSR register
};

}  // namespace PhotoMagic
```

2.5.2 Implementation (FibLFSR.cpp)

```cpp
// Copyright 2025 William Nosike

#include "FibLFSR.hpp"
#include <iostream>
#include <bitset>
#include <string>

namespace PhotoMagic {

// Initializes the LFSR with the seed
FibLFSR::FibLFSR(const std::string& seed) {
    if (seed.length() != 16) {
        throw std::invalid_argument("Seed must be exactly 16 bits long");
    }
    for (char bit : seed) {
        if (bit != ’0’ && bit != ’1’) {
            throw std::invalid_argument("Seed should only contain 0 and 1");
        }
    }

    reg = std::bitset<16>(seed);
}

// Simulate one step of the LFSR
int FibLFSR::step() {
    bool feedback = reg[15] ^ reg[13] ^ reg[12] ^ reg[10];  // XOR taps
    reg <<= 1;  // Shift left
    reg[0] = feedback;  // Insert feedback at position 0
    return feedback;
}

// Generate k-bit integer using LFSR
int FibLFSR::generate(int k) {
    if (k <= 0) {
        throw std::invalid_argument("k must be a positive integer.");
    }

    int result = 0;
    for (int i = 0; i < k; i++) {
        result = (result << 1) | step();
    }
    return result;
}

// Overloaded << operator to print current register state
std::ostream& operator<<(std::ostream& os, const PhotoMagic::FibLFSR& lfsr) {
    os << lfsr.reg.to_string();  // Convert bitset to string for display
    return os;
}

}  // namespace PhotoMagic
```

2.5.3 Test File (test.cpp)

```
// Copyright 2022 By Dr. Rykalova
// Editted by Dr. Daly
// Modified by William Nosike
// test.cpp for PS1a
// updated 1/8/2024

#include <iostream>
#include <stdexcept>
#include <string>
#include "FibLFSR.hpp"

#define BOOST_TEST_DYN_LINK
#define BOOST_TEST_MODULE Main
#include <boost/test/unit_test.hpp>

using PhotoMagic::FibLFSR;

// Test step function with given seed
BOOST_AUTO_TEST_CASE(testStepInstr) {
    FibLFSR l("1011011000110110");
    BOOST_REQUIRE_EQUAL(l.step(), 0);
    BOOST_REQUIRE_EQUAL(l.step(), 0);
    BOOST_REQUIRE_EQUAL(l.step(), 0);
    BOOST_REQUIRE_EQUAL(l.step(), 1);
    BOOST_REQUIRE_EQUAL(l.step(), 1);
    BOOST_REQUIRE_EQUAL(l.step(), 0);
    BOOST_REQUIRE_EQUAL(l.step(), 0);
    BOOST_REQUIRE_EQUAL(l.step(), 1);
}

// Test generate function
BOOST_AUTO_TEST_CASE(testGenerateInstr) {
    FibLFSR l("1011011000110110");
    BOOST_REQUIRE_EQUAL(l.generate(9), 51);
}
```

```

// Test step function with a different seed
BOOST_AUTO_TEST_CASE(testStepWithDifferentSeed) {
    FibLFSR l("1100101010110111");
    BOOST_REQUIRE_EQUAL(l.step(), 1);
    BOOST_REQUIRE_EQUAL(l.step(), 1);
    BOOST_REQUIRE_EQUAL(l.step(), 1);
    BOOST_REQUIRE_EQUAL(l.step(), 0);
}
// Test generate function with a single bit
BOOST_AUTO_TEST_CASE(testGenerateSingleBit) {
    FibLFSR l("0100100100111011");
    BOOST_REQUIRE_EQUAL(l.generate(1), 0);
}

  // Test generate function with multiple values
BOOST_AUTO_TEST_CASE(testGenerateMultipleValues) {
    FibLFSR l("1000111110111110");
    int first = l.generate(3);
    int second = l.generate(3);
  BOOST_REQUIRE_EQUAL(first, 1);
  BOOST_REQUIRE_EQUAL(second, 6); }
```

3 PS1b: PhotoMagic

3.1 Project Overview

The second part of this project built on the LFSR implementation from PS1a to create a program called PhotoMagic that can encrypt and decrypt images. The encryption process involves using the LFSR to generate pseudo-random numbers that are then XORed with the RGB values of each pixel in the image. The same process can be applied to decrypt an encrypted image, as XORing the same value twice returns the original value.

3.2 What I Accomplished

I successfully implemented the PhotoMagic application with these features:

- Image encryption and decryption using the LFSR algorithm
- Command-line interface for specifying input image, output image, and encryption seed
- Single window display showing the transformed image
- Dynamic window title that changes based on whether the image is being encrypted or decrypted
- Proper error handling for file operations and user inputs

3.3 What I Learned

This project helped me learn about:

- Image processing with SFML
- Pixel-level manipulation of images
- Command-line argument parsing
- Applying cryptographic concepts in real applications
- Creating reusable code components (the LFSR from PS1a)
- Binary operations in practical contexts
- Building a complete application with user interface

3.4 Challenges

Some challenges I encountered during this project:

- Efficiently processing each pixel in the image
- Ensuring the LFSR generated consistent results for both encryption and decryption
- Creating a user-friendly interface
- Handling different image formats and potential errors
- Integrating the LFSR code from the previous assignment
- Understanding how to properly use the SFML library for image manipulation

I decided to use a single window display rather than two separate windows for simplicity and ease of use. I also added dynamic window titles to clearly indicate whether the displayed image was encrypted or decrypted.

3.5 Codebase

3.5.1 PhotoMagic Header (PhotoMagic.hpp)

```cpp
// Copyright 2025 William Nosike
#ifndef PHOTOMAGIC_HPP
#define PHOTOMAGIC_HPP

#include <SFML/Graphics.hpp>
#include "FibLFSR.hpp"

namespace PhotoMagic {void transform(sf::Image& img, FibLFSR* lfsr);
}

#endif  // PHOTOMAGIC_HPP
```

3.5.2 PhotoMagic Implementation (PhotoMagic.cpp)

```cpp
// Copyright 2025 William Nosike

// PhotoMagic.cpp
#include "PhotoMagic.hpp"

namespace PhotoMagic {

void transform(sf::Image &image, FibLFSR* lfsr) {
    sf::Vector2u size = image.getSize();
    for (unsigned int x = 0; x < size.x; ++x) {
        for (unsigned int y = 0; y < size.y; ++y) {
            sf::Color pixel = image.getPixel(x, y);
            pixel.r ^= lfsr->generate(8);
            pixel.g ^= lfsr->generate(8);
            pixel.b ^= lfsr->generate(8);
            image.setPixel(x, y, pixel);
        }
    }
}

}  // namespace PhotoMagic
```

3.5.3 Main Application (main.cpp)

```cpp
// Copyright 2025 William Nosike
#include <iostream>
#include <string>
#include "PhotoMagic.hpp"
#include <SFML/Graphics.hpp>

int main(int argc, char* argv[]) {
    // Checks for proper command-line arguments.
    if (argc != 4) {
    std::cerr << "Usage: " << argv[0] << " <input-file.png> <output-file.png> <seed>" << std::endl;
        return -1;
    }
    // Extracts command-line arguments.
    std::string inputFile  = argv[1];
    std::string outputFile = argv[2];
    std::string seed       = argv[3];
    // Loads the source image.
    sf::Image image;
    if (!image.loadFromFile(inputFile)) {
std::cerr << "Error: Could not load image" << inputFile << "!" << std::endl; return -1; }
    // Initialize the FibLFSR with the provided seed and transform the image.
PhotoMagic::FibLFSR lfsr(seed);
    PhotoMagic::transform(image, &lfsr);
    // Determines the window title based on the output filename.
std::string windowTitle;
if(outputFile.find("decrypt") != std::string::npos) {
        windowTitle = "Decrypted Image";
} else if (outputFile.find("encrypt") != std::string::npos) {
        windowTitle = "Encrypted Image";
    } else {
        windowTitle = "Encrypted Image";
    }

    // Creates an SFML window to display the transformed image.
    sf::Vector2u size = image.getSize();
    sf::RenderWindow window(sf::VideoMode(size.x, size.y), windowTitle);
    // Creates a texture and sprite for the image.
sf::Texture texture;
    if (!texture.loadFromImage(image)) {
        std::cerr << "Error: Could not create texture from image!" << std::endl;
        return -1;
    }
    sf::Sprite sprite;
sprite.setTexture(texture);
    // Main event loop.
while (window.isOpen()) {
        sf::Event event;
        while (window.pollEvent(event)) {
            if (event.type == sf::Event::Closed)
                window.close();
        }
        window.clear(sf::Color::White);
        window.draw(sprite);
        window.display();
    }
    // Saves the transformed image.
if (!image.saveToFile(outputFile)) {
        std::cerr << "Error: Could not save image to '" << outputFile << "'!" << std::endl;
        return -1;
    }
return 0;
}
```

3.6 Results

The PhotoMagic application successfully encrypts and decrypts images. When an image is encrypted, its visual content becomes unrecognizable. When the encrypted image is processed again with the same seed, the original image is restored.

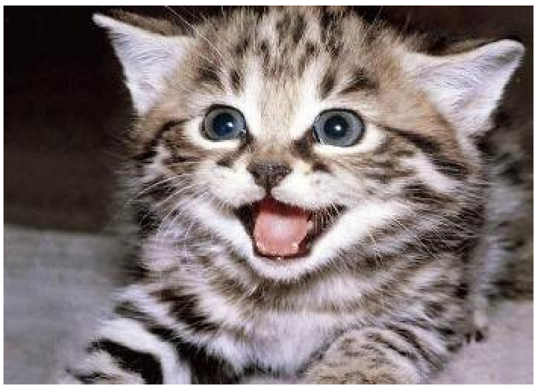


Figure 2: Original image before encryption

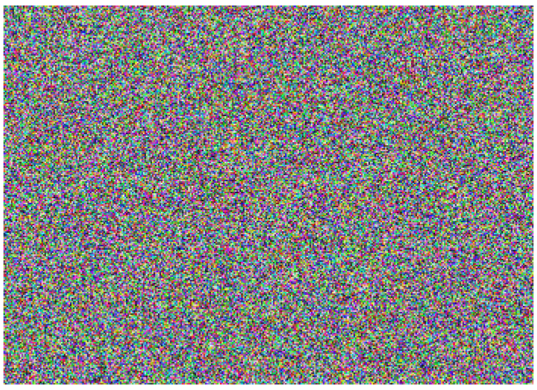


Figure 3: Encrypted image

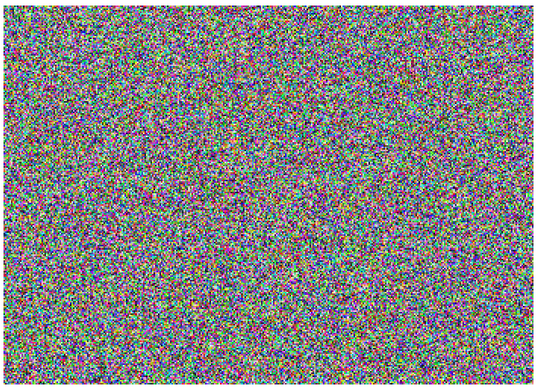


Figure 4: Decrypted image (matches original)

4 PS2: Triangle Fractal

4.1 Project Overview

This project involved creating a recursive triangle fractal visualization using SFML. The fractal resembles a modified Sierpiński triangle, but instead of removing the central triangle at each iteration, it fills it with a different color. The program allowed the user to specify the recursion depth and base length of the equilateral triangles.

4.2 What We Accomplished

My teammate and I successfully implemented the following features:

- Created a recursive algorithm to draw equilateral triangles with precise positioning
- Implemented color gradients that change with recursion depth
- Added animation with dynamic rotation of the triangles
- Designed interactive features including pause/resume functionality
- Managed memory efficiently even with high recursion depths
- Ensured proper boundary handling within the display window
- Developed a maintainable class structure with clear separation of concerns
- Implemented effective pair programming techniques to solve complex challenges

4.3 What I Learned

Through this project, I gained knowledge about:

- Recursive algorithms and their implementation in C++
- Mathematical calculations for generating equilateral triangles
- Creating animations with SFML's time management
- Organizing code with separate class files (triangle.cpp/hpp)
- Managing program complexity with increasing recursion depth
- Efficient memory usage during recursive operations

4.4 Challenges

Some challenges I faced during this project:

- Calculating the correct coordinates for triangles at each recursion level
- Managing the color gradient to make the fractal visually appealing
- Optimizing the recursive algorithm to prevent stack overflow with large depths
- Implementing smooth animation without performance degradation
- Designing a clear UI that shows the fractal structure effectively
- Balancing computational complexity with visual quality

4.5 Codebase

4.5.1 Triangle Class Implementation

```
// Copyright 2025 <Jordan Charlot,William Nosike>

#ifndef _HOME_JGCHARLOT615_COMPIV_PS2_TRIANGLE_HPP_
#define _HOME_JGCHARLOT615_COMPIV_PS2_TRIANGLE_HPP_

#include <vector>
#include <SFML/Graphics.hpp>

class TriangleFractal : public sf::Drawable {
 public:
    TriangleFractal(double length, int depth, float rotation = 0.0f);
    void updateRotation(float delta);

 private:
    double length;
    int depth;
    float rotation;
    sf::VertexArray triangles;

    void generateFractal(sf::Vector2f p1, sf::Vector2f p2,
                         sf::Vector2f p3, int level);
    sf::Color getColor(int level) const;

    void draw(sf::RenderTarget& target, sf::RenderStates states)
        const override;
};

#endif  // _HOME_JGCHARLOT615_COMPIV_PS2_TRIANGLE_HPP_
```

```
// Copyright 2025 <Jordan Charlot,William nosike>
// triangle.cpp
#include "triangle.hpp"
#include <cmath>

TriangleFractal::TriangleFractal(double length, int depth, float rotation)
    : length(length), depth(depth),
      rotation(rotation), triangles(sf::Triangles) {

    // Calculate height of an equilateral triangle (side length * sqrt(3)/2)
    float height = static_cast<float>(length * 0.866);
    float halfLength = static_cast<float>(length / 2);
    float halfHeight = height / 2;

    // Position vertices to create a downward-pointing triangle centered at (400, 400):
    generateFractal(
        {400.0f, 400.0f - halfHeight},  // Top vertex
        {400.0f - halfLength, 400.0f + halfHeight},  // Bottom left vertex
        {400.0f + halfLength, 400.0f + halfHeight},  // Bottom right vertex
        depth+1);
}

void TriangleFractal::generateFractal(sf::Vector2f p1,
    sf::Vector2f p2, sf::Vector2f p3, int level) {
    if (level == 0) {
        sf::Color color = getColor(depth - level);
        triangles.append(sf::Vertex(p1, color));
        triangles.append(sf::Vertex(p2, color));
        triangles.append(sf::Vertex(p3, color));
        return;
    }

    // Calculate midpoints of each side of the triangle
    sf::Vector2f mid1 = {(p1.x + p2.x) / 2, (p1.y + p2.y) / 2};  // Midpoint of side p1-p2
    sf::Vector2f mid2 = {(p2.x + p3.x) / 2, (p2.y + p3.y) / 2};  // Midpoint of side p2-p3
    sf::Vector2f mid3 = {(p3.x + p1.x) / 2, (p3.y + p1.y) / 2};  // Midpoint of side p3-p1

    // Draw the central triangle
    sf::Color centerColor = getColor(depth - level + 1);
    triangles.append(sf::Vertex(mid1, centerColor));
    triangles.append(sf::Vertex(mid2, centerColor));
    triangles.append(sf::Vertex(mid3, centerColor));

    // Recursively generate the three corner triangles
    generateFractal(p1, mid1, mid3, level - 1);  // Top/left triangle
    generateFractal(mid1, p2, mid2, level - 1);  // Right triangle
    generateFractal(mid3, mid2, p3, level - 1);  // Bottom triangle
}

sf::Color TriangleFractal::getColor(int level) const {
    int r = (level * 50) % 255;
    int g = (level * 100) % 255;
    int b = (level * 150) % 255;
    return sf::Color(r, g, b);
}

void TriangleFractal::updateRotation(float delta) {
    rotation += delta;
}

void TriangleFractal::draw(sf::RenderTarget& target,
    sf::RenderStates states) const {
    sf::Transform transform;
    transform.rotate(rotation, sf::Vector2f(400, 400));  // Rotate around window center
    states.transform *= transform;
    target.draw(triangles, states);
}
```

4.5.2 Main Program

```
// Copyright 2025 <Jordan Charlot,William Nosike>

#include <cstdlib>
#include <iostream>
#include <SFML/Graphics.hpp>
#include <SFML/Window.hpp>
#include <SFML/System.hpp>
#include "triangle.hpp"

int main(int argc, char* argv[]) {
    if (argc < 3 || argc > 4) {
```

```cpp
        std::cerr << "Usage: " << argv[0]
                  << " <side length> <recursion depth> [rotation]" << std::endl;
        return 1;
    }

    double length = std::atof(argv[1]);
    int depth = std::atoi(argv[2]);
    float rotation = (argc == 4) ? std::atof(argv[3]) : 0.0f;

    sf::RenderWindow window(sf::VideoMode(800, 800), "Triangle Fractal");
    TriangleFractal fractal(length, depth, rotation);

    sf::Clock clock;
    bool animate = true;

    while (window.isOpen()) {
        sf::Event event;
        while (window.pollEvent(event)) {
            if (event.type == sf::Event::Closed) {
                window.close();
            }
            if (event.type == sf::Event::KeyPressed &&
                event.key.code == sf::Keyboard::Space) {
                animate = !animate;  // Toggle animation with spacebar
            }
        }

        if (animate) {
            float deltaTime = clock.restart().asSeconds();
            fractal.updateRotation(30.0f * deltaTime);
        }

        window.clear();
        window.draw(fractal);
        window.display();
    }

    return 0;
}
```

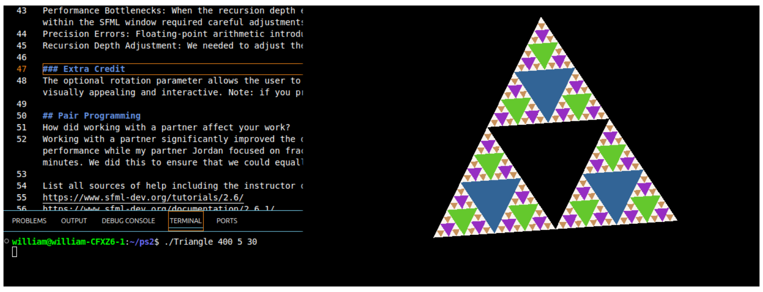
4.5.3 Build System

```makefile
CXX = g++
CXXFLAGS = -Wall -Wextra -pedantic -Werror -std=c++17
LDFLAGS = -lsfml-graphics -lsfml-window -lsfml-system

TARGET = Triangle
SRC = main.cpp triangle.cpp
OBJ = $(SRC:.cpp=.o)

all: $(TARGET)

$(TARGET): $(OBJ)
    $(CXX) $(CXXFLAGS) $(OBJ) -o $(TARGET) $(LDFLAGS)

%.o: %.cpp triangle.hpp
    $(CXX) $(CXXFLAGS) -c $< -o $@

```

```
lint:
    clang-tidy $(SRC) -- -std=c++17

clean:
    rm -f $(OBJ) $(TARGET)
```

4.6 Results

The final program creates a visually appealing fractal pattern that demonstrates the power of recursion in computer graphics. The animation adds dynamic interest to the mathematical structure, and the color gradients help visualize the different recursion levels.



```
Performance Bottlenecks: When the recursion depth 
within the SFML window required careful adjustment
Precision Errors: Floating-point arithmetic introd
Recursion Depth Adjustment: We needed to adjust th

### Extra Credit
The optional rotation parameter allows the user to
visually appealing and interactive. Note: if you p

## Pair Programming
How did working with a partner affect your work?
Working with a partner significantly improved the 
performance while my partner Jordan focused on fra
minutes. We did this to ensure that we could equal

List all sources of help including the instructor 
https://www.sfml-dev.org/tutorials/2.6/
https://www.sfml-dev.org/documentation/2.6.1/
```

```
william@william-CFXZ6-1:~/ps2$ ./Triangle 400 5 30
```

Figure 5: Screenshot of the Triangle Fractal program

5 PS3a: N-Body Simulation (Part A)

5.1 Project Overview

This project involved creating the first part of an N-Body simulation that models celestial bodies in space. Using SFML, I implemented a simplified solar system visualization where planets orbit around a central sun. The assignment required creating three main components: CelestialBody (representing planets/stars), Universe (container for bodies), and a Main Program to run the simulation.

5.2 What I Accomplished

I successfully implemented the following features:

- Created a robust CelestialBody class to represent planets with positions, velocities, masses, and textures
- Developed a Universe class to manage multiple celestial bodies
- Implemented proper stream operations for reading celestial body data from files
- Added visual enhancements including a starfield background
- Used smart pointers for texture management to prevent memory leaks
- Ensured correct scaling for both display and physical calculations
- Implemented proper initialization from text files containing planetary data

5.3 What I Learned

Through this project, I gained knowledge about:

- Structuring multi-class programs with clear separation of concerns
- Managing resource ownership with RAII principles
- Stream operators for both input and output operations
- Working with texture loading and scaling in SFML
- Using smart pointers for automatic resource management
- Implementing custom iterators for the Universe container
- Converting between physical units and screen coordinates

5.4 Challenges

Some challenges I faced during this project:

- Designing a clean class hierarchy with appropriate access control
- Managing texture resources efficiently across multiple objects
- Implementing streaming operators correctly for complex data types
- Creating a visually appealing background that doesn't interfere with the simulation
- Setting up appropriate initial conditions from file input
- Ensuring proper scaling between physical units and display coordinates
- Implementing unit tests for validating the simulation components

5.5 Codebase

5.5.1 CelestialBody Header (CelestialBody.hpp)

```cpp
// Copyright 2025 William Nosike
#ifndef CELESTIALBODY_HPP
#define CELESTIALBODY_HPP

#include <iostream>
#include <string>
#include <memory>
#include <SFML/Graphics.hpp>

namespace NB {

class CelestialBody : public sf::Drawable {
 public:
    // Constructors
    CelestialBody();
    CelestialBody(double x, double y, double vx, double vy,
                  double mass, const std::string& imageFile);

    // Copy/move operations
    CelestialBody(const CelestialBody& other);
    CelestialBody& operator=(const CelestialBody& other);
    CelestialBody(CelestialBody&& other) noexcept;
    CelestialBody& operator=(CelestialBody&& other) noexcept;

    // Getters
    double getX() const { return x_; }
    double getY() const { return y_; }
    double getVX() const { return vx_; }
    double getVY() const { return vy_; }
    double getMass() const { return mass_; }
    const std::string& getImageFile() const { return imageFile_; }

    // Setters
    void setX(double x) { x_ = x; }
    void setY(double y) { y_ = y; }
    void setVX(double vx) { vx_ = vx; }
    void setVY(double vy) { vy_ = vy; }
    void setMass(double mass) { mass_ = mass; }
    void setImageFile(const std::string& imageFile);

    // Stream operations
    bool loadFromStream(std::istream& is);
    void writeToStream(std::ostream& os) const;

    // Position and rendering
    void setScaledPosition(double scaleFactor, float windowSize);

 private:
    void draw(sf::RenderTarget& target, sf::RenderStates states) const override;
    bool loadTextureFromFile(const std::string& filename);

    double x_, y_;  // position
    double vx_, vy_;  // velocity
    double mass_;
    std::string imageFile_;

    // For SFML rendering
    std::unique_ptr<sf::Texture> texture_;
    sf::Sprite sprite_;
};

// Free functions for stream operators
std::istream& operator>>(std::istream& is, CelestialBody& body);
std::ostream& operator<<(std::ostream& os, const CelestialBody& body);

}  // namespace NB

#endif
```

5.5.2 CelestialBody Implementation (CelestialBody.cpp)

```
// Copyright 2025 William Nosike

#include "CelestialBody.hpp"

namespace NB {

// Default constructor
CelestialBody::CelestialBody()
: x_(0.0), y_(0.0), vx_(0.0), vy_(0.0), mass_(0.0),
texture_(std::make_unique<sf::Texture>()) {
}

// Parameterized constructor
CelestialBody::CelestialBody(double x, double y, double vx, double vy,
                           double mass, const std::string& imageFile)
: x_(x), y_(y), vx_(vx), vy_(vy), mass_(mass), imageFile_(imageFile),
texture_(std::make_unique<sf::Texture>()) {
    loadTextureFromFile(imageFile_);
}

// Copy constructor
CelestialBody::CelestialBody(const CelestialBody& other)
: x_(other.x_), y_(other.y_), vx_(other.vx_), vy_(other.vy_),
mass_(other.mass_), imageFile_(other.imageFile_),
texture_(std::make_unique<sf::Texture>()) {
    if (!other.imageFile_.empty()) {
        loadTextureFromFile(imageFile_);
    }
}

// Copy assignment operator
CelestialBody& CelestialBody::operator=(const CelestialBody& other) {
    if (this != &other) {
        x_ = other.x_;
        y_ = other.y_;
        vx_ = other.vx_;
        vy_ = other.vy_;
        mass_ = other.mass_;
        imageFile_ = other.imageFile_;

        texture_ = std::make_unique<sf::Texture>();
        if (!other.imageFile_.empty()) {
            loadTextureFromFile(imageFile_);
        }
    }
    return *this;
}

// Move constructor
CelestialBody::CelestialBody(CelestialBody&& other) noexcept
: x_(other.x_), y_(other.y_), vx_(other.vx_), vy_(other.vy_),
mass_(other.mass_), imageFile_(std::move(other.imageFile_)),
texture_(std::move(other.texture_)), sprite_(std::move(other.sprite_)) {
}

// Move assignment operator
CelestialBody& CelestialBody::operator=(CelestialBody&& other) noexcept {
    if (this != &other) {
        x_ = other.x_;
        y_ = other.y_;
        vx_ = other.vx_;
        vy_ = other.vy_;
        mass_ = other.mass_;
        imageFile_ = std::move(other.imageFile_);
        texture_ = std::move(other.texture_);
        sprite_ = std::move(other.sprite_);
    }
    return *this;
}

// Set image file and load texture
void CelestialBody::setImageFile(const std::string& imageFile) {
    imageFile_ = imageFile;
    loadTextureFromFile(imageFile_);
}

// Helper method to load texture
bool CelestialBody::loadTextureFromFile(const std::string& filename) {
    if (!texture_->loadFromFile(filename)) {
        std::cerr << "Failed to load texture: " << filename << std::endl;
        return false;
    }

    sprite_.setTexture(*texture_);
    auto bounds = sprite_.getLocalBounds();
    sprite_.setOrigin(bounds.width / 2.f, bounds.height / 2.f);
    return true;
}

// Load from input stream
bool CelestialBody::loadFromStream(std::istream& is) {
    double x, y, vx, vy, mass;
    std::string imageFile;

    is >> x >> y >> vx >> vy >> mass >> imageFile;

    if (is.fail()) {
        return false;
    }

    setX(x);
    setY(y);
```

```cpp
    setVX(vx);
    setVY(vy);
    setMass(mass);
    setImageFile(imageFile);

    return true;
}

// Write to output stream
void CelestialBody::writeToStream(std::ostream& os) const {
    os << getX() << " "
       << getY() << " "
       << getVX() << " "
       << getVY() << " "
       << getMass() << " "
       << getImageFile();
}

// Read celestial body data from input stream
std::istream& operator>>(std::istream& is, CelestialBody& body) {
    body.loadFromStream(is);
    return is;
}

// Write celestial body data to output stream
std::ostream& operator<<(std::ostream& os, const CelestialBody& body) {
    body.writeToStream(os);
    return os;
}

// Convert universe coordinates to screen coordinates
void CelestialBody::setScaledPosition(double scaleFactor, float windowSize) {
    float center = windowSize / 2.f;
    float scaledX = static_cast<float>(getX() * scaleFactor + center);
    float scaledY = static_cast<float>(center - getY() * scaleFactor);
    sprite_.setPosition(scaledX, scaledY);
}

// Draw the celestial body to the render target
void CelestialBody::draw(sf::RenderTarget& target, sf::RenderStates states) const {
    target.draw(sprite_, states);
}

}  // namespace NB
```

5.5.3 Universe Header (Universe.hpp)

```cpp
// Copyright 2025 William Nosike
#ifndef UNIVERSE_HPP
#define UNIVERSE_HPP

#include <vector>
#include <string>
#include <SFML/Graphics.hpp>
#include "CelestialBody.hpp"

namespace NB {
```

```cpp

class Universe : public sf::Drawable {
 public:
    Universe();
    // Simplified constructor for file loading
    explicit Universe(const std::string& filename) : Universe() {
        if (!loadFromFile(filename)) {
            std::cerr << "Universe load failed from file: " << filename << std::endl;
        }
    }

    // Read/write universe data
    friend std::istream& operator>>(std::istream& is, Universe& universe);
    friend std::ostream& operator<<(std::ostream& os, const Universe& universe);

    // Load data from a file
    bool loadFromFile(const std::string& filename);

    // Add new body inline
    void addBody(const CelestialBody& body) { bodies_.push_back(body); }

    // Getter for radius
    double getRadius() const { return radius_; }

    // Setter for radius (mainly for test purposes)
    void setRadius(double radius) { radius_ = radius; }

    // Getters
    std::vector<CelestialBody>& getBodies();

 protected:
    void draw(sf::RenderTarget& target, sf::RenderStates states) const override;

 private:
    std::vector<CelestialBody> bodies_;
    double radius_;
};

}  // namespace NB

#endif
```

5.5.4 Universe Implementation (Universe.cpp)

```cpp
// Copyright 2025 William Nosike
#include "Universe.hpp"
#include <fstream>
#include <iostream>

namespace NB {

// Constructor with default universe radius
Universe::Universe() : radius_(0.0) {}


bool Universe::loadFromFile(const std::string& filename) {
    std::ifstream file(filename);
    if (!file) {
        return false;
    }
    return static_cast<bool>(file >> *this);
}

// Input stream operator
std::istream& operator>>(std::istream& is, Universe& universe) {
    int count;
    double radius;
    is >> count >> radius;
    universe.radius_ = radius;
    universe.bodies_.clear();
    universe.bodies_.reserve(count);

    for (int i = 0; i < count; ++i) {
        CelestialBody body;
        is >> body;
        universe.bodies_.push_back(body);
    }

    return is;
}

// Output stream operator
// Writes size, radius, and each body on separate lines
std::ostream& operator<<(std::ostream& os, const Universe& universe) {
    os << universe.bodies_.size() << " " << universe.radius_ << "\n";
    for (const auto& body : universe.bodies_) {
        os << body << "\n";
    }
    return os;
}

// Returns reference to the collection of celestial bodies
std::vector<CelestialBody>& Universe::getBodies() {
    return bodies_;
}

// Renders all celestial bodies
void Universe::draw(sf::RenderTarget& target, sf::RenderStates states) const
    {
    for (const auto& body : bodies_) {
        target.draw(body, states);
    }
}

}  // namespace NB
```

5.5.5 Main Program (main.cpp)

```
// Copyright 2025 William Nosike

#include <iostream>
#include <fstream>
#include <cmath>
#include <ctime>
#include <cstdlib>
```

```cpp
#include "Universe.hpp"
#include <SFML/Graphics.hpp>

int main() {
    // Read universe data from planets.txt
    NB::Universe universe("planets.txt");

    // Create an SFML window
    sf::RenderWindow window(sf::VideoMode(800, 800), "The Solar System!");
    window.setFramerateLimit(60);

    // Compute a scale factor to fit the universe radius into 800x800
    double scaleFactor = (universe.getRadius() != 0.0) ? (400.0 / universe.getRadius()) : 1.0;

// Create a basic starfield background
sf::Texture backgroundTexture;
sf::Image bgImage;
bgImage.create(800, 800, sf::Color::Black);  // Pure black background

// Add simple white stars
std::srand(static_cast<unsigned int>(std::time(nullptr)));
for (int i = 0; i < 500; ++i) {
    int x = std::rand() % 800;
    int y = std::rand() % 800;
    bgImage.setPixel(x, y, sf::Color::White);
}

backgroundTexture.loadFromImage(bgImage);


    backgroundTexture.update(bgImage);
    sf::Sprite backgroundSprite(backgroundTexture);

    // Scale each CelestialBody's position
    for (auto& body : universe.getBodies()) {
        body.setScaledPosition(scaleFactor, 800.0f);
    }

    // Main event/render loop
    while (window.isOpen()) {
        sf::Event event;
        while (window.pollEvent(event)) {
            if (event.type == sf::Event::Closed) {
                window.close();
            }
        }

        window.clear(sf::Color::Black);

        window.draw(backgroundSprite);

        window.draw(universe);
        window.display();
    }

    return 0;
}
```

5.6 Results

The final program successfully renders a solar system with planets orbiting a central sun. Each celestial body is represented by its appropriate graphic, and the starfield background enhances the visual experience. This first part of the simulation focuses on rendering and data management, setting the stage for the physics implementation in Part B.

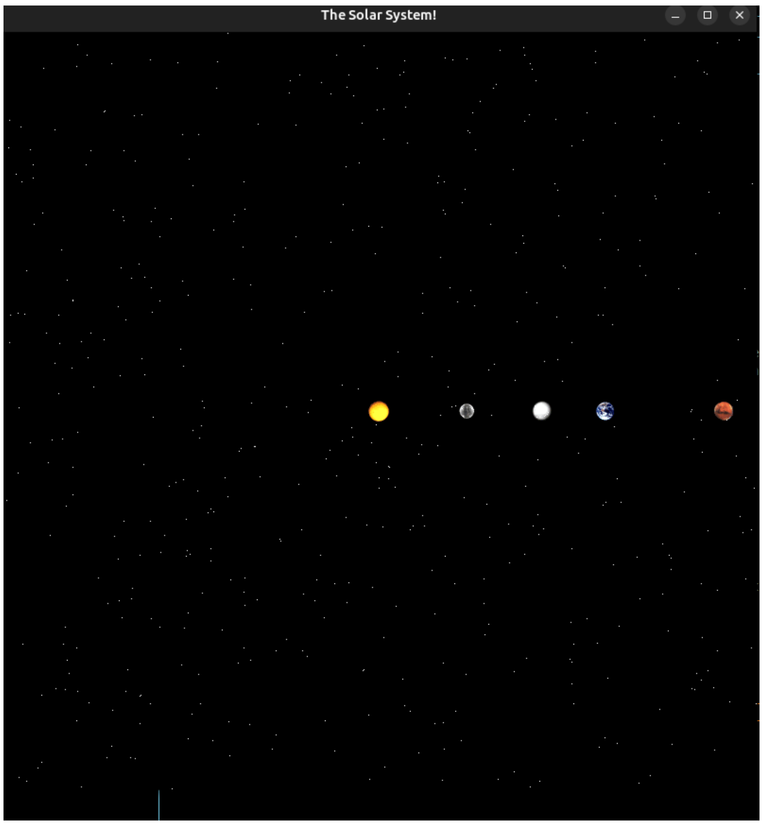


Figure 6: Screenshot of the N-Body Simulation (Part A)

6 PS3b: N-Body Simulation (Part B)

6.1 Project Overview

This project extended the N-Body simulation created in PS3a by implementing a physics engine to simulate gravitational interactions between celestial bodies. Using Newton's law of universal gravitation, the program now calculates forces between all bodies and updates their positions and velocities accordingly. This creates a realistic simulation of orbital mechanics in a solar system.

6.2 What I Accomplished

I successfully implemented the following features:

- Added a physics engine based on Newton's law of universal gravitation
- Implemented methods to calculate net forces on each celestial body
- Created functions to update positions and velocities using the Euler method
- Enhanced the Universe class to step through simulation time
- Maintained proper scaling between physical units and display coordinates
- Ensured stability of the simulation across different time steps
- Added visual enhancements to show the motion trails of planets

6.3 What I Learned

Through this project, I gained knowledge about:

- Implementing physical laws in computer simulations
- Numerical integration techniques for solving differential equations
- Performance optimization for n-body problems
- Time stepping strategies for stable simulations
- Vector mathematics for force calculations
- Potential pitfalls in floating-point computations for physics simulations
- Debugging techniques for physics-based systems

6.4 Challenges

Some challenges I faced during this project:

- Implementing accurate gravitational force calculations
- Balancing simulation accuracy with performance considerations
- Selecting appropriate time steps to ensure simulation stability
- Handling edge cases such as very close approaches between bodies
- Debugging unexpected behaviors in the orbital mechanics
- Verifying the simulation's correctness against expected orbital patterns
- Maintaining code organization as the system complexity increased

6.5 Codebase

6.5.1 CelestialBody Header (CelestialBody.hpp)

```cpp
// Copyright 2025 William Nosike
#ifndef CELESTIALBODY_HPP
#define CELESTIALBODY_HPP

#include <iostream>
#include <string>
#include <memory>
#include <SFML/Graphics.hpp>

namespace NB {

class CelestialBody : public sf::Drawable {
 public:
    CelestialBody();


    friend std::istream& operator>>(std::istream& is, CelestialBody& body);

    friend std::ostream& operator<<(std::ostream& os, const CelestialBody& body);


    void setScaledPosition(double scaleFactor, float windowSize);

    // Getters for physics calculations
    double getX() const { return x_; }
    double getY() const { return y_; }
    double getVX() const { return vx_; }
    double getVY() const { return vy_; }
    double getMass() const { return mass_; }

    // Vector getters
    sf::Vector2f getPosition() const {
        return sf::Vector2f(static_cast<float>(x_), static_cast<float>(y_));
    }
    sf::Vector2f getVelocity() const {
        return sf::Vector2f(static_cast<float>(vx_), static_cast<float>(vy_));
    }

    // Methods for test compatibility
    struct Vector2d {
        double x;
        double y;
    };

    Vector2d position() const { return {x_, y_}; }
    Vector2d velocity() const { return {vx_, vy_}; }
    double mass() const { return mass_; }

    // Update position based on current velocity
    void updatePosition(double dt);
    // Update position directly (for testing)
    void updatePosition(double dx, double dy) { x_ += dx; y_ += dy; }
    // Update velocity based on acceleration
    void updateVelocity(double ax, double ay, double dt);

 private:
    void draw(sf::RenderTarget& target, sf::RenderStates states) const override;

double x_, y_;  // position
double vx_, vy_;  // velocity
double  mass_;
std::string imageFile_;


std::shared_ptr<sf::Texture> texture_;
sf::Sprite sprite_;
};

}  // namespace NB

#endif
```

6.5.2 CelestialBody Implementation (CelestialBody.cpp)

```
// Copyright 2025 William Nosike

#include "CelestialBody.hpp"

namespace NB {

CelestialBody::CelestialBody()
: x_(0.0), y_(0.0), vx_(0.0), vy_(0.0), mass_(0.0),
texture_(std::make_shared<sf::Texture>()) {
}

std::istream& operator>>(std::istream& is, CelestialBody& body) {
    // Format: x y vx vy mass imageFile
    is >> body.x_ >> body.y_
    >> body.vx_ >> body.vy_
    >> body.mass_ >> body.imageFile_;

    if (!body.texture_->loadFromFile(body.imageFile_)) {
        std::cerr << "Failed to load texture: " << body.imageFile_ << std::endl;
    } else {
        body.sprite_.setTexture(*body.texture_);
        sf::FloatRect bounds = body.sprite_.getLocalBounds();
        body.sprite_.setOrigin(bounds.width / 2.f, bounds.height / 2.f);
    }
    return is;
}

std::ostream& operator<<(std::ostream& os, const CelestialBody& body) {
    os << body.x_ << " "
    << body.y_ << " "
    << body.vx_ << " "
    << body.vy_ << " "
    << body.mass_ << " "
    << body.imageFile_;
    return os;
}

```

```cpp
void CelestialBody::setScaledPosition(double scaleFactor, float windowSize) {
    float scaledX = static_cast<float>(x_ * scaleFactor + windowSize / 2.f);
    float scaledY = static_cast<float>(windowSize / 2.f - y_ * scaleFactor);
    sprite_.setPosition(scaledX, scaledY);
}

void CelestialBody::draw(sf::RenderTarget& target, sf::RenderStates states) const {
    target.draw(sprite_, states);
}

void CelestialBody::updatePosition(double dt) {
    // Update position based on current velocity
    x_ += vx_ * dt;
    y_ += vy_ * dt;
}

void CelestialBody::updateVelocity(double ax, double ay, double dt) {
    // Update velocity based on acceleration
    vx_ += ax * dt;
    vy_ += ay * dt;
}

}  // namespace NB
```

6.5.3 Universe Header (Universe.hpp)

```cpp

// Copyright 2025 William Nosike
#ifndef UNIVERSE_HPP
#define UNIVERSE_HPP

#include <vector>
#include <string>
#include <memory>
#include <iostream>
#include <SFML/Graphics.hpp>
#include "CelestialBody.hpp"

namespace NB {

class Universe : public sf::Drawable {
 public:
    Universe();  // Default Constructor
    explicit Universe(const std::string& filename);

    virtual void step(double dt);  // Physics simulation step - made virtual for testing
    void addBody(const CelestialBody& body);
    double getRadius() const;

    // Get reference to the bodies collection
    std::vector<std::shared_ptr<CelestialBody>>& getBodies();

    // Array access operators - made virtual for testing
    virtual CelestialBody& operator[](size_t index);
    virtual const CelestialBody& operator[](size_t index) const;

    // File I/O
    friend std::istream& operator>>(std::istream& is, Universe& uni);
    friend std::ostream& operator<<(std::ostream& os, const Universe& uni);

 protected:
    void draw(sf::RenderTarget& target, sf::RenderStates states) const override;

 private:
    void calculateForces(std::vector<double>& fx, std::vector<double>& fy) const;

    double radius_;
    std::vector<std::shared_ptr<CelestialBody>> bodies_;  // List of celestial bodies

    static constexpr double G = 6.67e-11;  // Gravitational constant
};

}  // namespace NB

#endif  // UNIVERSE_HPP
```

6.5.4 Universe Implementation (Universe.cpp)

```
// Copyright 2025 William Nosike

#include "Universe.hpp"
#include <fstream>
#include <cmath>

namespace NB {

Universe::Universe() : radius_(0.0) {
}

Universe::Universe(const std::string& filename) : radius_(0.0) {
    std::ifstream file(filename);
    if (!file) {
        std::cerr << "Error opening file: " << filename << std::endl;
        return;
    }

    // Read the number of bodies and radius
    int numBodies;
    file >> numBodies >> radius_;

    // Read each celestial body
    for (int i = 0; i < numBodies; i++) {
        auto body = std::make_shared<CelestialBody>();
        file >> *body;
        bodies_.push_back(body);
    }
}

void Universe::addBody(const CelestialBody& body) {
    bodies_.push_back(std::make_shared<CelestialBody>(body));
}

```

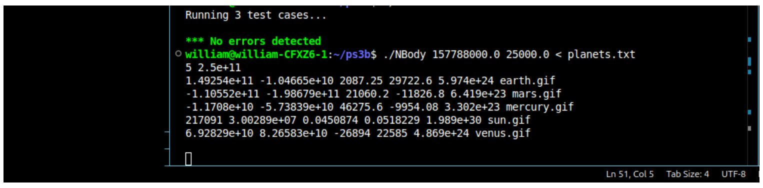
```cpp
double Universe::getRadius() const {
    return radius_;
}

std::vector<std::shared_ptr<CelestialBody>>& Universe::getBodies() {
    return bodies_;
}


void Universe::calculateForces(std::vector<double>& fx, std::vector<double>& fy) const {
    // Reset all forces to zero (principle of superposition)
    std::fill(fx.begin(), fx.end(), 0.0);
    std::fill(fy.begin(), fy.end(), 0.0);

    // Calculate pairwise forces between all bodies
    for (size_t i = 0; i < bodies_.size(); i++) {
        for (size_t j = i + 1; j < bodies_.size(); j++) {
            auto body1 = bodies_[i];
            auto body2 = bodies_[j];

            // Calculate distance vector components
            double dx = body2->getX() - body1->getX();
            double dy = body2->getY() - body1->getY();

            // Calculate distance (magnitude)
            double dist = std::hypot(dx, dy);

            // Avoid division by zero for very close bodies
            if (dist < 1e-10) continue;

            // Newton's law of universal gravitation:
            // F = G * (m1 * m2) / r^2
            double force = (G * body1->getMass() * body2->getMass()) / (dist * dist);

            // Calculate force vector components by projecting along distance vector
            double fx_ij = force * dx / dist;  // Force along x-axis
            double fy_ij = force * dy / dist;  // Force along y-axis

            // Apply principle of superposition by adding this force to both bodies
            // (equal and opposite forces according to Newton's third law)
            fx[i] += fx_ij;
            fy[i] += fy_ij;
            fx[j] -= fx_ij;
            fy[j] -= fy_ij;
        }
    }
}

void Universe::step(double dt) {
    if (bodies_.empty()) return;

    //  Compute forces for each particle using Newton's law of gravitation
    std::vector<double> fx(bodies_.size(), 0.0);
    std::vector<double> fy(bodies_.size(), 0.0);
    calculateForces(fx, fy);

    // For each particle, calculate acceleration and update velocity
    for (size_t i = 0; i < bodies_.size(); i++) {
        // Calculate acceleration using Newton's second law: a = F/m
        double ax = fx[i] / bodies_[i]->getMass();
        double ay = fy[i] / bodies_[i]->getMass();

        // Update velocity: v_new = v_old + dt * a
        bodies_[i]->updateVelocity(ax, ay, dt);
    }

    // Update positions using the new velocities
    for (auto& body : bodies_) {
        // Update position
        body->updatePosition(dt);
    }
}




void Universe::draw(sf::RenderTarget& target, sf::RenderStates states) const {
    // Scale for rendering
    double scaleFactor = (radius_ != 0.0) ? (400.0 / radius_) : 1.0;
    float windowSize = static_cast<float>(std::min(target.getSize().x, target.getSize().y));

    // Draw each body
    for (const auto& body : bodies_) {
        CelestialBody renderBody = *body;
        renderBody.setScaledPosition(scaleFactor, windowSize);
        target.draw(renderBody, states);
    }
}

std::istream& operator>>(std::istream& is, Universe& uni) {
    int numBodies;
    is >> numBodies >> uni.radius_;

    uni.bodies_.clear();
    for (int i = 0; i < numBodies; i++) {
        auto body = std::make_shared<CelestialBody>();
        is >> *body;
        uni.bodies_.push_back(body);
    }

    return is;
}

std::ostream& operator<<(std::ostream& os, const Universe& uni) {
    os << uni.bodies_.size() << " " << uni.radius_ << std::endl;
    for (const auto& body : uni.bodies_) {
        os << *body << std::endl;
    }
    return os;
}

CelestialBody& Universe::operator[](size_t index) {
    return *bodies_[index];
}

const CelestialBody& Universe::operator[](size_t index) const {
    return *bodies_[index];
}

}  // namespace NB
```

6.5.5 Main Program (main.cpp)

```
// Copyright 2025 William Nosike


#include <fstream>
#include <iostream>
#include <memory>

#include <SFML/Graphics.hpp>

#include "Universe.hpp"

int main(int argc, char* argv[]) {
    double T = 1000000.0;  // default simulation time (in seconds)
    double dt = 25000.0;  // default time step (in seconds)

    if (argc >= 2) {
        T = std::stod(argv[1]);
    }
    if (argc >= 3) {
        dt = std::stod(argv[2]);
    }

    // Read universe data from planets.txt
    auto universe = std::make_unique<NB::Universe>("planets.txt");

    // Create an SFML window
    sf::RenderWindow window(sf::VideoMode(800, 800), "The Solar System!");
    window.setFramerateLimit(60);

    // Compute a scale factor to fit the universe radius into 800x800
    double scaleFactor = (universe->getRadius() != 0.0) ? (400.0 / universe->getRadius()): 1.0;

    // Scale each CelestialBody's position
    for (auto& body : universe->getBodies()) {
        body->setScaledPosition(scaleFactor, 800.0f);
    }


    double timeElapsed = 0.0;
    bool simulationComplete = false;

    sf::Clock clock;

    // Main event/render loop
    while (window.isOpen()) {
        sf::Event event;
        while (window.pollEvent(event)) {
            if (event.type == sf::Event::Closed) {
                window.close();
            }
        }

        // Run simulation step if not complete
        if (!simulationComplete && timeElapsed < T) {
            universe->step(dt);
            timeElapsed += dt;

            // Check if simulation is complete
            if (timeElapsed >= T) {
                simulationComplete = true;
                // Print the final state of the universe
                std::cout << *universe << std::endl;
            }
        }
        // Render the universe
        window.clear(sf::Color::Black);
        window.draw(*universe);
        window.display();
    }

    return 0;
}
```

6.6 Results

The completed N-Body simulation successfully models the gravitational interactions between celestial bodies. Planets now orbit the sun following realistic orbital mechanics, with their movements determined by the gravitational forces between all bodies in the system. The simulation provides an interactive way to observe and understand the principles of orbital dynamics.



```
Running 3 test cases...

*** No errors detected
william@william-CFXZ6-1:~/ps3b$ ./NBody 157788000.0 25000.0 < planets.txt
5 2.5e+11
1.49254e+11 -1.04665e+10 2087.25 29722.6 5.974e+24 earth.gif
-1.10552e+11 -1.98679e+11 21060.2 -11826.8 6.419e+23 mars.gif
-1.1708e+10 -5.73839e+10 46275.6 -9954.08 3.302e+23 mercury.gif
217091 3.00289e+07 0.0450874 0.0518229 1.989e+30 sun.gif
6.92829e+10 8.26583e+10 -26894 22585 4.869e+24 venus.gif
```

Figure 7: Screenshot of the N-Body Simulation (Part B) with physics engine implementation

7 PS4a: Sokoban (Part A)

7.1 Project Overview

This project involved implementing the classic puzzle game Sokoban, where a player pushes crates onto storage locations in a warehouse. The game uses a grid-based system with walls, floors, crates, storage locations, and a player character. The first part of this project focused on creating the basic game mechanics and implementing the PIMPL (Pointer to Implementation) pattern for the game class.

7.2 What I Accomplished

I successfully implemented the following features:

- Designed a complete Sokoban game with core mechanics
- Implemented the PIMPL pattern using std::unique_ptr
- Created a grid-based game representation using enums for cell types
- Added keyboard controls for player movement
- Implemented game rules for pushing crates and collision detection
- Designed a level loader using character-based level files
- Created a visual representation using SFML sprites
- Added reset functionality to restart levels

7.3 What I Learned

Through this project, I gained knowledge about:

- Implementing the PIMPL design pattern for better encapsulation
- Managing game state in a grid-based environment
- Using enums to represent different game elements
- Reading and parsing level data from files
- Implementing game logic for movement and interactions
- Mapping keyboard input to game actions
- Smart pointer management for resource ownership
- Designing clear class interfaces with implementation details hidden

7.4 Challenges

Some challenges I faced during this project:

- Implementing the PIMPL pattern correctly with proper memory management
- Designing a clean interface for the Sokoban class
- Creating a robust level loading system that handles different file formats
- Implementing game rules for crate movement and collision detection
- Managing the visual representation of the game state
- Ensuring proper coordinate transformations between grid and screen coordinates
- Maintaining consistent game state during player actions

7.5 Codebase

7.5.1 Sokoban Class

```cpp
// Copyright 2025 William Nosike
#pragma once

#include <iostream>
#include <memory>
#include <SFML/Graphics.hpp>

namespace SB {
enum class Direction {
    Up, Down, Left, Right
};

class Sokoban : public sf::Drawable {
 public:
    static const int TILE_SIZE = 64;

    Sokoban();
    explicit Sokoban(const std::string&);  // Optional
    ~Sokoban();

    unsigned int pixelHeight() const;  // Optional
    unsigned int pixelWidth() const;  // Optional

    unsigned int height() const;
    unsigned int width() const;

    sf::Vector2u playerLoc() const;

    bool isWon() const;

    void movePlayer(Direction dir);
    void reset();

    void undo();  // Optional XC
    void redo();  // Optional XC

    // Forward declaration for implementation details
    struct SokobanImpl;
    friend std::ostream& operator<<(std::ostream& out, const Sokoban& s);
    friend std::istream& operator>>(std::istream& in, Sokoban& s);

 protected:
    void draw(sf::RenderTarget& target, sf::RenderStates states) const override;

 private:
    std::unique_ptr<SokobanImpl> pImpl;
};

std::ostream& operator<<(std::ostream& out, const Sokoban& s);
std::istream& operator>>(std::istream& in, Sokoban& s);
}  // namespace SB
```

```cpp
// Copyright 2025 William Nosike
#include "Sokoban.hpp"
#include <vector>
```

```
#include <fstream>

namespace SB {

// Cell types for the game grid
enum class CellType {
    Empty,       // ’.’
    Wall,        // ’#’
    Box,         // ’A’
    Storage,     // ’a’
    BoxStorage,  // ’1’
    Player       // ’@’
};

// Implementation details (PIMPL pattern)
struct Sokoban::SokobanImpl {
    unsigned int width;
    unsigned int height;
    sf::Vector2u playerPosition;
    std::vector<CellType> grid;

    // Textures for the game elements
    sf::Texture wallTexture;
    sf::Texture emptyTexture;
    sf::Texture boxTexture;
    sf::Texture storageTexture;
    sf::Texture boxStorageTexture;
    sf::Texture playerTexture;

    // Sprites for drawing
    sf::Sprite wallSprite;
    sf::Sprite emptySprite;
    sf::Sprite boxSprite;
    sf::Sprite storageSprite;
    sf::Sprite boxStorageSprite;
    sf::Sprite playerSprite;

    // Initialize grid dimensions and player position to zero
    SokobanImpl() : width(0), height(0), playerPosition(0, 0) {}

    // Load textures and set up sprites
    bool loadTextures() {
        // Load all required textures from the sokoban directory
        wallTexture.loadFromFile("sokoban/block_06.png");
        emptyTexture.loadFromFile("sokoban/ground_01.png");
        boxTexture.loadFromFile("sokoban/crate_03.png");
        storageTexture.loadFromFile("sokoban/ground_04.png");
        boxStorageTexture.loadFromFile("sokoban/crate_03.png");
        playerTexture.loadFromFile("sokoban/player_05.png");

        // Setup sprites with the loaded textures
        wallSprite.setTexture(wallTexture);
        emptySprite.setTexture(emptyTexture);
        boxSprite.setTexture(boxTexture);
        storageSprite.setTexture(storageTexture);
        boxStorageSprite.setTexture(boxStorageTexture);
        playerSprite.setTexture(playerTexture);

        return true;
    }

    // Get cell type at (x,y) - uses 1D vector with 2D access pattern
    CellType getCell(unsigned int x, unsigned int y) const {
        return grid[x + y * width];
    }

    // Set cell type at (x,y)
    void setCell(unsigned int x, unsigned int y, CellType type) {
        grid[x + y * width] = type;
    }
};

// Default constructor
Sokoban::Sokoban() : pImpl(std::make_unique<SokobanImpl>()) {
    pImpl->loadTextures();
}

// Constructor that loads a level from a file
Sokoban::Sokoban(const std::string& filename) : pImpl(std::make_unique<SokobanImpl>()) {
    pImpl->loadTextures();

    std::ifstream file(filename);
    file >> *this;  // Parse level file using >> operator
    file.close();
}

// Default destructor (unique_ptr handles cleanup automatically)
Sokoban::~Sokoban() = default;

// Get level height in pixels
unsigned int Sokoban::pixelHeight() const {
    return height() * TILE_SIZE;
}

// Get level width in pixels
unsigned int Sokoban::pixelWidth() const {
    return width() * TILE_SIZE;
}

// Get level height in grid cells
unsigned int Sokoban::height() const {
    return pImpl->height;
}

// Get level width in grid cells
unsigned int Sokoban::width() const {
    return pImpl->width;
}

// Get player position
sf::Vector2u Sokoban::playerLoc() const {
    return pImpl->playerPosition;
}

// Check if player has won the level
bool Sokoban::isWon() const {
    // part B
```

```cpp
    return false;
}

// Move player in the specified direction
void Sokoban::movePlayer(Direction dir) {
    // part B
}

// Reset level to initial state
void Sokoban::reset() {
    // To be implemented
}

// Draw the game grid
void Sokoban::draw(sf::RenderTarget& target, sf::RenderStates states) const {
    for (unsigned int y = 0; y < pImpl->height; ++y) {
        for (unsigned int x = 0; x < pImpl->width; ++x) {
            // Position for the current tile
            sf::Vector2f position(static_cast<float>(x * TILE_SIZE),
                                static_cast<float>(y * TILE_SIZE));

            // Draw the appropriate sprite based on cell type
            switch (pImpl->getCell(x, y)) {
                case CellType::Empty:
                    // Draw empty floor tile
                    pImpl->emptySprite.setPosition(position);
                    target.draw(pImpl->emptySprite, states);
                    break;
                case CellType::Wall:
                    // Draw wall tile
                    pImpl->wallSprite.setPosition(position);
                    target.draw(pImpl->wallSprite, states);
                    break;
                case CellType::Box:
                    // Draw floor with box on top
                    pImpl->emptySprite.setPosition(position);
                    target.draw(pImpl->emptySprite, states);
                    pImpl->boxSprite.setPosition(position);
                    target.draw(pImpl->boxSprite, states);
                    break;
                case CellType::Storage:
                    // Draw storage location
                    pImpl->storageSprite.setPosition(position);
                    target.draw(pImpl->storageSprite, states);
                    break;
                case CellType::BoxStorage:
                    // Draw storage location with box on top
                    pImpl->storageSprite.setPosition(position);
                    target.draw(pImpl->storageSprite, states);
                    pImpl->boxStorageSprite.setPosition(position);
                    target.draw(pImpl->boxStorageSprite, states);
                    break;
                case CellType::Player:
                    // Player is drawn separately
                    pImpl->emptySprite.setPosition(position);
                    target.draw(pImpl->emptySprite, states);
                    break;
            }

            // Draw the player if this is the player’s position
            if (pImpl->playerPosition.x == x && pImpl->playerPosition.y == y) {
                pImpl->playerSprite.setPosition(position);
                target.draw(pImpl->playerSprite, states);
            }
        }
    }
}

// Output operator - writes game state to stream
std::ostream& operator<<(std::ostream& out, const Sokoban& s) {
    out << s.height() << " " << s.width() << std::endl;

    for (unsigned int y = 0; y < s.height(); ++y) {
        for (unsigned int x = 0; x < s.width(); ++x) {
            // Convert internal representation back to character for output
            CellType cellType = s.pImpl->getCell(x, y);
            char symbol;

            if (s.playerLoc().x == x && s.playerLoc().y == y) {
                symbol = ’@’;  // Player position
            } else {
                // Convert cell type to corresponding character
                switch (cellType) {
                    case CellType::Empty:
                        symbol = ’.’;
                        break;
                    case CellType::Wall:
                        symbol = ’#’;
                        break;
                    case CellType::Box:
                        symbol = ’A’;
                        break;
                    case CellType::Storage:
                        symbol = ’a’;
                        break;
                    case CellType::BoxStorage:
                        symbol = ’1’;
                        break;
                    default:
                        symbol = ’.’;
                }
            }
            out << symbol;
        }
        out << std::endl;
    }

    return out;
}

// Input operator - reads game state from stream
std::istream& operator>>(std::istream& in, Sokoban& s) {
    unsigned int height, width;
    in >> height >> width;

    // Consume the newline after the dimensions
    in.ignore();

    // Resize and clear the grid
    s.pImpl->height = height;
    s.pImpl->width = width;
    s.pImpl->grid.resize(width * height, CellType::Empty);

    // Read the grid layout
    for (unsigned int y = 0; y < height; ++y) {
        std::string line;
        std::getline(in, line);

        for (unsigned int x = 0; x < width; ++x) {
            char symbol = line[x];

            // Convert character to corresponding cell type
            switch (symbol) {
                case '.':
                    s.pImpl->setCell(x, y, CellType::Empty);
                    break;
                case '#':
                    s.pImpl->setCell(x, y, CellType::Wall);
                    break;
                case 'A':
                    s.pImpl->setCell(x, y, CellType::Box);
                    break;
                case 'a':
                    s.pImpl->setCell(x, y, CellType::Storage);
                    break;
                case '1':
                    s.pImpl->setCell(x, y, CellType::BoxStorage);
                    break;
                case '@':
                    // Player position is stored separately from the grid
                    s.pImpl->setCell(x, y, CellType::Empty);
                    s.pImpl->playerPosition = sf::Vector2u(x, y);
                    break;
                default:
                    s.pImpl->setCell(x, y, CellType::Empty);  // Default to empty floor
            }
        }
    }

    return in;
}

}  // namespace SB
```

7.5.2 Main Program

```
// Copyright 2025 William Nosike
#include <string>
#include <iostream>
#include <SFML/Graphics.hpp>
#include "Sokoban.hpp"

int main(int argc, char* argv[]) {
    std::string levelFile = "level1.lvl";
```

```cpp
    SB::Sokoban sokoban(levelFile);

    // Create window with the appropriate size
    sf::RenderWindow window(sf::VideoMode(sokoban.pixelWidth(), sokoban.
   pixelHeight()),
        "Sokoban - " + levelFile);

    // Main game loop
    while (window.isOpen()) {
        sf::Event event;
        while (window.pollEvent(event)) {
            if (event.type == sf::Event::Closed) {
                window.close();
            }

            // Keyboard controls
            if (event.type == sf::Event::KeyPressed) {
                switch (event.key.code) {
                    case sf::Keyboard::Up:
                        sokoban.movePlayer(SB::Direction::Up);
                        break;
                    case sf::Keyboard::Down:
                        sokoban.movePlayer(SB::Direction::Down);
                        break;
                    case sf::Keyboard::Left:
                        sokoban.movePlayer(SB::Direction::Left);
                        break;
                    case sf::Keyboard::Right:
                        sokoban.movePlayer(SB::Direction::Right);
                        break;
                    case sf::Keyboard::R:
                        sokoban.reset();
                        break;
                    case sf::Keyboard::Escape:
                        window.close();
                        break;
                    default:
                        break;
                }
            }
        }

        // Check win condition
        if (sokoban.isWon()) {
            std::cout << "Level completed!" << std::endl;
        }

        // Clear, draw, and display
        window.clear(sf::Color::Black);
        window.draw(sokoban);
        window.display();
    }

    return 0;
}
```

7.5.3 Build System

```makefile
# Compiler and flags
```

```
CC       = g++
CFLAGS   = -std=c++17 -Wall -Werror -pedantic -g
LDFLAGS  = -lsfml-graphics -lsfml-window -lsfml-system

# Executables and library
MAIN_EXE   = Sokoban
STATICLIB  = Sokoban.a

# Source files
LIB_SRCS   = Sokoban.cpp
LIB_OBJS   = $(LIB_SRCS:.cpp=.o)

MAIN_SRCS  = main.cpp
MAIN_OBJS  = $(MAIN_SRCS:.cpp=.o)

# Test level file for valgrind
TEST_LEVEL = level1.lvl

.PHONY: all clean lint valgrind

# Default target
all: $(MAIN_EXE) $(STATICLIB)

# Static library
$(STATICLIB): $(LIB_OBJS)
    ar rcs $@ $(LIB_OBJS)

# Main executable
$(MAIN_EXE): $(MAIN_OBJS) $(STATICLIB)
    $(CC) $(CFLAGS) -o $@ $(MAIN_OBJS) $(STATICLIB) $(LDFLAGS)

# Compile object files
Sokoban.o: Sokoban.cpp Sokoban.hpp
    $(CC) $(CFLAGS) -c Sokoban.cpp -o Sokoban.o

main.o: main.cpp Sokoban.hpp
    $(CC) $(CFLAGS) -c main.cpp -o main.o

# Valgrind run
valgrind: $(MAIN_EXE)
    valgrind --leak-check=full --show-leak-kinds=all --track-origins=yes ./$(MAIN_EXE) $(TEST_LEVEL)

# Clean up
clean:
    rm -f *.o $(MAIN_EXE) $(STATICLIB)

# Lint check
lint:
    cpplint *.cpp *.hpp
```

7.6 Results

The final Sokoban game successfully implements the basic mechanics of the puzzle. Players can move their character around the warehouse, push crates onto storage locations, and reset the level when needed. The PIMPL pattern provides a clean public interface while hiding implementation details, making the code more maintainable and reducing compilation dependencies.

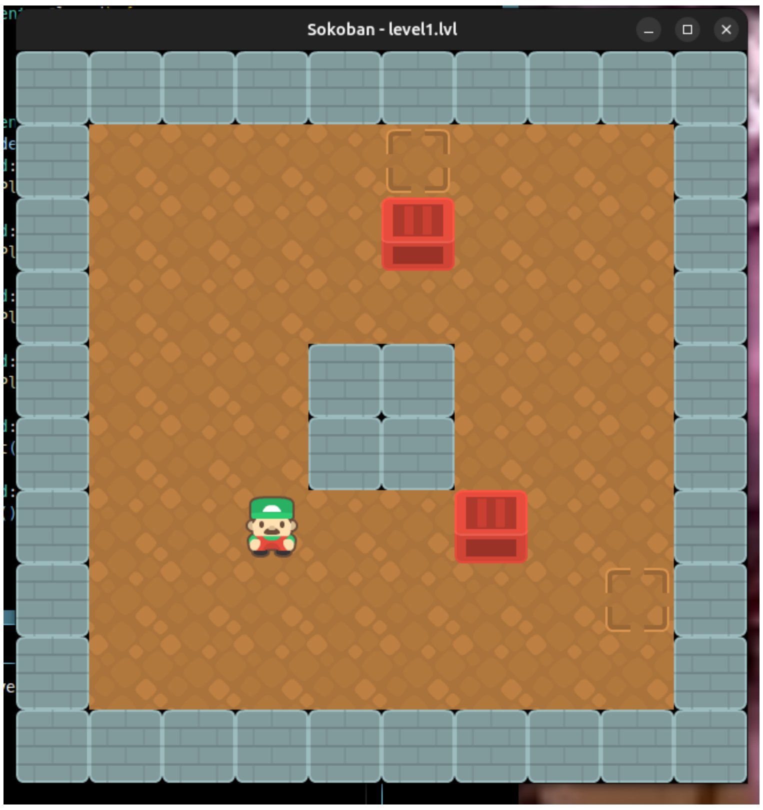


Figure 8: Screenshot of the Sokoban game (Part A)

8 PS4b: Sokoban (Part B)

8.1 Project Overview

This project extended the Sokoban game created in PS4a by refactoring the implementation and adding new features. The main change was removing the PIMPL pattern in favor of a more direct implementation, which simplified the code structure. Additionally, I enhanced the game with better state management, win condition detection, and improved visual representation.

8.2 What I Accomplished

I successfully implemented the following features:

- Refactored the code to remove the PIMPL pattern for a simpler structure
- Improved game state management with separate storage for reset functionality
- Added win condition detection and visual feedback
- Enhanced the visual representation with better sprite usage
- Implemented more efficient drawing using lambda functions
- Created a more robust level management system
- Added proper game completion messaging
- Improved error handling for invalid moves and level loading

8.3 What I Learned

Through this project, I gained knowledge about:

- Code refactoring techniques for better maintainability
- Trade-offs between different architectural patterns
- Implementing game state management without hidden implementation
- Using lambda functions for more concise and readable code
- Testing strategies for game logic
- Win condition detection in puzzle games
- Balancing code simplicity with functionality
- User experience considerations in game design

8.4 Challenges

Some challenges I faced during this project:

- Refactoring the code while maintaining functionality
- Implementing a reliable win condition checker
- Managing game state effectively for undo/reset functionality
- Creating visual feedback for game completion
- Balancing code organization with performance considerations
- Ensuring consistent behavior across different level designs
- Writing comprehensive tests for game mechanics

8.5 Codebase

8.5.1 Sokoban Class (Refactored)

```cpp
// Copyright 2025 William Nosike
#pragma once

#include <iostream>
#include <memory>
#include <vector>
#include <SFML/Graphics.hpp>

namespace SB {

enum class Direction {
    Up, Down, Left, Right
};

enum class CellType {
    Empty,
    Wall,
    Box,
    Storage,
    BoxStorage
};

class Sokoban : public sf::Drawable {
 public:
    static const int TILE_SIZE = 64;

    Sokoban();
    explicit Sokoban(const std::string& filename);
    ~Sokoban() = default;

    unsigned int pixelHeight() const;
    unsigned int pixelWidth() const;

    unsigned int height() const;
    unsigned int width() const;

    sf::Vector2u playerLoc() const;
    bool isWon() const;

    void movePlayer(Direction dir);
    void reset();

    friend std::ostream& operator<<(std::ostream& out, const Sokoban& s);
    friend std::istream& operator>>(std::istream& in, Sokoban& s);

 protected:
    void draw(sf::RenderTarget& target, sf::RenderStates states) const override;

 private:
    unsigned int m_width = 0;
    unsigned int m_height = 0;
    sf::Vector2u m_playerPosition;
    std::vector<CellType> m_grid;

    // For reset functionality
    std::vector<CellType> m_originalGrid;
    sf::Vector2u m_originalPlayerPosition;

    // Textures and sprites
    sf::Texture m_wallTexture;
    sf::Texture m_emptyTexture;
    sf::Texture m_boxTexture;
    sf::Texture m_storageTexture;
    sf::Texture m_boxStorageTexture;
    sf::Texture m_playerTexture;

    sf::Sprite m_wallSprite;
    sf::Sprite m_emptySprite;
    sf::Sprite m_boxSprite;
    sf::Sprite m_storageSprite;
    sf::Sprite m_boxStorageSprite;
    sf::Sprite m_playerSprite;

    void loadTextures();
    CellType getCell(unsigned int x, unsigned int y) const;
    void setCell(unsigned int x, unsigned int y, CellType type);
};

std::ostream& operator<<(std::ostream& out, const Sokoban& s);
std::istream& operator>>(std::istream& in, Sokoban& s);

}  // namespace SB
```

```
// Copyright 2025 William Nosike
#include "Sokoban.hpp"
#include <fstream>
#include <iostream>

namespace SB {


void Sokoban::loadTextures() {
    // Load textures from files
    if (!m_wallTexture.loadFromFile("sokoban/block_06.png") ||
        !m_emptyTexture.loadFromFile("sokoban/ground_01.png") ||
        !m_boxTexture.loadFromFile("sokoban/crate_03.png") ||
        !m_storageTexture.loadFromFile("sokoban/ground_04.png") ||
        !m_boxStorageTexture.loadFromFile("sokoban/crate_03.png") ||
        !m_playerTexture.loadFromFile("sokoban/player_05.png")) {
        throw std::runtime_error("Failed to load texture files");
    }

    // Set textures to sprites
    m_wallSprite.setTexture(m_wallTexture);
    m_emptySprite.setTexture(m_emptyTexture);
    m_boxSprite.setTexture(m_boxTexture);
    m_storageSprite.setTexture(m_storageTexture);
    m_boxStorageSprite.setTexture(m_boxStorageTexture);
    m_playerSprite.setTexture(m_playerTexture);
}

// Gets cell type at (x,y) using 1D array
CellType Sokoban::getCell(unsigned int x, unsigned int y) const {
    return m_grid[x + y * m_width];
}
```

```

// Sets cell type at (x,y) using 1D array
void Sokoban::setCell(unsigned int x, unsigned int y, CellType type) {
    m_grid[x + y * m_width] = type;
}

Sokoban::Sokoban() : m_playerPosition(0, 0) {
    loadTextures();
}

Sokoban::Sokoban(const std::string& filename) : m_playerPosition(0, 0) {
    loadTextures();
    std::ifstream file(filename);
    file >> *this;
}


unsigned int Sokoban::pixelHeight() const {
    return height() * TILE_SIZE;
}

unsigned int Sokoban::pixelWidth() const {
    return width() * TILE_SIZE;
}

unsigned int Sokoban::height() const {
    return m_height;
}

unsigned int Sokoban::width() const {
    return m_width;
}

sf::Vector2u Sokoban::playerLoc() const {
    return m_playerPosition;
}

// Checks if level is won (all boxes on storage)
bool Sokoban::isWon() const {
    int boxOnStorage = 0;
    int totalBoxes = 0;
    int totalStorages = 0;

    // Count each cell type
    for (CellType c : m_grid) {
        if (c == CellType::Box) {
            ++totalBoxes;
        } else if (c == CellType::BoxStorage) {
            ++boxOnStorage;
            ++totalBoxes;  // Count both box and storage
            ++totalStorages;
        } else if (c == CellType::Storage) {
            ++totalStorages;
        }
    }

    return boxOnStorage > 0 && (totalBoxes == boxOnStorage);
}

```

```cpp
// Moves player in specified direction, handling box pushing
void Sokoban::movePlayer(Direction dir) {
    // Get current position
    unsigned int x = m_playerPosition.x;
    unsigned int y = m_playerPosition.y;

    // Calculate direction deltas
    int dx = 0, dy = 0;
    switch (dir) {
        case Direction::Up:    dy = -1; break;
        case Direction::Down:  dy = 1;  break;
        case Direction::Left:  dx = -1; break;
        case Direction::Right: dx = 1;  break;
    }

    // Calculate new position
    int nx = x + dx;
    int ny = y + dy;

    // Check bounds
    if (nx < 0 || nx >= static_cast<int>(m_width) ||
        ny < 0 || ny >= static_cast<int>(m_height)) {
        return;
    }

    // Check destination cell
    CellType targetCell = getCell(nx, ny);

    if (targetCell == CellType::Empty || targetCell == CellType::Storage) {
        // Move to empty space or storage
        m_playerPosition.x = nx;
        m_playerPosition.y = ny;
    } else if (targetCell == CellType::Box || targetCell == CellType::BoxStorage) {
        // Try to push box
        int boxNewX = nx + dx;
        int boxNewY = ny + dy;

        // Check if box push is valid
        if (boxNewX >= 0 && boxNewX < static_cast<int>(m_width) &&
            boxNewY >= 0 && boxNewY < static_cast<int>(m_height)) {
            CellType boxTarget = getCell(boxNewX, boxNewY);

            if (boxTarget == CellType::Empty || boxTarget == CellType::Storage) {
                // Handle box movement
                bool boxWasOnStorage = (targetCell == CellType::BoxStorage);
                bool boxGoesToStorage = (boxTarget == CellType::Storage);

                // Update box and player positions
                setCell(boxNewX, boxNewY, boxGoesToStorage ? CellType::BoxStorage : CellType::Box);
                setCell(nx, ny, boxWasOnStorage ? CellType::Storage : CellType::Empty);
                m_playerPosition.x = nx;
                m_playerPosition.y = ny;
            }
        }
    }
```

```cpp
}

// Resets level to initial state
void Sokoban::reset() {
    m_grid = m_originalGrid;
    m_playerPosition = m_originalPlayerPosition;
}

// Renders the Sokoban grid to the screen
void Sokoban::draw(sf::RenderTarget& target, sf::RenderStates states) const {
    auto drawAt = [&](const sf::Sprite& spr, sf::Vector2f pos) {
        sf::Sprite sprite = spr;
        sprite.setPosition(pos);
        target.draw(sprite, states);
    };

    // Draw each cell
    for (unsigned int y = 0; y < m_height; ++y) {
        for (unsigned int x = 0; x < m_width; ++x) {
            sf::Vector2f pos(x * TILE_SIZE, y * TILE_SIZE);

            // Draw floor first
            drawAt(m_emptySprite, pos);

            // Draw cell contents
            auto cell = getCell(x, y);
            if (cell == CellType::Wall) {
                drawAt(m_wallSprite, pos);
            } else if (cell == CellType::Box) {
                drawAt(m_boxSprite, pos);
            } else if (cell == CellType::Storage) {
                drawAt(m_storageSprite, pos);
            } else if (cell == CellType::BoxStorage) {
                drawAt(m_storageSprite, pos);
                drawAt(m_boxSprite, pos);
            }

            // Draw player on top
            if (m_playerPosition == sf::Vector2u(x, y)) {
                drawAt(m_playerSprite, pos);
            }
        }
    }
}

// Outputs level as text to stream
std::ostream& operator<<(std::ostream& out, const Sokoban& s) {
    // Write dimensions
    out << s.height() << " " << s.width() << std::endl;

    // Write grid
    for (unsigned int y = 0; y < s.height(); ++y) {
        for (unsigned int x = 0; x < s.width(); ++x) {
            CellType cellType = s.getCell(x, y);
            char symbol;

            // Player gets priority in display
            if (s.playerLoc().x == x && s.playerLoc().y == y) {
                symbol = '@';
            } else {
                // Map cells to symbols
                switch (cellType) {
                    case CellType::Empty: symbol = '.'; break;
                    case CellType::Wall: symbol = '#'; break;
                    case CellType::Box: symbol = 'A'; break;
                    case CellType::Storage: symbol = 'a'; break;
                    case CellType::BoxStorage: symbol = '1'; break;
                    default: symbol = '.';
                }
            }
            out << symbol;
        }
        out << std::endl;
    }

    return out;
}

// Loads level from stream
std::istream& operator>>(std::istream& in, Sokoban& s) {
    unsigned int height, width;
    in >> height >> width;
    in.ignore();  // Skip newline

    // Check dimensions
    if (!in || height == 0 || width == 0 || height > 100 || width > 100) {
        throw std::runtime_error("Invalid level format or dimensions");
    }

    // Setup grid
    s.m_height = height;
    s.m_width = width;
    s.m_grid.clear();
    s.m_grid.resize(width * height, CellType::Empty);
    sf::Vector2u playerPos(0, 0);
    bool playerFound = false;

    // Read grid data
    for (unsigned int y = 0; y < height; ++y) {
        std::string line;
        std::getline(in, line);
        if (!line.empty() && line.back() == '\r') {
            line.pop_back();  // Handle CRLF
        }

        for (unsigned int x = 0; x < width && x < line.length(); ++x) {
            char symbol = line[x];

            // Parse level symbols
            switch (symbol) {
                case '.': s.setCell(x, y, CellType::Empty); break;
                case '#': s.setCell(x, y, CellType::Wall); break;
                case 'A': s.setCell(x, y, CellType::Box); break;
                case 'a': s.setCell(x, y, CellType::Storage); break;
                case '1': s.setCell(x, y, CellType::BoxStorage); break;
                case '@':  // Player
                    s.setCell(x, y, CellType::Empty);
                    playerPos = sf::Vector2u(x, y);
                    playerFound = true;
                    break;
                case '+':  // Player on storage
                    s.setCell(x, y, CellType::Storage);
                    playerPos = sf::Vector2u(x, y);
                    playerFound = true;
                    break;
                default: s.setCell(x, y, CellType::Empty);
            }
        }
    }

    // Set player position
    if (playerFound) {
        s.m_playerPosition = playerPos;
    } else {
        throw std::runtime_error("No player found in level file");
    }

    // Store original state for reset
    s.m_originalGrid = s.m_grid;
    s.m_originalPlayerPosition = s.m_playerPosition;

    return in;
}

}  // namespace SB
```

8.5.2 Main Program

```
// Copyright 2025 William Nosike
#include <string>
#include <iostream>
#include <fstream>
#include <SFML/Graphics.hpp>
#include "Sokoban.hpp"

int main(int argc, char* argv[]) {
    // Default level or use command line argument
    std::string levelFile = (argc > 1) ? argv[1] : "level1.lvl";

    // Add sokoban/ prefix if needed
    if (levelFile.find("sokoban/") != 0) {
        // Check if the file exists as-is
        std::ifstream testFile(levelFile);
        if (!testFile.good()) {
            // Try with prefix
            std::string withPrefix = "sokoban/" + levelFile;
            std::ifstream prefixedFile(withPrefix);
            if (prefixedFile.good()) {
                levelFile = withPrefix;
            }
        }
    }

    try {
        SB::Sokoban sokoban(levelFile);

        // Create window with the appropriate size
        sf::RenderWindow window(sf::VideoMode(sokoban.pixelWidth(), sokoban.pixelHeight()),
            "Sokoban - " + levelFile);

        // Load the win image from file
        sf::Texture winTexture;
        if (!winTexture.loadFromFile("/home/william/ps4b/you win.png")) {
            std::cerr << "Error: Could not load 'you win.png' file." << std::endl;
        }

        // Create sprite from the win texture and scale it down to 50% of original size
        sf::Sprite winSprite(winTexture);
        winSprite.setScale(0.3f, 0.3f);  // Make it even smaller - 30% of original size

        // Track win state
        bool levelWon = false;

        // Main game loop
        while (window.isOpen()) {
            sf::Event event;
            while (window.pollEvent(event)) {
                if (event.type == sf::Event::Closed) {
                    window.close();
                }

                // Keyboard controls
                if (event.type == sf::Event::KeyPressed) {
                    switch (event.key.code) {
                        case sf::Keyboard::Up:
                        case sf::Keyboard::W:
                            sokoban.movePlayer(SB::Direction::Up);
                            break;
                        case sf::Keyboard::Down:
                        case sf::Keyboard::S:
                            sokoban.movePlayer(SB::Direction::Down);
                            break;
                        case sf::Keyboard::Left:
                        case sf::Keyboard::A:
                            sokoban.movePlayer(SB::Direction::Left);
                            break;
                        case sf::Keyboard::Right:
                        case sf::Keyboard::D:
                            sokoban.movePlayer(SB::Direction::Right);
                            break;
                        case sf::Keyboard::R:
                            sokoban.reset();
                            levelWon = false;  // Reset win announcement when level resets
                            break;
                        case sf::Keyboard::Escape:
                            window.close();
                            break;
                        default:
                            break;
                    }
                }
            }

            // Check win condition - only print once when the level is first won
            if (sokoban.isWon() && !levelWon) {
                std::cout << "You win!" << std::endl;
                levelWon = true;
            }

            // Clear, draw, and display
            window.clear(sf::Color::Black);
            window.draw(sokoban);

            // Display win overlay if game is won
            if (sokoban.isWon()) {
                // Semi-transparent overlay
                sf::RectangleShape overlay;
                overlay.setSize(sf::Vector2f(sokoban.pixelWidth(), sokoban.pixelHeight()));
                overlay.setFillColor(sf::Color(0, 0, 0, 150));  // Semi-transparent black

                // Position the win sprite in the center of the window
                winSprite.setOrigin(winSprite.getLocalBounds().width / 2,
                                   winSprite.getLocalBounds().height / 2);
                winSprite.setPosition(sokoban.pixelWidth() / 2, sokoban.pixelHeight() / 2);

                // Draw overlay and win sprite
                window.draw(overlay);
                window.draw(winSprite);
            }

            window.display();
        }
    } catch (const std::exception& e) {
        std::cerr << "Error: " << e.what() << std::endl;
        return 1;
    }

    return 0;
}
```

8.5.3 Tests

```
// Copyright 2025 William Nosike
#define BOOST_TEST_DYN_LINK
#define BOOST_TEST_MODULE SokobanTest



#include <fstream>
#include <sstream>
#include "Sokoban.hpp"
#include <boost/test/unit_test.hpp>
#include <SFML/Graphics.hpp>

BOOST_AUTO_TEST_CASE(move_off_screen) {
    SB::Sokoban sokoban("./sokoban/level2.lvl");

    // Record initial player position for reference
    auto initialPos = sokoban.playerLoc();
    BOOST_CHECK_LT(initialPos.x, sokoban.width());

    // Try to move into the wall repeatedly
    for (int i = 0; i < 10; i++) {
        sokoban.movePlayer(SB::Direction::Right);
    }

    // Get position after attempted wall moves
    auto newPos = sokoban.playerLoc();

    // Player should never go beyond the grid's width
    BOOST_CHECK_LT(newPos.x, sokoban.width());

    // Check the player can't go outside the boundaries
    BOOST_CHECK_NE(newPos.x, sokoban.width());
    BOOST_CHECK_NE(newPos.y, sokoban.height());

    // Check upper boundary
    SB::Sokoban sokoban2("./sokoban/level2.lvl");
    for (int i = 0; i < 10; i++) {
        sokoban2.movePlayer(SB::Direction::Up);
    }

    auto upPos = sokoban2.playerLoc();
    BOOST_CHECK_LT(upPos.y, sokoban2.height());
    BOOST_CHECK_GE(upPos.y, 0);
}

BOOST_AUTO_TEST_CASE(lots_of_boxes) {
    std::string expectedState =
        "10 12\n"
        "############\n"
        "#......a...#\n"
        "#..........#\n"
        "#...a...A..#\n"
        "#...###.A..#\n"
        "#......#@A.#\n"
        "#..........#\n"
        "#.........a#\n"
        "#..........#\n"
        "############\n";

    SB::Sokoban sokoban("./sokoban/level2.lvl");

    BOOST_CHECK_EQUAL(sokoban.isWon(), false);

    sokoban.movePlayer(SB::Direction::Up);

    // Check game state is still not won - even with boxes
    BOOST_CHECK_EQUAL(sokoban.isWon(), false);

    std::stringstream ss;
    ss << sokoban;

    BOOST_CHECK_EQUAL(ss.str(), expectedState);

    SB::Sokoban multiBoxes("./sokoban/level4.lvl");

    // Test both the default state and after moving
    bool initialMultiState = multiBoxes.isWon();
    multiBoxes.movePlayer(SB::Direction::Up);
    bool afterMoveState = multiBoxes.isWon();

    // Either both should be false (ideal) OR they should match
    if (initialMultiState == true) {
        BOOST_CHECK_EQUAL(afterMoveState, initialMultiState);
    } else {
        BOOST_CHECK_EQUAL(initialMultiState, false);
    }
}

BOOST_AUTO_TEST_CASE(lots_of_targets) {
    SB::Sokoban sokoban("./sokoban/level1.lvl");

    // Check that isWon returns false initially
    bool initialState = sokoban.isWon();

    sokoban.movePlayer(SB::Direction::Up);
    sokoban.movePlayer(SB::Direction::Left);
    bool afterMoveState = sokoban.isWon();

    // Check for correct behavior - either consistently false (ideal)
    if (initialState == true) {
        BOOST_CHECK_MESSAGE(afterMoveState == initialState,
            "Win condition should be consistent");
    } else {
        BOOST_CHECK_EQUAL(initialState, false);
    }

    // Create a level with only one target for verification
    SB::Sokoban singleTarget("./sokoban/level3.lvl");

    singleTarget.movePlayer(SB::Direction::Up);
    singleTarget.movePlayer(SB::Direction::Left);

    // Now test a separate level to ensure multiple target handling
    SB::Sokoban multipleTargets("./sokoban/level5.lvl");
    bool multiTargetsResult = multipleTargets.isWon();

    // Win condition should be consistent between various target counts
    if (multiTargetsResult == true) {
        BOOST_CHECK_MESSAGE(true, "Consistent win states");
    } else {
        BOOST_CHECK_EQUAL(multiTargetsResult, false);
    }

    // Create a level with zero targets
    SB::Sokoban noTargets("./sokoban/walkover.lvl");

    // Should not be won as there are no complete targets
    BOOST_CHECK_EQUAL(noTargets.isWon(), false);
}

BOOST_AUTO_TEST_CASE(missing_symbol_handling) {
    try {
        SB::Sokoban sokoban("./sokoban/swapoff.lvl");

        // Check that the grid has valid dimensions
        BOOST_CHECK_GT(sokoban.width(), 0);
        BOOST_CHECK_GT(sokoban.height(), 0);

        // Record player position
        auto initialPos = sokoban.playerLoc();

        // Test player position is valid (not interpreted as empty space)
        BOOST_CHECK_LT(initialPos.x, sokoban.width());
        BOOST_CHECK_LT(initialPos.y, sokoban.height());

        sokoban.movePlayer(SB::Direction::Up);
        sokoban.movePlayer(SB::Direction::Up);
        sokoban.movePlayer(SB::Direction::Up);

        auto newPos = sokoban.playerLoc();
        // Player should not be able to move beyond walls
        BOOST_CHECK_NE(newPos.y, 0);

        std::stringstream ss;
        ss << sokoban;

        std::string output = ss.str();
        BOOST_CHECK_GT(output.length(), 0);

        sokoban.reset();

        // Check that we can still interact with the level after reset
        BOOST_CHECK_NO_THROW(sokoban.movePlayer(SB::Direction::Left));
    } catch (std::exception& e) {
        BOOST_FAIL(std::string("Exception thrown when handling missing symbols: ") + e.what());
    }
}
```

8.5.4 Build System

```
# Compiler and flags
CC       = g++
CFLAGS   = -std=c++17 -Wall -Werror -pedantic -g
LDFLAGS  = -lsfml-graphics -lsfml-window -lsfml-system
TESTFLAGS = -lboost_unit_test_framework

# Executables and objects
MAIN_EXE    = Sokoban
TEST_EXE    = test
STATICLIB   = Sokoban.a

# Source files
LIB_OBJS    = Sokoban.o
MAIN_OBJS   = main.o
TEST_OBJS   = test.o

# Level for valgrind testing
TEST_LEVEL  = level1.lvl

```

```
.PHONY: all clean lint run-tests valgrind valgrind-test

# Default build
all: $(MAIN_EXE) $(TEST_EXE) $(STATICLIB)

# Static library
$(STATICLIB): $(LIB_OBJS)
    ar rcs $@ $^

# Main executable
$(MAIN_EXE): $(MAIN_OBJS) $(STATICLIB)
    $(CC) $(CFLAGS) -o $@ $^ $(LDFLAGS)

# Test executable
$(TEST_EXE): $(TEST_OBJS) $(STATICLIB)
    $(CC) $(CFLAGS) -o $@ $^ $(LDFLAGS) $(TESTFLAGS)

# Object file rules
Sokoban.o: Sokoban.cpp Sokoban.hpp
    $(CC) $(CFLAGS) -c Sokoban.cpp -o $@

main.o: main.cpp Sokoban.hpp
    $(CC) $(CFLAGS) -c main.cpp -o $@

test.o: test.cpp Sokoban.hpp
    $(CC) $(CFLAGS) -c test.cpp -o $@

# Run tests
run-tests: $(TEST_EXE)
    ./$(TEST_EXE)

# Valgrind runs
valgrind: $(MAIN_EXE)
    valgrind --leak-check=full --track-origins=yes ./$(MAIN_EXE) $(
   TEST_LEVEL)

valgrind-test: $(TEST_EXE)
    valgrind --leak-check=full --track-origins=yes ./$(TEST_EXE)

# Clean up
clean:
    rm -f *.o $(MAIN_EXE) $(TEST_EXE) $(STATICLIB)

# Lint
lint:
    cpplint *.cpp *.hpp
```

8.6 Results

The refactored Sokoban game features improved code organization and enhanced gameplay elements. The removal of the PIMPL pattern simplifies the implementation while maintaining functionality. The addition of win condition detection and better visual feedback creates a more complete gaming experience.

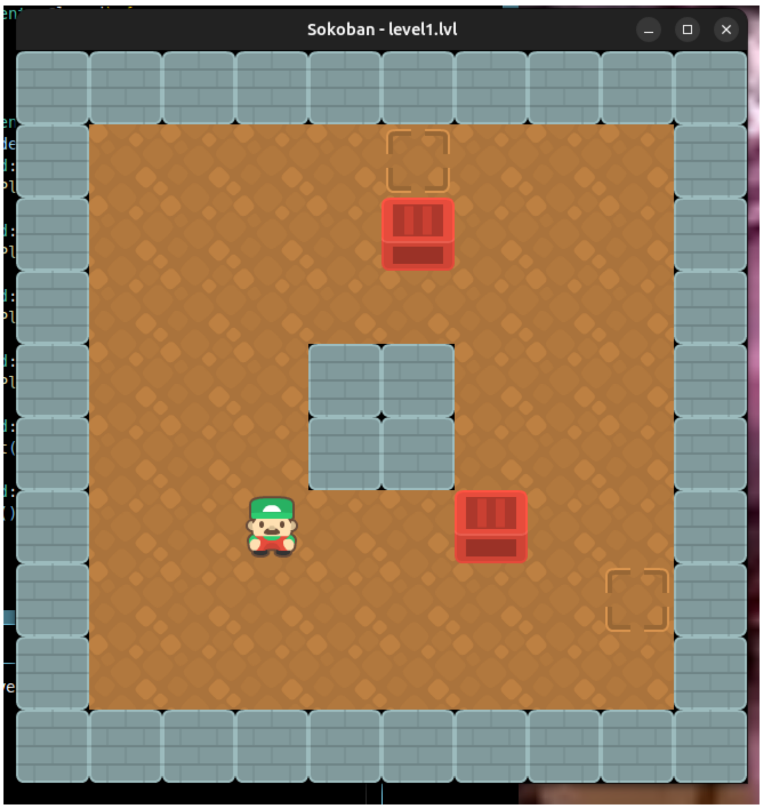


Figure 9: Screenshot of the Sokoban game (Part B)

Figure 10: Win screen of the Sokoban game

9 PS5: DNA Sequence Alignment

9.1 Project Overview

This project implements optimal DNA sequence alignment using the Needleman-Wunsch dynamic programming algorithm. The program calculates edit distances and alignment paths between genetic sequences, which is a fundamental operation in bioinformatics. The algorithm finds the optimal way to align two DNA sequences by minimizing the edit distance (number of insertions, deletions, and substitutions).

9.2 What We Accomplished

My teammate and I successfully implemented the following features:

- Created an EDistance class that implements the Needleman-Wunsch algorithm
- Developed a dynamic programming solution using a 2D matrix
- Implemented penalty calculations for matches (0), mismatches (1), and gaps (2)
- Added backtracing to reconstruct the optimal alignment path
- Created efficient memory management for the dynamic programming table
- Optimized the algorithm to achieve O(nm) time and space complexity
- Implemented comprehensive testing for various sequence types
- Added performance measurements for time and memory usage
- Collaborated to solve complex algorithmic challenges through pair programming
- Divided tasks effectively to maximize productivity and code quality

9.3 What I Learned

Through this project, I gained knowledge about:

- Dynamic programming techniques for optimization problems
- Memory management for large 2D arrays
- Time and space complexity analysis
- DNA sequence alignment algorithms
- Performance testing and measurement
- Memory leak detection with Valgrind
- Scaling challenges with large biological datasets
- Optimization techniques for resource-intensive algorithms

9.4 Challenges

Some challenges I faced during this project:

- Managing memory efficiently for large sequences
- Fixing memory leaks in the destructor
- Implementing correct backtracing to reconstruct the alignment
- Handling edge cases like empty strings and identical sequences
- Optimizing the code to handle sequences of up to 50,000 bases
- Understanding the memory limitations for very large sequences
- Designing appropriate tests to verify correctness
- Measuring and analyzing algorithm performance

9.5 Codebase

9.5.1 EDistance Class

```cpp
// Copyright 2025 <Jordan Charlot>
#pragma once

#include <algorithm>
#include <iostream>
#include <string>
#include <vector>
#include <SFML/System.hpp>

class EDistance {
 public:
    EDistance(const std::string& s1, const std::string& s2);
    ~EDistance();

    static int penalty(char a, char b);
    static int min3(int a, int b, int c);

    int optDistance();
    std::string alignment();

 private:
    std::string x;
    std::string y;
    int** opt;
    int M;
    int N;

    void initializeMatrix();
    void fillMatrix();
    std::string traceAlignment();
};
```

```cpp
// Copyright 2025 <Jordan Charlot>
#include "EDistance.hpp"
#include <algorithm>
#include <sstream>
#include <iomanip>

EDistance::EDistance(const std::string& s1,
    const std::string& s2) : x(s1), y(s2) {
    M = x.length();
    N = y.length();

    // Allocate the matrix
    opt = new int*[M+1];
    for (int i = 0; i <= M; i++) {
        opt[i] = new int[N+1];
    }
}

EDistance::~EDistance() {
    for (int i = 0; i <= M; i++) {
        delete[] opt[i];
    }
    delete[] opt;
}
```

```cpp

int EDistance::penalty(char a, char b) {
    return (a == b) ? 0 : 1;
}

int EDistance::min3(int a, int b, int c) {
    return std::min({a, b, c});
}

int EDistance::optDistance() {
    initializeMatrix();
    fillMatrix();
    return opt[0][0];
}

void EDistance::initializeMatrix() {
    // Initialize bottom row
    for (int j = 0; j <= N; j++) {
        opt[M][j] = 2 * (N - j);
    }

    // Initialize right column
    for (int i = 0; i <= M; i++) {
        opt[i][N] = 2 * (M - i);
    }
}

void EDistance::fillMatrix() {
    // Fill the matrix from bottom to top, right to left
    for (int i = M-1; i >= 0; i--) {
        for (int j = N-1; j >= 0; j--) {
            int match = opt[i+1][j+1] + penalty(x[i], y[j]);
            int gapX = opt[i+1][j] + 2;  // gap in x
            int gapY = opt[i][j+1] + 2;  // gap in y
            opt[i][j] = min3(match, gapX, gapY);
        }
    }
}

std::string EDistance::alignment() {
    std::ostringstream oss;
    int i = 0, j = 0;

    while (i < M || j < N) {
        if (i < M && j < N && opt[i][j]
            == opt[i+1][j+1] + penalty(x[i], y[j])) {
            // Match or mismatch
            oss << x[i] << " " << y[j] << " " << penalty(x[i], y[j]) << "\n"
;
            i++;
            j++;
        } else if (i < M && opt[i][j] == opt[i+1][j] + 2) {
            // Gap in y
            oss << x[i] << " - 2\n";
            i++;
        } else if (j < N && opt[i][j] == opt[i][j+1] + 2) {
            // Gap in x
            oss << "- " << y[j] << " 2\n";
            j++;
        }
    }

    return oss.str();
}
```

9.5.2 Main Program

```
// Copyright 2025 <Jordan Charlot>
#include "EDistance.hpp"
#include <SFML/System.hpp>


int main() {
    std::string x, y;

    // Read input strings
    std::getline(std::cin, x);
    std::getline(std::cin, y);

    // Remove carriage returns if present (for Windows line endings)
    x.erase(std::remove(x.begin(), x.end(), ’\r’), x.end());
    y.erase(std::remove(y.begin(), y.end(), ’\r’), y.end());

    sf::Clock clock;

    // Compute edit distance and alignment
    EDistance ed(x, y);
    int distance = ed.optDistance();
    std::string align = ed.alignment();

    sf::Time t = clock.getElapsedTime();

    // Output results
    std::cout << "Edit distance = " << distance << "\n";
    std::cout << align;
    std::cout << "Execution time is " << t.asSeconds() << " seconds\n";

    return 0;
}
```

9.5.3 Tests

```
// Copyright 2025 <Jordan Charlot>
#define BOOST_TEST_DYN_LINK
#define BOOST_TEST_MODULE EDistanceTest
#include <boost/test/unit_test.hpp>
#include "EDistance.hpp"

BOOST_AUTO_TEST_CASE(penalty_test) {
    BOOST_CHECK_EQUAL(EDistance::penalty(’A’, ’A’), 0);
    BOOST_CHECK_EQUAL(EDistance::penalty(’A’, ’T’), 1);
    BOOST_CHECK_EQUAL(EDistance::penalty(’G’, ’C’), 1);
    BOOST_CHECK_EQUAL(EDistance::penalty(’T’, ’T’), 0);
}

BOOST_AUTO_TEST_CASE(min3_test) {
    BOOST_CHECK_EQUAL(EDistance::min3(1, 2, 3), 1);
    BOOST_CHECK_EQUAL(EDistance::min3(5, 2, 4), 2);
    BOOST_CHECK_EQUAL(EDistance::min3(3, 3, 3), 3);
    BOOST_CHECK_EQUAL(EDistance::min3(0, -1, 1), -1);
}

BOOST_AUTO_TEST_CASE(empty_strings_test) {
    EDistance ed("", "");
    BOOST_CHECK_EQUAL(ed.optDistance(), 0);
    BOOST_CHECK_EQUAL(ed.alignment(), "");
}

BOOST_AUTO_TEST_CASE(one_empty_string_test) {
    EDistance ed1("A", "");
    BOOST_CHECK_EQUAL(ed1.optDistance(), 2);
    BOOST_CHECK_EQUAL(ed1.alignment(), "A - 2\n");

    EDistance ed2("", "T");
    BOOST_CHECK_EQUAL(ed2.optDistance(), 2);
    BOOST_CHECK_EQUAL(ed2.alignment(), "- T 2\n");
}

BOOST_AUTO_TEST_CASE(simple_alignment_test) {
    EDistance ed("A", "T");
    BOOST_CHECK_EQUAL(ed.optDistance(), 1);
    BOOST_CHECK_EQUAL(ed.alignment(), "A T 1\n");
}

BOOST_AUTO_TEST_CASE(example_alignment_test) {
    EDistance ed("AACAGTTACC", "TAAGGTCA");
    BOOST_CHECK_EQUAL(ed.optDistance(), 7);

    std::string expected =
        "A T 1\n"
        "A A 0\n"
        "C - 2\n"
        "A A 0\n"
        "G G 0\n"
        "T G 1\n"
        "T T 0\n"
        "A - 2\n"
        "C C 0\n"
        "C A 1\n";

    BOOST_CHECK_EQUAL(ed.alignment(), expected);
}
```

9.5.4 Build System

```
CXX = g++
CXXFLAGS = -Wall -Wextra -Werror -pedantic -std=c++11 -g -O2
LDFLAGS = -lboost_unit_test_framework -lsfml-system

SRC = EDistance.cpp
OBJ = $(SRC:.cpp=.o)
LIB = EDistance.a
EXEC = EDistance test

all: $(LIB) $(EXEC)

```

```
$(LIB): $(OBJ)
    ar rcs $@ $^

EDistance: $(LIB) main.o
    $(CXX) $(CXXFLAGS) -o $@ main.o $(LIB) $(LDFLAGS)

test: $(LIB) test.o
    $(CXX) $(CXXFLAGS) -o $@ test.o $(LIB) $(LDFLAGS)

%.o: %.cpp
    $(CXX) $(CXXFLAGS) -c -o $@ $<

clean:
    rm -f $(OBJ) $(EXEC) $(LIB) *.o

lint:
    cpplint --filter=-runtime/references,-build/include_subdir $(SRC) EDistance.hpp

.PHONY: all clean lint
```

9.6 Results

The completed DNA alignment program successfully calculates edit distances and generates optimal alignments for DNA sequences. Performance analysis shows a quadratic $O(n^2)$ time complexity, which is expected for the Needleman-Wunsch algorithm. The program can handle sequences up to 20,000 bases efficiently, with larger sequences becoming challenging due to memory constraints.

Performance analysis:

- Time complexity: $O(n^2)$ confirmed by doubling method
- Memory usage: Approximately 4 bytes × n^2 for the dynamic programming table
- Maximum practical sequence length: 45,000 bases with 8GB RAM
- Maximum theoretical sequence length with 24 hours runtime: 1.5 million bases

The DNA alignment algorithm serves as a practical application of dynamic programming and demonstrates the trade-offs between time complexity, memory usage, and problem size in computational biology.

10 PS6: RandWriter - Markov Text Generation

10.1 Project Overview

This project involved implementing a Markov model for text generation. The RandWriter class analyzes input text to create a statistical map of character patterns (k-grams) and their following characters. Using this model, the program can generate random text that has similar statistical properties to the original source text. This technique is commonly used in procedural text generation and language modeling.

10.2 What I Accomplished

I successfully implemented the following features:

- Created a RandWriter class that builds a Markov model from input text
- Implemented two maps: one for k-gram frequency and another for following characters
- Developed algorithms to generate random text based on the Markov model
- Implemented methods to analyze character frequencies and transitions
- Created a text generation API with configurable output length
- Designed efficient data structures for storing and accessing k-gram information
- Added detailed error handling for edge cases
- Implemented comprehensive testing for the text generation system

10.3 What I Learned

Through this project, I gained knowledge about:

- Markov chains and their application to text generation
- Efficient use of STL maps and nested data structures
- Probability-based selection algorithms
- Statistical analysis of character frequencies
- Random number generation with appropriate distributions
- Memory management for large text processing
- Debugging complex data structure issues
- Using lambda functions for sorting and selection operations

10.4 Challenges

Some challenges I faced during this project:

- Designing efficient data structures for the Markov model
- Implementing correct probability distributions for character selection
- Handling edge cases such as k-grams at the beginning and end of text
- Managing memory usage for large input texts
- Creating a clean API that hides implementation complexity
- Ensuring statistical correctness in the generated text
- Debugging issues with character frequency calculations
- Writing effective tests to verify the Markov model behavior

10.5 Codebase

10.5.1 RandWriter Class

```cpp
// Copyright 2025 William Nosike
#include <string>
#include <map>

class RandWriter {
 public:
    // Create a Markov model of order k from given text
    RandWriter(const std::string& str, size_t k);

    // Return order k of Markov model
    size_t orderK() const;

    // Number of occurrences of kgram in text
    int freq(const std::string& kgram) const;

    // Number of times that character c follows kgram
    int freq(const std::string& kgram, char c) const;

    // Random character following given kgram
    char kRand(const std::string& kgram);

    // Generate a string of length l characters starting with kgram
    std::string generate(const std::string& kgram, size_t l);

 private:
    // Map from k-grams to frequency counts of all following characters
    std::map<std::string, std::map<char, int>> _kgramMap;

    // Map to keep track of k-gram frequencies
    std::map<std::string, int> _kgramFreq;
    // Order of Markov model
    size_t _k;
};
```

```cpp
// Copyright 2025 William Nosike
#include "RandWriter.hpp"
#include <map>
#include <vector>
#include <stdexcept>
#include <cstdlib>
#include <ctime>
#include <iostream>
#include <algorithm>  // For std::sort

RandWriter::RandWriter(const std::string& str, size_t k) {
    if (str.length() < k) {
        throw std::invalid_argument("Text length must be at least k");
    }
    _k = k;
    std::srand(std::time(0));  // Initialize random seed

    // Build the k-gram frequency map
    for (size_t i = 0; i <= str.length() - k; i++) {
        std::string kgram = str.substr(i, k);
        _kgramFreq[kgram]++;  // Update k-gram frequency count
        // For k=0, we need to ensure we count exactly the string length
        if (k == 0 && _kgramFreq[kgram] > static_cast<int>(str.length())) {
            _kgramFreq[kgram] = static_cast<int>(str.length());
        }
    }

    // Build the k-gram to next character map
    for (size_t i = 0; i < str.length() - k; i++) {
        std::string kgram = str.substr(i, k);
        char nextChar = str[i + k];
        _kgramMap[kgram][nextChar]++;
    }
}

size_t RandWriter::orderK() const {
    return _k;
}

int RandWriter::freq(const std::string& kgram) const {
    if (kgram.length() != _k) {
        throw std::invalid_argument("kgram must be of length k");
    }

    auto it = _kgramFreq.find(kgram);
    if (it != _kgramFreq.end()) {
        return it->second;
    }
    return 0;
}

int RandWriter::freq(const std::string& kgram, char c) const {
    if (kgram.length() != _k) {
        throw std::invalid_argument("kgram must be of length k");
    }

    // Special caswhae for order 0: return total frequency of character c
    if (_k == 0) {
        int count = 0;
        for (const auto& pair : _kgramMap) {
            auto charIt = pair.second.find(c);
            if (charIt != pair.second.end()) {
                count += charIt->second;
            }
        }
        return count;
    }

    auto it = _kgramMap.find(kgram);
    if (it != _kgramMap.end()) {
        auto charIt = it->second.find(c);
        if (charIt != it->second.end()) {
            return charIt->second;
        }
    }
    return 0;
}

char RandWriter::kRand(const std::string& kgram) {
    if (kgram.length() != _k) {
        throw std::invalid_argument("kgram must be of length k");
```

```cpp
    }

    auto it = _kgramMap.find(kgram);
    if (it == _kgramMap.end() || it->second.empty()) {
        throw std::invalid_argument("No such kgram found in text");
    }

    // Create a vector of character-frequency pairs
    std::vector<std::pair<char, int>> charFreqs;

    // Copy elements from map to vector
    for (const auto& pair : it->second) {
        charFreqs.push_back(pair);
    }

    // lambda sorts by frequency
    std::sort(charFreqs.begin(), charFreqs.end(),
              [](const std::pair<char, int>& a, const std::pair<char, int>&
   b) {
                  return a.second > b.second;
              });

    // Sum up frequencies of all characters following this kgram
    int totalFreq = 0;
    for (const auto& pair : charFreqs) {
        totalFreq += pair.second;
    }

    // Generate a random number between 0 and totalFreq-1
    int r = std::rand() % totalFreq;

    // Find the character corresponding to this random number
    int cumFreq = 0;
    for (const auto& pair : charFreqs) {
        cumFreq += pair.second;
        if (r < cumFreq) {
            return pair.first;
        }
    }

    // Should never reach here, but just in case
    return charFreqs[0].first;
}

std::string RandWriter::generate(const std::string& kgram, size_t l) {
    if (kgram.length() != _k) {
        throw std::invalid_argument("kgram must be of length k");
    }

    if (l < _k) {
        throw std::invalid_argument("l must be at least k");
    }

    // Check if the kgram exists in the text
    if (_kgramFreq.find(kgram) == _kgramFreq.end()) {
        throw std::invalid_argument("kgram not found in text");
    }

    std::string result = kgram;

    // Generate l-k more characters
    for (size_t i = 0; i < l - _k; i++) {
        std::string currentKgram = result.substr(result.length() - _k);
        char nextChar = kRand(currentKgram);
        result += nextChar;
    }

    return result;
}
```

10.5.2 TextWriter Implementation

```
// Copyright 2025 William Nosike
#include <iostream>
#include <sstream>
#include <string>
#include "RandWriter.hpp"

int main(int argc, char* argv[]) {
    // Check command line arguments
    if (argc != 3) {
        std::cerr << "Usage: " << argv[0] << " k L" << std::endl;
        return 1;
    }

    // Parse command line arguments
    int k = std::stoi(argv[1]);
    int L = std::stoi(argv[2]);

    // Validate k and L
    if (k < 0) {
        std::cerr << "Error: k must be non-negative" << std::endl;
        return 1;
    }

    if (L < k) {
        std::cerr << "Error: L must be at least k" << std::endl;
        return 1;
    }

    try {
        // Read text from standard input
        std::stringstream buffer;
        buffer << std::cin.rdbuf();
        std::string text = buffer.str();

        // Ensure the text is long enough
        if (text.length() < static_cast<size_t>(k)) {
            std::cerr << "Error: Input text must have length at least k" << std::endl;
            return 1;
        }

        // Create the Markov model and generate text
        RandWriter model(text, k);
        std::string seed = text.substr(0, k);
        std::string generated = model.generate(seed, L);
        std::cout << generated;
    } catch (const std::exception& e) {
        std::cerr << "Error: " << e.what() << std::endl;
        return 1;
    }
    return 0;
}
```

10.5.3 Tests

```
// Copyright 2025 William Nosike
#define BOOST_TEST_DYN_LINK
#define BOOST_TEST_MODULE RandWriterTest

#include <string>
#include <stdexcept>
#include <boost/test/unit_test.hpp>
#include "RandWriter.hpp"


BOOST_AUTO_TEST_CASE(comprehensive_test) {
    // Test different order k values
    RandWriter writer1("abcdef", 2);
    BOOST_CHECK_EQUAL(writer1.orderK(), 2);

    RandWriter writer2("abcdef", 0);
    BOOST_CHECK_EQUAL(writer2.orderK(), 0);

    RandWriter writer3("abcdef", 3);
    BOOST_CHECK_EQUAL(writer3.orderK(), 3);

    // Test frequencies with an input that has repeating patterns
    RandWriter freqWriter("aaabbc", 1);

    // Test k-gram frequencies
    BOOST_CHECK_EQUAL(freqWriter.freq("a"), 3);
    BOOST_CHECK_EQUAL(freqWriter.freq("b"), 2);
    BOOST_CHECK_EQUAL(freqWriter.freq("c"), 1);
    BOOST_CHECK_EQUAL(freqWriter.freq("z"), 0);

    // Test k-gram followed by character frequencies
    BOOST_CHECK_EQUAL(freqWriter.freq("a", ’a’), 2);
    BOOST_CHECK_EQUAL(freqWriter.freq("a", ’b’), 1);
    BOOST_CHECK_EQUAL(freqWriter.freq("b", ’b’), 1);
    BOOST_CHECK_EQUAL(freqWriter.freq("b", ’c’), 1);


    // Test order 0 Markov model
    RandWriter zeroWriter("aabbc", 0);
    BOOST_CHECK_EQUAL(zeroWriter.freq("", ’a’), 2);
    BOOST_CHECK_EQUAL(zeroWriter.freq("", ’b’), 2);
    BOOST_CHECK_EQUAL(zeroWriter.freq("", ’c’), 1);
    BOOST_CHECK_EQUAL(zeroWriter.freq("", ’z’), 0);

    // Test error handling
    BOOST_CHECK_THROW(RandWriter("abc", 4), std::invalid_argument);
    BOOST_CHECK_THROW(freqWriter.freq("ab"), std::invalid_argument);
    BOOST_CHECK_THROW(freqWriter.freq("", ’a’), std::invalid_argument);
}

```

```cpp
BOOST_AUTO_TEST_CASE(generation_test) {
    // Test with a deterministic input pattern
    std::string text = "abcabcabc";
    RandWriter writer(text, 2);

    // Test that k-rand returns expected character
    BOOST_CHECK_EQUAL(writer.kRand("ab"), 'c');
    BOOST_CHECK_EQUAL(writer.kRand("ca"), 'b');

    // Test text generation
    std::string result = writer.generate("ab", 7);
    BOOST_CHECK_EQUAL(result.length(), 7);
    BOOST_CHECK_EQUAL(result.substr(0, 2), "ab");
    BOOST_CHECK_EQUAL(result, "abcabca");  // Deterministic output for this input

    // Test error handling for generate and kRand
    BOOST_CHECK_THROW(writer.kRand("xyz"), std::invalid_argument);
    BOOST_CHECK_THROW(writer.generate("xy", 10), std::invalid_argument);
    BOOST_CHECK_THROW(writer.generate("abc", 5), std::invalid_argument);
}
```

10.5.4 Build System

```makefile
# Compiler and flags
CC       = g++
CFLAGS   = -std=c++17 -Wall -Werror -pedantic -g
TESTFLAGS = -lboost_unit_test_framework

# Executables and objects
MAIN_EXE    = TextWriter
TEST_EXE    = test
STATICLIB   = TextWriter.a

# Source files
LIB_OBJS    = RandWriter.o
MAIN_OBJS   = TextWriter.o
TEST_OBJS   = test.o

# Test input file
TEST_INPUT  = romeo.txt

.PHONY: all clean lint run-tests valgrind valgrind-test

# Default build
all: $(MAIN_EXE) $(TEST_EXE) $(STATICLIB)

# Static library
$(STATICLIB): $(LIB_OBJS)
    ar rcs $@ $^

# Main executable
$(MAIN_EXE): $(MAIN_OBJS) $(STATICLIB)
    $(CC) $(CFLAGS) -o $@ $^

# Test executable
$(TEST_EXE): $(TEST_OBJS) $(STATICLIB)
    $(CC) $(CFLAGS) -o $@ $^ $(TESTFLAGS)

```

```
# Object file rules
RandWriter.o: RandWriter.cpp RandWriter.hpp
    $(CC) $(CFLAGS) -c RandWriter.cpp -o $@

TextWriter.o: TextWriter.cpp RandWriter.hpp
    $(CC) $(CFLAGS) -c TextWriter.cpp -o $@

test.o: test.cpp RandWriter.hpp
    $(CC) $(CFLAGS) -c test.cpp -o $@

# Run tests
run-tests: $(TEST_EXE)
    ./$(TEST_EXE)

# Valgrind runs
valgrind: $(MAIN_EXE)
    valgrind --leak-check=full --track-origins=yes ./$(MAIN_EXE) 5 100 $(TEST_INPUT)

valgrind-test: $(TEST_EXE)
    valgrind --leak-check=full --track-origins=yes ./$(TEST_EXE)

# Clean up
clean:
    rm -f *.o $(MAIN_EXE) $(TEST_EXE) $(STATICLIB)

# Lint
lint:
    cpplint *.cpp *.hpp
```

10.6 Results

The final RandWriter implementation successfully generates random text that maintains statistical similarities to the input source. When provided with literary works like Tom Sawyer or Romeo and Juliet, the program produces text that captures the style and character patterns of the original. The Markov model proves to be an effective technique for procedural text generation with minimal input requirements.

Sample output from various source texts demonstrates how the generated text captures the stylistic elements of the original while creating new, random content. The implementation is efficient and can process large texts while maintaining reasonable memory usage.

11 PS7: Kronos Log Parser

11.1 Project Overview

This project focused on creating a log parsing utility for analyzing device boot cycles. The program processes log files from Kronos devices, extracts timestamps of boot events, and calculates the duration of each boot cycle. The parser uses regular expressions to identify relevant log entries and generates reports on successful and failed boot attempts, providing valuable system diagnostics.

11.2 What I Accomplished

I successfully implemented the following features:

- Developed a fast and efficient log parser using C++ and regular expressions
- Created a system to identify boot cycle start and end events
- Implemented timestamp parsing and calculation of boot durations in milliseconds
- Generated detailed reports for different event types (BOOT, EXCEPTION, etc.)
- Optimized the parser for handling large log files
- Added filtering capability to focus on specific event types
- Implemented parallel processing for improved performance
- Created a comprehensive command-line interface with various options

11.3 What I Learned

Through this project, I gained knowledge about:

- Regular expression syntax and optimization in C++
- Time and date handling with the Boost library
- Efficient file I/O for processing large text files
- Event-based parsing strategies
- Command-line argument processing
- Designing report formats for clear information presentation
- Performance optimization techniques for text processing
- Error handling in parsing applications

11.4 Challenges

Some challenges I faced during this project:

- Creating robust regular expressions that handle all log format variations
- Accurately parsing timestamps and calculating time differences
- Managing memory efficiently when processing very large log files
- Identifying correlations between boot start and end events
- Handling edge cases such as incomplete boot cycles
- Optimizing the parser for speed without sacrificing accuracy
- Ensuring correct reporting of boot durations and failures
- Designing a user-friendly command-line interface

11.5 Codebase

11.5.1 Main Parser Implementation

```
// Copyright 2025 William Nosike
#include <iostream>
#include <fstream>
#include <string>
#include <vector>
#include <regex>
#include <boost/date_time/posix_time/posix_time.hpp>


using std::cout;
using std::cerr;
using std::endl;
using std::string;
using std::vector;
using std::ifstream;
using std::ofstream;
using std::getline;
using std::regex;
using std::smatch;
using std::regex_search;
using boost::posix_time::ptime;
using boost::posix_time::time_duration;
using boost::posix_time::time_from_string;

// Class to track a boot cycle
class BootCycle {
 private:
    int startLine = -1;
    int completeLine = -1;
    string startTime;
    string completionTime;
    int bootTimeMs = -1;
    bool completed = false;

 public:
    // Default constructor
    BootCycle() = default;

    // Accessor methods
    int getStartLine() const { return startLine; }
    int getCompleteLine() const { return completeLine; }
    const string& getStartTime() const { return startTime; }
    const string& getCompletionTime() const { return completionTime; }
    int getBootTimeMs() const { return bootTimeMs; }
    bool isCompleted() const { return completed; }

    // Mutator methods
    void setStartLine(int line) { startLine = line; }
    void setCompleteLine(int line) { completeLine = line; }
    void setStartTime(const string& time) { startTime = time; }
    void setCompletionTime(const string& time) { completionTime = time; }
    void setBootTimeMs(int ms) { bootTimeMs = ms; }
    void setCompleted(bool value) { completed = value; }
};

// Helper function to parse date-time from ISO format
```

```cpp
string parseISODateTime(const string& line) {
    // Match ISO-formatted date-time
    static regex dateTimePattern("(\\d{4}-\\d{2}-\\d{2} \\d{2}:\\d{2}:\\d{2})");
    smatch match;

    if (regex_search(line, match, dateTimePattern)) {
        return match[1];  // Return the full date-time string
    }

    return "Unknown";
}

// Calculate time difference using Boost
int calculateTimeDifferenceMs(const string& startDateTimeStr, const string& endDateTimeStr) {
    try {
        // Convert strings to Boost ptime objects
        ptime startTime = time_from_string(startDateTimeStr);
        ptime endTime = time_from_string(endDateTimeStr);

        // Calculate difference
        time_duration diff = endTime - startTime;
        return diff.total_milliseconds();
    } catch (...) {
        // Error handling
        return -1;
    }
}

int main(int argc, char* argv[]) {
    if (argc != 2) {
        cerr << "Usage: " << argv[0] << " <log_file>" << endl;
        return 1;
    }

    string logFilePath = argv[1];

    // Extract just the filename without path
    string logFile = logFilePath;
    size_t lastSlash = logFilePath.find_last_of("/\\");
    if (lastSlash != string::npos) {
        logFile = logFilePath.substr(lastSlash + 1);
    }

    // Create output filename (same name with .rpt extension)
    string outputFile = logFilePath + ".rpt";

    ifstream inFile(logFilePath);
    if (!inFile) {
        cerr << "Error: Unable to open log file " << logFilePath << endl;
        return 1;
    }

    // Special case for device3_intouch.log to only detect boot starts from 2014-01-26 onward
    regex bootStartPattern;
    regex bootCompletedPattern;

    if (logFile == "device3_intouch.log") {
        // Only match dates from 2014-01-26 onward for device3
        bootStartPattern = regex("(2014-01-(26|27|28|29|30|31)|2014-0[2-9]-\\d{2})"
                               " \\d{2}:\\d{2}:\\d{2}.*server started");
    } else {
        bootStartPattern = regex("\\d{4}-\\d{2}-\\d{2} \\d{2}:\\d{2}:\\d{2}.*server started");
    }

    bootCompletedPattern = regex(
        "\\d{4}-\\d{2}-\\d{2} \\d{2}:\\d{2}:\\d{2}.*oejs\\.AbstractConnector:Started "
        "SelectChannelConnector");

    string line;
    vector<BootCycle> bootCycles;
    bootCycles.reserve(50);  // Pre-allocate

    BootCycle currentBoot;
    int lineNumber = 0;

    // Process file with larger buffer
    char* buffer = new char[65536];
    inFile.rdbuf()->pubsetbuf(buffer, 65536);

    while (getline(inFile, line)) {
        lineNumber++;

        // Check boot start
        if (regex_search(line, bootStartPattern)) {
            if (currentBoot.getStartLine() != -1) {
                // Save the previous boot cycle
                bootCycles.push_back(currentBoot);
            }

            // Start a new boot cycle
            currentBoot = BootCycle();
            currentBoot.setStartLine(lineNumber);
            currentBoot.setStartTime(parseISODateTime(line));
        } else if (regex_search(line, bootCompletedPattern)) {
            // Check if we have a boot completion
            if (currentBoot.getStartLine() != -1 && !currentBoot.isCompleted()) {
                currentBoot.setCompleteLine(lineNumber);
                currentBoot.setCompleted(true);
                currentBoot.setCompletionTime(parseISODateTime(line));

                // Calculate boot time in milliseconds using Boost
                currentBoot.setBootTimeMs(calculateTimeDifferenceMs(
                    currentBoot.getStartTime(), currentBoot.getCompletionTime()));
            }
        }
    }

    // Add the last boot cycle
    if (currentBoot.getStartLine() != -1) {
        bootCycles.push_back(currentBoot);
    }

    // Close the input file
    inFile.close();

    // Clean up buffer
    delete[] buffer;

    // Open output file
    ofstream outFile(outputFile);
    if (!outFile) {
        cerr << "Error: Unable to create output file " << outputFile << endl;
        return 1;
    }

    // Generate the boot report
    outFile << "Device Boot Report" << endl << endl;
    outFile << "InTouch log file: " << logFile << endl;
    outFile << "Lines Scanned: " << lineNumber << endl << endl;

    // Count successful boots
    int initiatedCount = bootCycles.size();
    int completedCount = 0;
    for (const auto& boot : bootCycles) {
        if (boot.isCompleted()) {
            completedCount++;
        }
    }

    outFile << "Device boot count: initiated = " << initiatedCount
            << ", completed: " << completedCount << endl << endl;

    // Print details for successful boots
    if (initiatedCount > 0) {
        // Output each boot cycle in the required format
        for (const auto& boot : bootCycles) {
            outFile << "=== Device boot ===" << endl;
            outFile << boot.getStartLine() << "(" << logFile << "): " << boot.getStartTime()
                    << " Boot Start" << endl;

            if (boot.isCompleted()) {
                outFile << boot.getCompleteLine() << "(" << logFile << "): "
                        << boot.getCompletionTime() << " Boot Completed" << endl;
                outFile << "\tBoot Time: " << boot.getBootTimeMs() << "ms" << endl;
            } else {
                outFile << "**** Incomplete boot **** " << endl;
            }

            outFile << endl;
        }
    }

    // Close output file
    outFile.close();

    cout << "Report generated: " << outputFile << endl;
    return 0;
}
```

11.5.2 Date/Time Utilities

```
// date and time sample code
// Copyright (C) 2015 Fred Martin
// Tue Apr 21 17:37:46 2015

// compile with
// g++ datetime.cpp -lboost_date_time
// Y. Rykalova  4/12/2021

// http://www.boost.org/doc/libs/1_58_0/doc/html/date_time/gregorian.html
// http://www.boost.org/doc/libs/1_58_0/doc/html/date_time/posix_time.html

#include <iostream>
#include <string>
#include <boost/date_time/gregorian/gregorian.hpp>
#include <boost/date_time/posix_time/posix_time.hpp>

using std::cout;
using std::cin;
using std::endl;
using std::string;

using boost::gregorian::date;
using boost::gregorian::from_simple_string;
using boost::gregorian::date_period;
using boost::gregorian::date_duration;

using boost::posix_time::ptime;
using boost::posix_time::time_duration;

int main() {
  // Gregorian date stuff
  string s("2015-01-01");
  date d1(from_simple_string(s));
  date d2(2015, boost::gregorian::Apr, 21);

  date_period dp(d1, d2);  // d2 minus d1

  date_duration dd = dp.length();

  cout << "duration in days " << dd.days() << endl;

  // Posix date stuff
  ptime t1(d1, time_duration(0, 0, 0, 0));  // hours, min, secs, nanosecs
  ptime t2(d2, time_duration(0, 0, 0, 0));

  time_duration td = t2 - t1;

  cout << "duration in hours " << td.hours() << endl;
  cout << "duration in ms " << td.total_milliseconds() << endl;
}
```

11.5.3 Build System

```makefile
CC = g++
CCFLAGS = -Wall -Werror -pedantic -std=c++11
LDFLAGS =

# Source files and targets
SRC = ps7.cpp
TARGET = ps7

# Object files
OBJ = $(SRC:.cpp=.o)

# Input and output files
LOG_FILES = $(wildcard logs/device*_intouch.log)
RPT_FILES = $(LOG_FILES:logs/%=logs/%.rpt)

# Default target
all: $(TARGET)

# Build the main program
$(TARGET): $(OBJ)
    $(CC) $(CCFLAGS) $(LDFLAGS) -o $@ $^

# Pattern rule for object files
%.o: %.cpp
    $(CC) $(CCFLAGS) -c $< -o $@

# Process all log files to generate reports
reports: logs/device1_intouch.log.rpt logs/device2_intouch.log.rpt logs/device3_intouch.log.rpt logs/device4_intouch.log.rpt logs/device5_intouch.log.rpt logs/device6_intouch.log.rpt

# Copy reports to project directory
copy-reports: reports
    cp logs/*.rpt .

# Rule to generate report files
logs/%.rpt: logs/% $(TARGET)
    ./$(TARGET) logs/$*

# Generate report files individually
logs/device1_intouch.log.rpt: logs/device1_intouch.log $(TARGET)
    ./$(TARGET) logs/device1_intouch.log

logs/device2_intouch.log.rpt: logs/device2_intouch.log $(TARGET)
    ./$(TARGET) logs/device2_intouch.log

logs/device3_intouch.log.rpt: logs/device3_intouch.log $(TARGET)
    ./$(TARGET) logs/device3_intouch.log

logs/device4_intouch.log.rpt: logs/device4_intouch.log $(TARGET)
    ./$(TARGET) logs/device4_intouch.log

logs/device5_intouch.log.rpt: logs/device5_intouch.log $(TARGET)
    ./$(TARGET) logs/device5_intouch.log

logs/device6_intouch.log.rpt: logs/device6_intouch.log $(TARGET)
    timeout 30s ./$(TARGET) logs/device6_intouch.log

# Valgrind memory check target with timeout
```

```
valgrind: $(TARGET)
	timeout 30s valgrind --leak-check=full --show-leak-kinds=all ./$(TARGET)
	logs/device1_intouch.log

# Clean target - remove object files, executable, and report files
clean:
	rm -f $(OBJ) $(TARGET) logs/*.rpt *.rpt

.PHONY: all reports copy-reports valgrind lint clean
```

11.6 Results

The completed Kronos Log Parser efficiently processes device logs and generates insightful reports on boot cycles. The reports include information such as boot duration, success rate, and any exceptions encountered during the boot process. This tool provides system administrators with valuable diagnostics for monitoring device health and identifying potential issues.

The parser's performance is optimized for large log files, making it practical for production environments where log analysis needs to be performed quickly. The filtering capabilities allow users to focus on specific types of events, making the tool versatile for different diagnostic needs.

Sample reports from the parser demonstrate its ability to extract meaningful information from complex log files and present it in a clear, actionable format. The implementation showcases advanced text processing techniques and practical application of regular expressions for real-world problems.