



SET09121 Games Engineering

Workbook 2018

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List of Algorithms

Lesson 1

Getting Started

Welcome to Games Engineering!

The pre-requisite knowledge you require is:

- a working knowledge of object-oriented programming in a high-level language. In an ideal world this is C++ but Java and C# programmers should be able to cope with the material.
- at least a grasp of mathematical concepts such as trigonometry, algebra, and geometry. Linear algebra and matrix mathematics are very advantageous.
- a willingness to spend time solving the problems presented in this workbook. Some of the exercises are challenging and require effort. There is no avoiding this. However, solving these problems will significantly aid your understanding.
- Git version control basics

1.0.1 Git Repos

The practical content is available from a Git repository and via Moodle.

```
git clone https://github.com/edinburgh-napier/set09121
```

or

```
git clone git@gitgud.napier.ac.uk:set/set09121.git
```

You could make a fork of this, or create your own code repo from scratch. (We will walk through this now). Later on you will need to create a separate repository for your coursework, which you will share with one other developer. But for now, we are just dealing with practical content. As you work through the practicals, commit your work to your repo.

1.0.2 Development Environment

You will be able to work on this module on any operating system that has a modern C++ compiler. We will be using the CMake build system, so you won't need to use a specific IDE. We recommend Visual Studio 2017 on Windows, and Clion on Mac/Linux. This module expects that you follow best practices when it comes to software development: i.e use version control

effectively and properly, maintain a clean codebase, and implement testing procedures (more on this later). You will also need Git and CMake installed, and added to your PATH.

SFML You may be glad to know that for this module, the Rendering of your games projects will be handled for you. We will be making use of the 2D Games/Graphics library SFML www.sfml-dev.org. This handles many of the low-level grunt-work that goes into making games, allowing us to focus on the high level design. There is also a wide array of tutorials and pre-existing support available around the internet if you run into a SFML-specific problem.

1.0.3 Workbook Style

The workbook is task and lesson based, requiring you to solve problems in each chapter to continue to the next. Unlike other games modules, no code will be given for you to start with, some listings will be provided in the workbook that you may copy verbatim, but even these may require you to fix them. For clarity; missing sections you have to complete are highlighted in stars:

```
1 int score = 3;
2 while(true){
3 // *****
4 // You have to complete this problem
5
6
7 // *****
8 }
```

In some cases, there may not be "missing code", but rather larger sections of logic that you will have to solve in your own way, rather than filling in the blanks.

```
1 auto h = renderer::window->GetHeight();
2 auto w = renderer::window->GetWidth()
3 //Calculate aspect ratio
4 //Scale Ui accordingly
```

The problems faced generally build on previous lessons until you become familiar with the work involved.

1.1 Getting started for real

1.1.1 Step 1 - Create a Github Repo for your project

Let's create our repo to work in, you can do this either via github first and pull down, or create locally and then push up. We'll start via github (or any repository hosting website of your choice i.e bitbucket / gitgud.anpier.ac.uk).

If you have not already created a github account, create one and sign in.

(As a student you get some cool swag from github: <https://education.github.com/pack>)

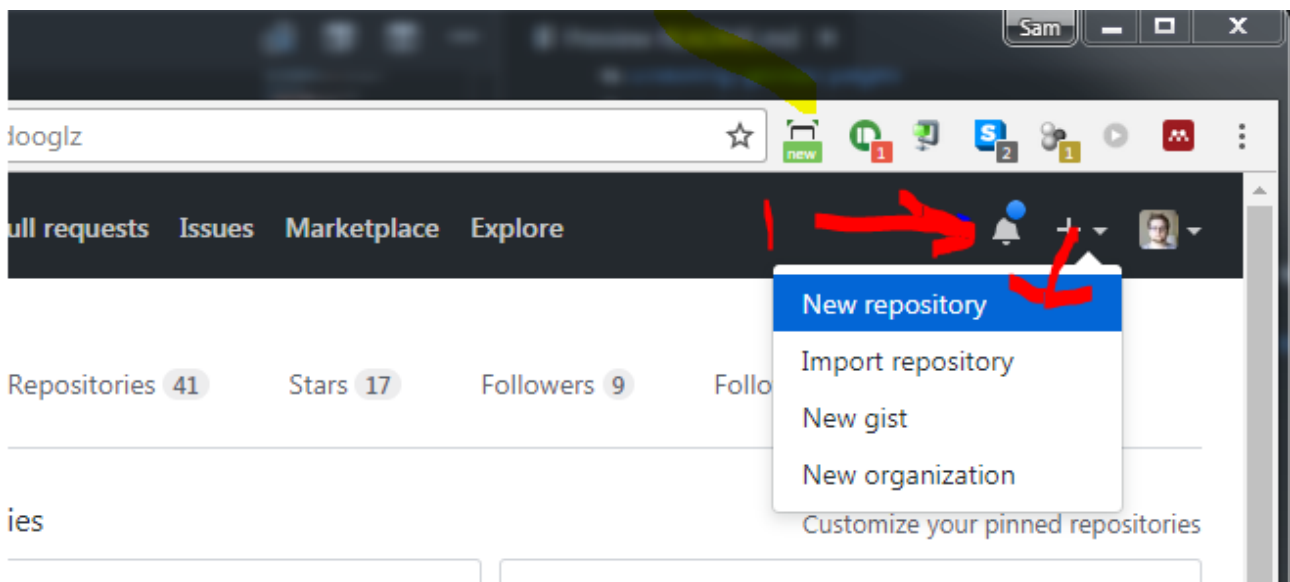


Figure 1.1: New Repo process

Create a new repository

A repository contains all the files for your project, including the revision history.

Owner: dooglz / Repository name: ✓

Great repository names are short and memorable. Need inspiration? How about **urban-parakeet**.

Description (optional):

☒ Public
Anyone can see this repository. You choose who can commit.

☐ Private
You choose who can see and commit to this repository.

☒ Initialize this repository with a README
This will let you immediately clone the repository to your computer. Skip this step if you're importing an existing repository.

Add .gitignore: | Add a license: ⓘ

Figure 1.2: New Repo Options

Give your repo a simple name and descriptive description

Check - Initialize with a readme

Choose an open source license, so people cant legally steal your work without crediting you. The inbuilt guide from github covers this neatly, when in doubt: choose MIT license.

After this stage Github will create the repo for you and you should see something like the following image, now it's time to **clone** the repo down so you can start to work within it. Click the green clone button and copy the link within the box

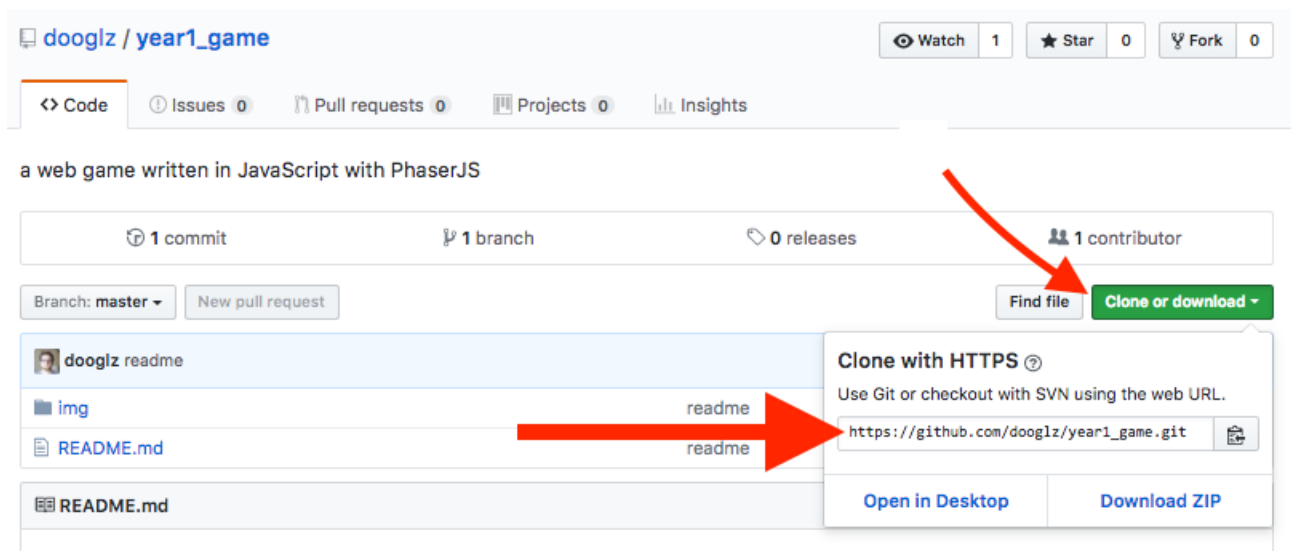


Figure 1.3: Clone from Github

1.1.2 Step 2 - Clone your repo

If you haven't installed Git on your pc yet, git-scm.com/downloads

Open a cmd (or git-bash) window somewhere (desktop is best). Now clone your repo down

```
1 git clone https://github.com/you/set09121_labs
```

This will create a folder named set09121_labs (or whatever you called you repo). Let's move into that folder in the terminal

```
1 cd set09121_labs
```

Now if you run

```
1 git status
```

You should see something similar to

```
1 On branch master
2 Your branch is up-to-date with 'origin/master'.
3 nothing to commit, working tree clean
```

Now we can Start to get to work properly.

1.1.3 Step 3 - Setup project structure

Create the following empty folders.

- **res** (where resources go, like images and fonts)
- **lib** (libraries that we need)
- **practical_1** (source code for practical 1)

Next, create a **.gitignore** file, open with a text editor. Navigate to www.gitignore.io and create an ignore file for “C++” and the IDE you intend to use, i.e “Visual Studio”. Copy the generated file into your gitignore file and save it. Git will not look at or track any files that match the rules in the gitignore file, keeping junk you don’t need out of your repo.

1.1.4 Step 4 - Get SFML

We will be building SFML from source, which means we need to get the code. We will be doing this via Git Submodules, which makes it look like the SFML code is now copied into your repo, but is actually saved a virtual link to the separate SFML repo.

```
1 git submodule add https://github.com/SFML/SFML.git lib/sfml
2 git submodule init
3 git submodule update
```

1.1.5 Step 5 - Write some test code

With a simple text editor, create a **main.cpp** file in the practical_1 folder, input the following code:

```
1 #include <SFML/Graphics.hpp>
2
3 int main(){
4     sf::RenderWindow window(sf::VideoMode(200, 200), "SFML works!");
5     sf::CircleShape shape(100.f);
6     shape.setFillColor(sf::Color::Green);
7
8     while (window.isOpen()){
9         sf::Event event;
10        while (window.pollEvent(event)){
11            if (event.type == sf::Event::Closed){
12                window.close();
13            }
14        }
15        window.clear();
16        window.draw(shape);
17        window.display();
18    }
19    return 0;
20 }
```

Listing 1.1: practical_1/main.cpp

1.1.6 Step 6 - Create the CMake script

With a simple text editor, create a **CMakeLists.txt** file in the root folder, input the following code:

```

1 cmake_minimum_required(VERSION 3.9)
2 # Require modern C++
3 set(CMAKE_CXX_STANDARD 14)
4 set(CMAKE_CXX_STANDARD_REQUIRED ON)
5
6 project(Games_Engineering)
7
8 ##### Setup Directories #####
9 #Main output directory
10 SET(OUTPUT_DIRECTORY "${CMAKE_BINARY_DIR}/bin/")
11 # Output all DLLs from all libs into main build folder
12 SET(CMAKE_RUNTIME_OUTPUT_DIRECTORY ${OUTPUT_DIRECTORY})
13
14 ##### Add External Dependencies #####
15 add_subdirectory("lib/sfml")
16 set(SFML_INCS "lib/sfml/include")
17 link_directories("${CMAKE_BINARY_DIR}/lib/sfml/lib")
18
19 ##### Practical 1 #####
20 file(GLOB_RECURSE SOURCES practical_1/*.cpp practical_1/*.h)
21 add_executable(PRACTICAL_1 ${SOURCES})
22 target_include_directories(PRACTICAL_1 PRIVATE ${SFML_INCS})
23 target_link_libraries(PRACTICAL_1 sfml-graphics)

```

Listing 1.2: CMakeLists.txt

Creating the Solution, with CMake If you are unfamiliar with CMake; Follow this guide: https://github.com/edinburgh-napier/aux_guides/blob/master/cmake_guide.pdf

Remember to place the build folder outside of the set09121 folder. Preferably your desktop, NOT your H drive

NEVER Build from your H drive!

Or a memorystick / External HDD

The build folder will never contain work you need to save or commit. All code resides in the source directory.

Once configured and generated, you can open the .sln file in the build folder. You should not need to touch any solution or project settings form within Visual Studio. The solution is set up so you don't have to do much work yourself or even understand Visual Studio settings.

1.1.7 Step 7 - Run The solution

Cmake should have generated a solution project for you in your build folder, open it. Practical_1 should be available as a project within it. Compile and run it! You should see a green

circle.

1.1.8 Step 8 - Saving your work

You should take this opportunity to commit and push your work. If you know the basics of git, this is nothing new.

```
1 git status
```

Running git status should show you all the files you have modified so far. We need to "Stage" or "add" these files.

```
1 git add .
```

This is a shorthand to tell git that we want to commit everything.

```
1 git commit -m "SFML hello world working"
```

Now we run the actual commit, which will store the current version of all your ("Staged") files to the local repo. Note that this is only local, you now need to push it up to github.

```
1 git push
```

This is a light-speed gloss over what version control can do for you. If this is new and strange to you, you really should take some time to look through some online git tutorials and guides to get comfortable with what it does and how it works.

1.1.9 Starting from scratch

If you want to work on another pc, or at home. You obviously don't need to create a new repo. The steps you need to do are simply

1. Clone/Pull the repo down from your github
2. Get/update SFML by running:

```
git submodule update --init --recursive
```

3. Run Cmake to generate your build folder

The key here is that you only need to version control your source folder, which only contains source files. The build folder, generated by CMake is full of large junk that visual studio needs, you don't need to save this or even really care about what's in there. You can re-generate it anytime anywhere using CMake.

Lesson 2

Pong

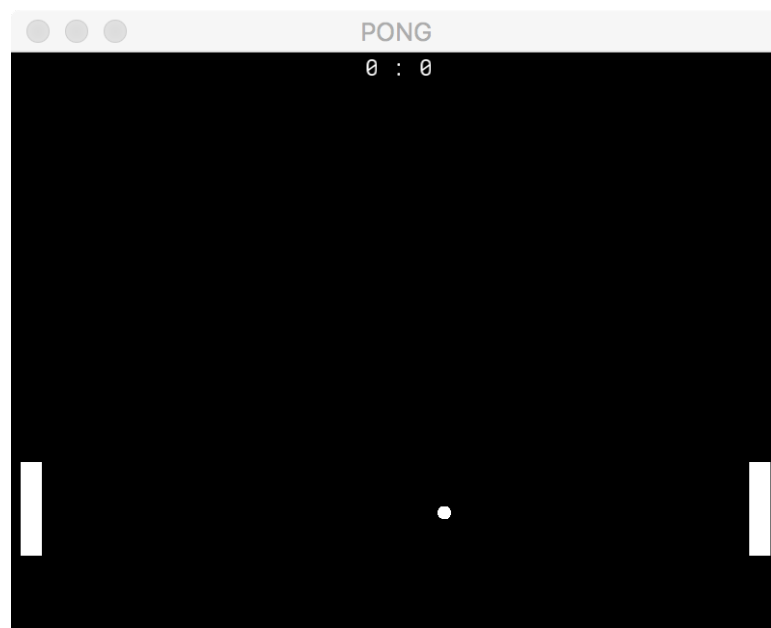


Figure 2.1: **Completed PONG**

For your first practical, we will be going back to the most basic of basic, Creating the classic arcade game PONG. For this we will be chucking some of the software practises you may be used to out the window. We will be using one single main.cpp file, no classes, no OO at all. You should be able to have a working pong game, with AI, in under 200 lines of code.

The purpose of this exercise is to get you acquainted with SFML. We will come back to the exercise often as an example of simple software design, as it useful as a base to compare more complex approaches.

Before we get stuck in, let's cover some of the fundamentals.

2.1 The game Loop

The fundamental core of all games, is the game loop. While some engines may hide this away, behind the scenes you can be sure that the code for any game can be stripped away to the fundamental game loop. It looks like this.

```

1 void Update(double dt) {
2     // Update Everything
3 }
4
5 void Render() {
6     // Draw Everything
7 }
8
9 int main () {
10    //initialise and load
11    while(!shouldQuit){
12        //Caluclate DT
13        Update(dt);
14        Render();
15        //Wait for Vsync
16    }
17    //Unload and shutdown
18 }
```

Listing 2.1: Standard Game Loop

The program starts as all programs do, with the `main()` function. Here we would load in anything we need at the start of the game, create the window, load settings, and all the usual start-up things you can imagine. If we weren't using SFML we would have to detect the capabilities of the system and enable or disable certain code paths accordingly (or throw an error and quit). SFML does all this work for us, and so we only need to care about loading things directly relevant to our game.

From there we enter a while loop of some kind. This will be based on some boolean value that determines if the game should quit or not. The game logic will set this from true to false when some event has happened (e.g, ESC key pressed, or player presses quit button). This loop will continuously run two functions, Update and Render. Update is where all game-logic code will go. This includes input processing, physics, content loading/unloading, networking.. etc. The rate at which we loop through this loop is the games framerate.

Once the Game update has been completed, the game can render a frame. No rendering will take place during the update function. The simple way of thinking is that the Update function determines where everything is and what it's doing. The render function then draws the results of the update.

Before calling Update, the Delta-Time (DT) is calculated. This is the amount of time that has passed between now and the previous frame. With a game updating at a steady 60fps, dt should be approximately 16ms (1/60). To actually calculate DT, you can use inbuilt C++ timers, or just use the handy SFML Clock.

```

1 static sf::Clock clock;
2 const float dt = clock.restart().asSeconds();
```

Listing 2.2: SFML DT

2.1.1 Update(dt)

This is also commonly called the game "Tick". While in our games we only do one "Tick" per frame, we could do more. If the game's logic could be executed quickly, and the game relies on fast action, it may be beneficial to do as many updates as you can between frames. While we aren't going to implement this, what you should take away is that: The Update function should be decoupled from Render(), so that multiple calls to Update() before a call to Render() should not break your game.

Framerate Independence The use of DT is to allow time related logic to take place (i.e a countdown timer) accurately, and for movement and physics code to work properly - independent of the framerate. A problem that arises with games is that the frametime can vary, sometime not by much, sometimes drastically (lower end PCs). Ideally we want a solid 16ms, but we won't always get that. A stuttering game doesn't look good graphically, but if we don't account for it within the game-logic, it can actually cause major problems. Imagine a player moving left at a speed of 10 units a second. With an ideal frame-rate of 60fps. We are calling Update() 60 times per second. So we should move the player by 0.16 (10/60) units each update.

```
1 const float playerSpeed = 10.f;
2 const float idealFps = 60.f;
3
4 void Update(double dt) {
5     player.move(playerSpeed / idealFps);
6 }
```

Listing 2.3: Shonky movement code

This would work, but if the frametime suddenly drops to 30fps, or starts varying between 30 or 60, the update() function will be called less, and so the player will move slower. Conversely, if the fps skyrockets, then our player will start moving at light-speed. The solution is to **Always include DT in calculations that involve time. i.e speed, movement, acceleration.** Here is the proper way to do it:

```
1 const float playerSpeed = 10.f;
2
3 void Update(double dt) {
4     player.move(playerSpeed * dt);
5 }
```

Listing 2.4: Framerate Independent movement code

Let's look at the maths here.

- when the game is running slower – DT gets larger (it's the time between frames).
- When the game is running faster – DT gets smaller.
- When the game is running at our ideal rate of 60fps – $DT = 1/60$.
- If the game drops down to 30fps – $DT = 1/30$
- When the game is running slower – the player moves faster.
- When the game is running faster – the player moves slower.

2.1.2 Render()

The render function does what you would expect, renders everything in the game to screen. There may be additional logic that goes on to do with optimisation and sending things back and forth between the GPU, but we are not dealing with any of this for a 2D game in SFML. To us, the render function is simply where we tell SFML to draw to the screen. In a multi-threaded engine, this could be happening alongside an update function (more on this later).

Vsync One other piece of logic that is important the game loop is the "buffer-swap" or "swap-chain" or "Vsync". This is a function that we can call that let's us know that the rendering has finished, and therefore it's the end of the frame, and time to start a new one.

```
1 //End the frame - send to monitor - do this every frame
2 window.display();
3
4 // enable or disable vsync -
5 // do at start of game, or via options menu
6 window.setVerticalSyncEnabled(true/false);
```

Listing 2.5: Swapchain in SFML

If we have enabled Vertical-sync(Vsync), the game will limit itself to the refresh rate of the connected monitor (usually 60hz, so 60fps). In this scenario once we have finished rendering everything in under 16ms, and we call `window.display()`, the game will wait for the remaining time of the frame before continuing. This is a carry-over from low level graphics programming where you don't want to send a new image to the monitor before it has finished drawing the previous (this causes visual Tearing). So if we are rendering faster than 60fps, the game will wait at the end of the render function while the monitor catches up. Before starting again the next frame. With vsync disabled, once we have finished rendering a frame, `window.display()` does not pause after sending the image and we continue to render the next frame immediately.

An important gotcha that can happen here is that the graphics drivers can manually override and forcefully enable or disable Vsync. So don't depend on it always being in the state that you set it.

2.2 Starting PONG

I'll get you started off with the top of your file. It's the usual imports and namespaces, followed by some variables we will use for game rules, and then 3 shapes, 1 circle for the ball, and 2 rectangles stored in an array for the paddles.

We then move onto the `Load()` function, we would load in assets here if we had any, and then we set-up the game by resizing and moving our shapes.

Line 32 and 34 are left incomplete for you to complete later. We can come back to it after looking at our other functions.

```

1 #include <SFML/Graphics.hpp>
2
3 using namespace sf;
4 using namespace std;
5
6 const Keyboard::Key controls[4] = {
7     Keyboard::A,    // Player1 UP
8     Keyboard::Z,    // Player1 Down
9     Keyboard::Up,   // Player2 UP
10    Keyboard::Down  // Player2 Down
11 };
12 const Vector2f paddleSize(25.f, 100.f);
13 const float ballRadius = 10.f;
14 const int gameWidth = 800;
15 const int gameHeight = 600;
16 const float paddleSpeed = 400.f;
17
18 CircleShape ball;
19 RectangleShape paddles[2];
20
21 void Load() {
22     // Set size and origin of paddles
23     for (auto &p : paddles) {
24         p.setSize(paddleSize - Vector2f(3, 3));
25         p.setOrigin(paddleSize / 2.f);
26     }
27     // Set size and origin of ball
28     ball.setRadius(ballRadius - 3);
29     ball.setOrigin(ballRadius / 2, ballRadius / 2);
30     // reset paddle position
31     paddles[0].setPosition(10 + paddleSize.x / 2, gameHeight / 2);
32     paddles[1].setPosition(...);
33     // reset Ball Position
34     ball.setPosition(...);
35 }

```

Listing 2.6: `practical_1/main.cpp`

The Update Here – as we have covered previously – is where our gamelogic goes. This runs every frame. Firstly we calculate DT, then process any events that sfml passes to us. From there we are free to do whatever we want, and what we want to do is make PONG. We will come back and add to this, you don't need to edit anything just now

```

36 void Update(RenderWindow &window) {
37     // Reset clock, recalculate deltatime
38     static Clock clock;
39     float dt = clock.restart().asSeconds();
40     // check and consume events
41     Event event;
42     while (window.pollEvent(event)) {
43         if (event.type == Event::Closed) {
44             window.close();
45             return;
46         }
47     }
48
49     // Quit Via ESC Key
50     if (Keyboard::isKeyPressed(Keyboard::Escape)) {
51         window.close();
52     }
53
54     // handle paddle movement
55     float direction = 0.0f;
56     if (Keyboard::isKeyPressed(controls[0])) {
57         direction--;
58     }
59     if (Keyboard::isKeyPressed(controls[1])) {
60         direction++;
61     }
62     paddles[0].move(0, direction * paddleSpeed * dt);
63 }

```

Listing 2.7: practical_1/main.cpp

Render and Main Our last section of the file is our super simple render function. I mean, just look at it. Isn't SFML awesome? Then we have our standard Main entrypoint, with our gameloop code. Not much to see here.

```

64 void Render(RenderWindow &window) {
65     // Draw Everything
66     window.draw(paddles[0]);
67     window.draw(paddles[1]);
68     window.draw(ball);
69 }
70
71 int main() {
72     RenderWindow window(VideoMode(gameWidth, gameHeight), "PONG");
73     Load();
74     while (window.isOpen()) {
75         window.clear();
76         Update(window);
77         Render(window);
78         window.display();
79     }
80     return 0;
81 }

```

Listing 2.8: practical_1/main.cpp

Once you've typed all of the above in: you should have something like this:

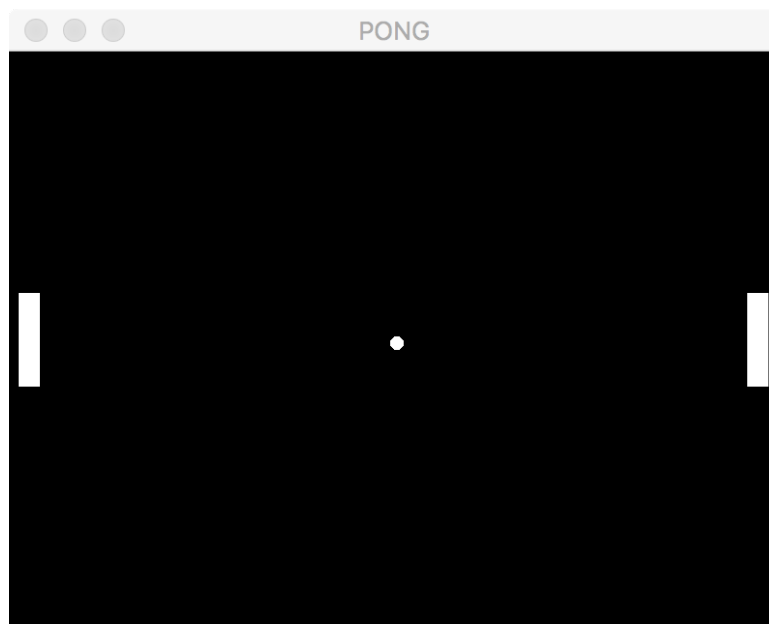


Figure 2.2: PONG hello world

2.2.1 Moving the ball

Add the following to the declarations at the start of the file.

```
1 Vector2f ballVelocity;
2 bool server = false;
```

Add this to the Load() function

```
1 ballVelocity = {(server ? 100.0f : -100.0f), 60.0f};
```

Add this to the Update() function

```
1 ball.move(ballVelocity * dt);
```

What we have done here is store a 2D vector of the **velocity**(speed+direction) of the ball. SFML stores the **position** of the ball internally so we don't need an extra variable for that. In our update function we then move the ball by its velocity. If we were coding the move function manually it would look like this

$$newBallPosition = oldBallPosition + (ballVelocity * TimePassed)$$

Which is just simple physics. I've introduced another piece of logic, the 'server' boolean. This decided which direction the ball starts moving at the start of the game. The weird piece of code that you added to the load function is an 'inline IF statement'. It's just the same as a IF block, but in one line. If the statement before the ? is true, then ballVelocity.x is set to -100, if server is false, ballVelocity.x = 60.0f.

2.2.2 Ball collision

”Bouncing” the ball is one of those cheap tricks that looks harder than it is. As we are storing the ball velocity as a vector. Negating it with respect to wall it bounced off of is as easy as multiplying the right element (X or Y) by -1. We actually multiply by -1.1, and 1.1 here so the ball not only bounces, but gets faster. All in two lines of code. Maths *is* fun.

In a perfect world that would be fine, but if the ball was flying super fast, it might get ”stuck within the wall” where the collision code will constantly negate it’s velocity, while speeding it up. This will cause the ball to stop, wiggle, then form a black hole of big numbers. This is bad. To get around this we chat and teleport the ball out of the wall by 10 units. Pong is a fast paced game so no one will notice. (This foreshadows some of the nastiness that happens when trying to write good physics code, we will talk about much later)

Add the following to the Update(). There is no functional purpose for the bx and by variables, but as we are going to use them a lot it’s nicer to have them to keep our code small.

```

1  // check ball collision
2  const float bx = ball.getPosition().x;
3  const float by = ball.getPosition().y;
4  if (by > gameHeight) {
5      // bottom wall
6      ballVelocity.x *= 1.1f;
7      ballVelocity.y *= -1.1f;
8      ball.move(0, -10);
9  } else if (by < 0) {
10     // top wall
11     ballVelocity.x *= 1.1f;
12     ballVelocity.y *= -1.1f;
13     ball.move(0, 10);
14 }

```

Left and right ”Score walls” This is a very easy check. We will be extending on the previous section of code with more else if statements. What is new here is that if we have collided with these walls, then we don’t bounce. We reset the balls and the paddles, and increment the score. Ignore score for now, but you should implement the reset function. You should pull out some of the logic from the load() function and then call Reset() at the beginning of the game. Repeated code is bad code.

```

1  else if (bx > gameWidth) {
2      // right wall
3      reset();
4  } else if (bx < 0) {
5      // left wall
6      reset();
7  }

```

Collision with paddles This is a simple ”Circle - Rectangle” collision check. But as we know that the paddles only move in the Y axis, we can take some shortcuts, we only need to check if the ball is within the top and bottom edge of the paddle.

```
1 else if (  
2     //ball is inline or behind paddle  
3     bx < paddleSize.x &&  
4     //AND ball is below top edge of paddle  
5     by > paddles[0].getPosition().y - (paddleSize.y * 0.5) &&  
6     //AND ball is above bottom edge of paddle  
7     by < paddles[0].getPosition().y + (paddleSize.y * 0.5)  
8 ) {  
9     // bounce off left paddle  
10 } else if (...) {  
11     // bounce off right paddle  
12 }
```

2.2.3 Two Player and Validated moves

You should now extend your game logic code to allow for moving both paddles (use the controls array defined at the top of the file). This should simply be a case of adding two extra IF statements to the Update(). Further to this, players shouldn't be able to move off of the screen. Given you have already done collision code, this should be a simple addition for you to complete.

2.2.4 AI

At this stage, we want to keep the code simple, so for AI, the AI paddle will try to match it's position to be the same height as the ball. However, keep it fair, AI should always play by the same rules as the player. The AI paddles should move at the same speed as the player, and not teleport to the correct position.

I've not given you any code for this, you should try to implement this yourself.

2.2.5 Adding score text

Loading and displaying text is super easy with SFML. Firstly you will need to find a font.ttf file somewhere, and use the following code

Add the following to Load()

```
1 // Load font-face from res dir
2 font.loadFromFile("res/fonts/RobotoMono-Regular.ttf");
3 // Set text element to use font
4 text.setFont(font);
5 // set the character size to 24 pixels
6 text.setCharacterSize(24);
```

Add the following to your Reset()

```
1 // Update Score Text
2 text.setString(...);
3 // Keep Score Text Centered
4 text.setPosition((gameWidth * 0.5f) - (text.getLocalBounds().width * ←
    0.5f), 0);
```

Finally, you need to add to your Render() function. I'll let you figure out what.

Runtime Resources If you have written your code correctly, you will get an error during runtime, that it can't find the font file specified. You will need to have your font file relative to the “working directory” of your game. Traditionally this is wherever the .exe is (In the build folder), but IDEs can change this to be other places. There is a proper way to do this, and we will cover this in the next practical. For now you should investigate where your program looks for files and place the font there manually.

2.2.6 Done

At this point you should have a fully featured PONG game, feel free to add more features, but the point of this exercise is to make a simple game with as few lines as possible of simple code. It's refreshing to be able to work in these conditions, without having to think about software design and large scale functionality. The next project we will work though will get progressively more complex until we are building an entire games engine. So keep you simple PONG game around, as something to look back on fondly as a statement of how easy it can be sometime to make great games.

Lesson 3

Space Invaders

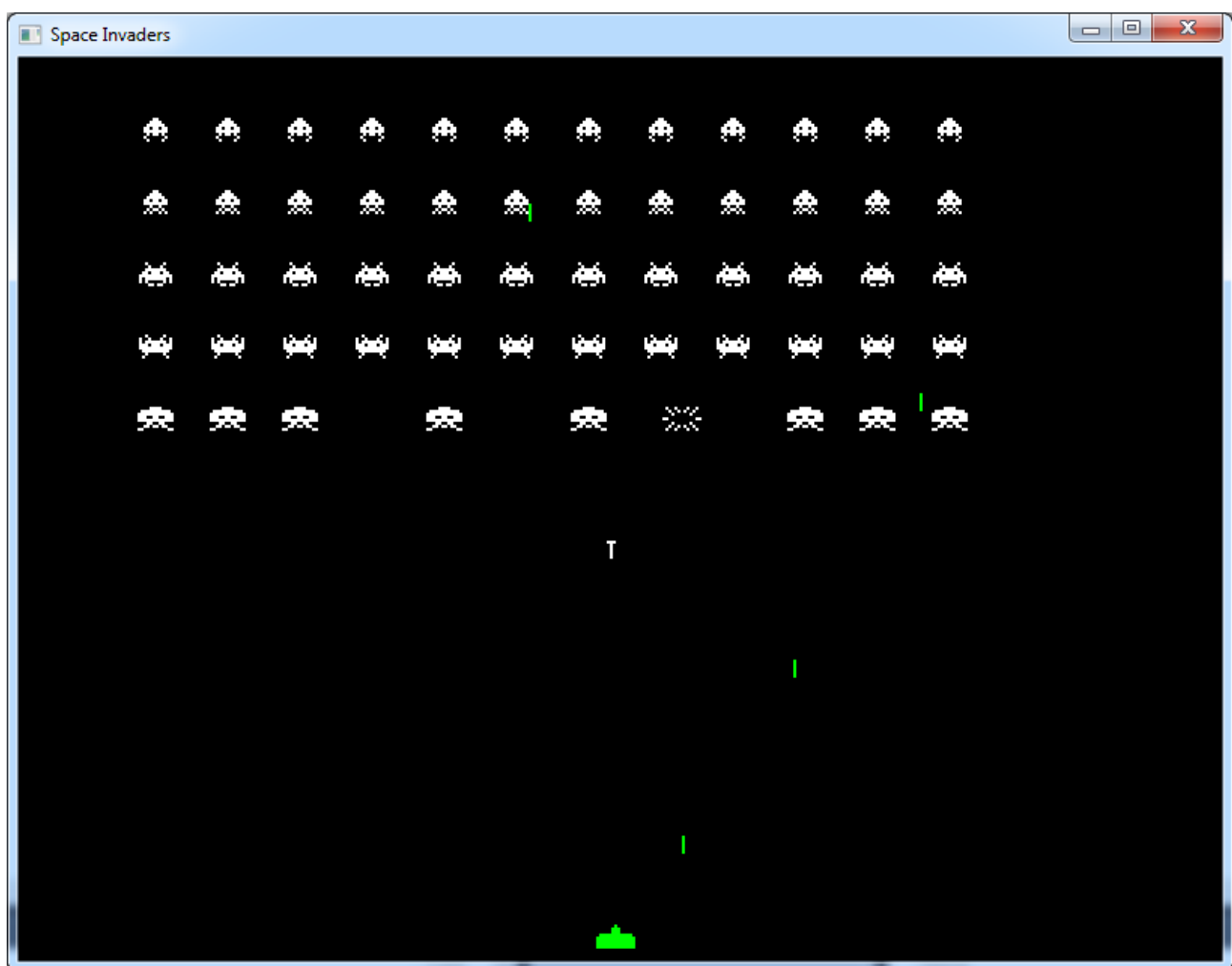


Figure 3.1: Completed Space Invaders

This lab is design to introduce you to: Object Orientation(OO) in C++, Working with C++ header files, and a small amount of memory and resource management.

3.1 Adding another project

We will be adding this lab a 'project' to our already existing 'Games Engineering solution'. Note: this is the vernacular of Visual studio. In CMake Terms we are adding another 'Executable' to the 'project'.

- Create a "practical_2" folder inside your repo.
- Within that, create a main.cpp, feel free to copy some boilerplate SFML code into it.

```

1 ## Space invaders
2 file(GLOB_RECURSE SOURCES practical_2/*.cpp practical_2/*.h)
3 add_executable(PRACTICAL_2_INVADERS ${SOURCES} )
4 target_include_directories(PRACTICAL_2_INVADERS SYSTEM PRIVATE ${←
    SFML_INCS})
5 target_link_libraries(PRACTICAL_2_INVADERS sfml-graphics)

```

Listing 3.1: Addition to CMakeLists.txt

- Configure and generate from CMake.

Helpful hint: on Re-configuring CMake Whenever we alter the CMake script, or add/remove source files from the source repo, we must configure and generate from CMake again. There is a short-cut to doing this. In your open solution in visual studio, CMake builds a helper project called "ZERO.CHECK". Building this project runs a script to configure and regenerate in the background. So we can edit and rebuild the CMakeLists.txt without leaving Visual studio.

A note on creating additional files As you know, we have all our source code in the source 'repo' folder, and all the project and build files in the ephemeral 'build' directory that CMake generates for us. CMake links the source files directly in the project files. When you edit a .cpp file in Visual Studio, it is editing the real file in the repo directory, even though all of visual studios files are in the 'build' directory.

One annoying caveat of this is that if you try to create a new file from visual studio, it incorrectly puts it in the build directory. You can manually type in the correct directory in the create file dialogue, or create the files manually and re-run CMake. Note: you will have to re-run CMake anyway when adding or removing files in the source directory.

3.2 Sprite-sheets

Before we get stuck in, you should have already have a standard boiler plate gameloop written to open a window and poll for events.

A common technique for 2D art assets in games is to combine what would be many separate images into one "sprite sheet". This saves time when loading in files, and a small amount of graphics memory. Images are places into tiles within a larger image, sprites are rendered by taking a 'cut out' of the larger image. In terms of optimisation this makes life very easy for the GPU – as it doesn't have to switch texture units.

The primary benefit of sprite sheets however is sprite-animation. It is commonplace to have each tile in the sheet be the same square size. With this restriction in place, picking the dimensions to 'cut' are a simple multiplication operation. Rendering a sequence of frames as an animation is as simple as moving the 'cut' windows to the right each frame.



Figure 3.2: **Animation Frames** Sonic will be rendered using different frames from the sprite-sheet each time, looping to the start once all frame have been rendered. Creating the illusion of fluid movement

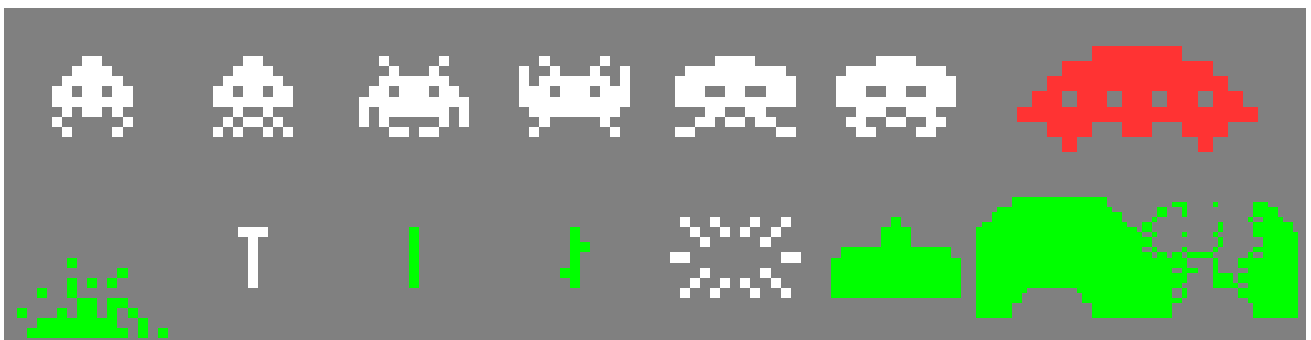


Figure 3.3: **Our Space Invaders Sprite-sheet** It's actually a transparent image - grey background just for clarity.



Figure 3.4: **Minecraft's Textures** Having all the textures in one image allows for easy mod-ability. The multiple squares of water and lava are animation frames.

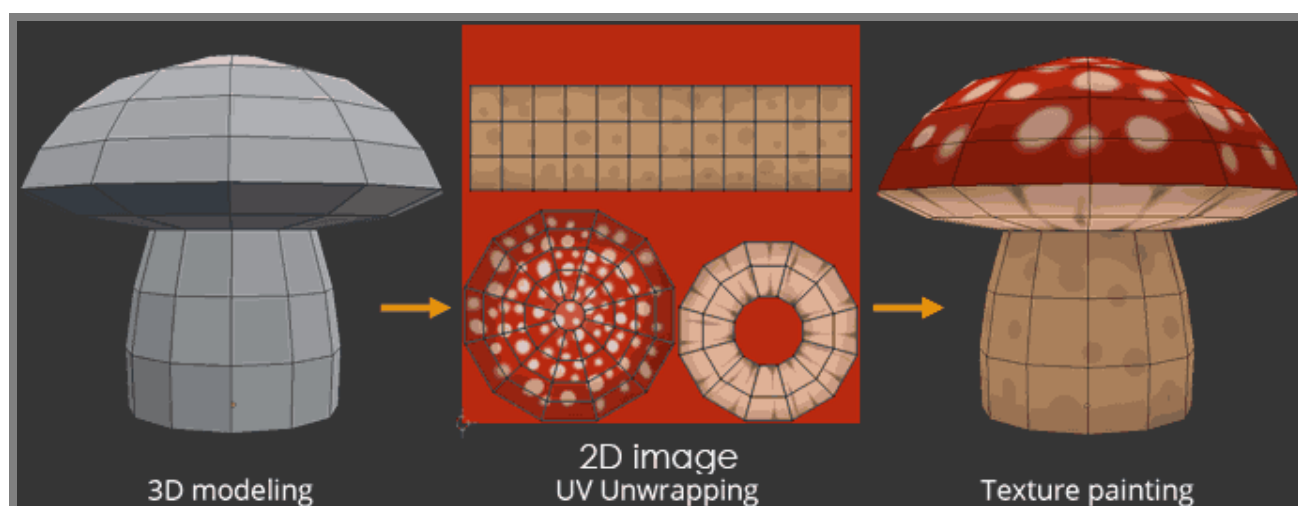


Figure 3.5: **Sprite sheets are not UV maps** Although visually similar - don't confuse sprite-sheets for unwrapped UV textures. These are used to apply a texture to a 3d model. Sprite-sheets are for 2d sprites

3.3 Loading a sprite-sheet

Workign with Sprite-sheets in SFML couldn't be easier. Take a look at this:

```

1 sf::Texture spritesheet;
2 sf::Sprite invader;
3
4
5 void Load() {
6     if (!spritesheet.loadFromFile("res/img/invaders_sheet.png")) {
7         cerr << "Failed to load spritesheet!" << std::endl;
8     }
9     invader.setTexture(spritesheet);
10    invader.setTextureRect(sf::IntRect(0, 0, 32, 32));
11 }
12
13
14 void Render() {
15     window.draw(invader);
16 }

```

Listing 3.2: Sprite sheet code

Totally easy. Take note of this line:

```

1 sprite.setTextureRect(sf::IntRect(0, 0, 32, 32));

```

The rectangle structure takes the form of (Left, Top, Width, Height). Our sprite-sheet is dived into squares of 32x32 pixels. So this line of code set the 'cut' do be the top left square in the image, aka. The first invader sprite.

Note that the invader doesn't take up the whole 32x32 square, it's surrounded by transparent pixels. SFML takes care of doing the rendering with correct modes so as to cuts out the background, but we may have to be careful when it comes to physics and collision code.

3.3.1 Runtime Resources Done Right

Before we can get this code running, we need to get the spritesheet image to somewhere where the running game can find it. In the previous practical we just dropped the image into the build folder, now we are going to do it properly.

Firstly, get Visual studio running in the right place Before we know where to put out resources, we need to know where Visual studio is running our program from. This could be the source folder, it could be somewhere in the build folder. This cmake script will alter VS to run your program out of the folder it was built into. i.e. "build/bin/debug".

```

1 set_target_properties(PRACTICAL_2_INVADERS
2     PROPERTIES VS_DEBUGGER_WORKING_DIRECTORY
3     ${CMAKE_RUNTIME_OUTPUT_DIRECTORY}/${Configuration}
4 )

```

Listing 3.3: Setting VS working directory

Now we know that's where we need to put our resources.

Method 1 : Altering the working directory A commonly used practise for getting your runtime resources where you need them is altering the debugging "Working Directory" to point to the source folder (like we did just above, but set to the source directory). This runs your game out of the build directory, but it looks for files in the source directory.

This works great for development but it means you can't run your program outside of Visual studio, and you have to remember to copy all the required files from your source directory when it comes time to package up an installer.

There is an even better way.

Method 2 : Copy all resources via POST_BUILD Visual studio allows you to input simple command-line scripts to run after certain events are triggered, such as Before-Build and Post-Build. This means we can write a script to automatically copy everything in source/resources to correct build folder whenever we build the application. This would involve digging through Visual studio windows, but thankfully CMake can do this for us.

CMake code just an example, don't actually write this

```
1 add_custom_command(TARGET YOUR_EXECUTABLE POST_BUILD
2   COMMAND ${CMAKE_COMMAND} -E copy_if_different "resource_dir"
3     ${TARGET_FILE_DIR:${YOUR_EXECUTABLE}}/res
4 )
```

Listing 3.4: POST Build script

This is a pretty good solution, but come with ing downsides. Visual studio only triggers POST_BUILD on build events, not on RUN events. So if you change a resource file in any way, you will have to rebuild your game to get it to trigger the copy script. There is one final step we need to do to perfect our workflow:

Method 3 : Copy all resources via Custom Target CMake can add more than just executables to the solution, it can also add "custom targets". We just aht below, and add a slightly modified version of our copy script within it.

```
1 add_custom_target(copy_resources ALL COMMAND ${CMAKE_COMMAND}
2   -E copy_directory
3     "${PROJECT_SOURCE_DIR}/res"
4     ${CMAKE_RUNTIME_OUTPUT_DIRECTORY}/${CONFIGURATION}/res
5 )
```

Listing 3.5: custom target script

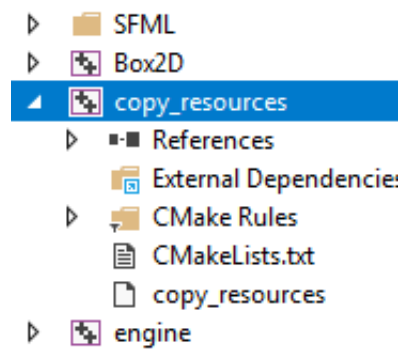
[If you are on osx, see Appendix A.1.]

And there we have it, a project in Visual studio we can 'Build' at any time that will copy everything we need from the source directory to the build directory

Oh, I almost forgot, there's one last thing to do in our CMake:

```
1 add_dependencies(PRACTICAL_2_INVADERS copy_resources)
```

Listing 3.6: custom target dependancy



Now whenever we build Space_Invaders, Visual studio will make sure that 'copy_resources' has been run. Excellent.

3.4 Creating the Ship Class

It's been a long journey since we wrote some space invaders code, let's get back to it. As with all software projects, as the complexity of the software grows, so do the potential different ways to implement it. That is to say, this may not be the best way to implement space invaders, we like to think it's at least a 'good' way. The point of building it this way is to expose you to many different aspects of C++ OO. Any programmer worth their salt will have an opinion on how they could improve someone else's code, and if you feel at the end of this that you have some ideas, then this lesson was successful.

Let's go OO We are going to need at least two different entities for our invaders game. Invaders and the player. Invaders are all identical other than their starting position and sprite. They also exhibit some non-trivial individual logic. Your software engineering brain should be starting to form the basis for properties and methods of the invader class by this point. To add to the fun, consider the player, and how similar it is also to the invader. they both shoot bullets, move, and can explode. This sounds like inheritance should be joining this party.

The way we are going to go about this to have an *abstract base class* **Ship**, which is inherited from by a **Player** class and an **Invader** Class.

Functionality of the Ship The ship class will contain all logic that is common for both the player and invaders. Primarily this will be "moving around". We could go with the full entity model and have Ship be a base class, with variables for it's position and rotation and such. We would then also have a `sf::Sprite` member attached where we would call upon all the SFML render logic. This is a good idea – for a larger game. For space invaders that would involve lot's of code to keep the sprite in sync with the ship Entity. Instead we are going to take a super short cut, and inherit for `sf::sprite`.

This means that Ship will have all teh same methods as a `sf::sprite`, including all the usual 'SetPostition()' and 'move()' commands we have been using already. It also means we can pass a ship object directly to `window.draw()`.

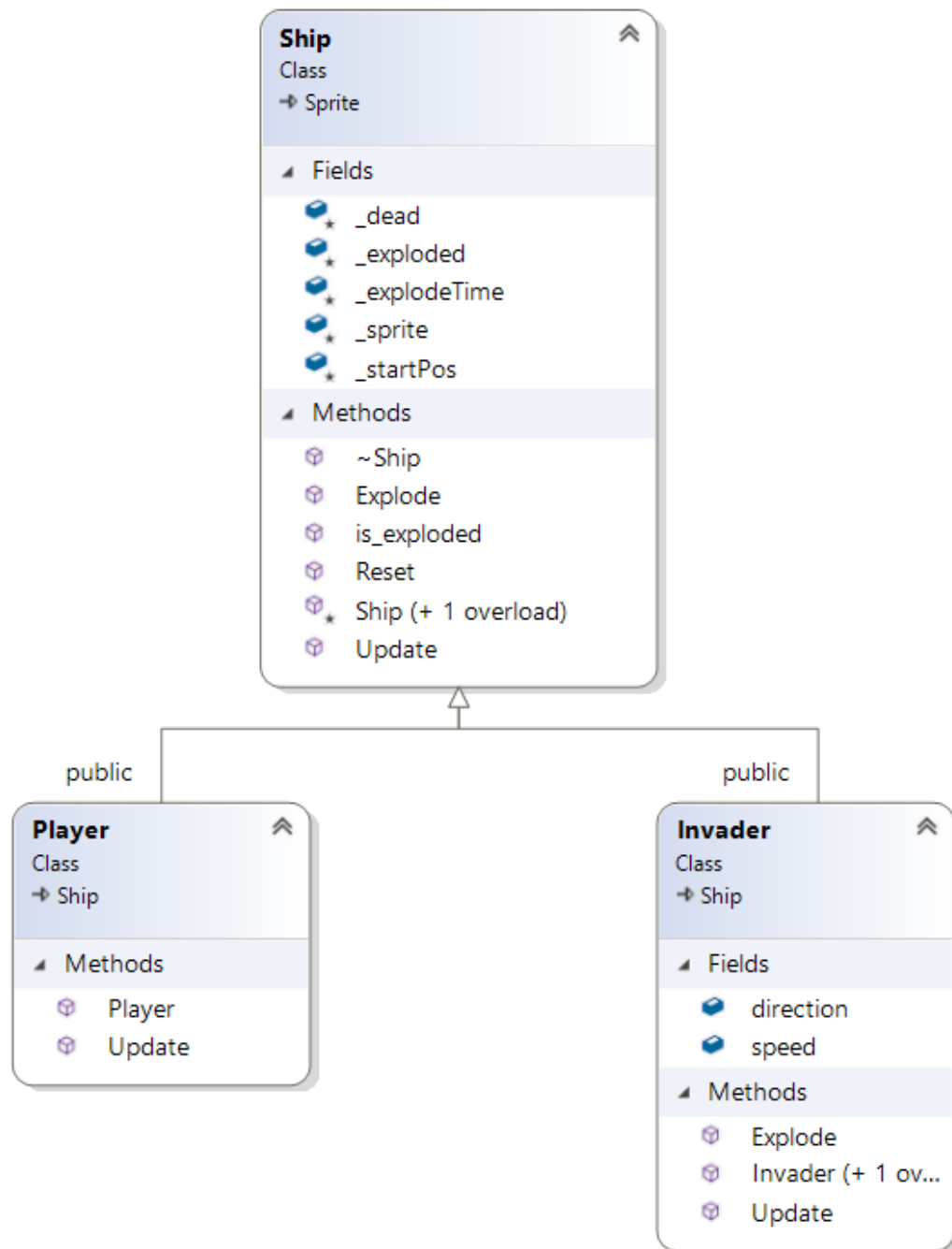


Figure 3.6: **Completed Space Invaders Class Diagram** don't worry about implmenting all these properties just yet

Create Ship.h Create a file inside the invaders source folder called “ship.h”. This will be our Header file for the Ship class. Header files contain the declaration of our class, i.e only the function declarations. Headers shouldn’t contain any code (some common exemptions apply). the reason we do this is to keep the logic of the class stored inside a .cpp file, any peice of code that want’s to access this functionality only needs the header. This concept does not exist inside java or C#, wherein you provide the full definition of a function inside a class in one file. the code runtime parses this and allows other classes to link to it. C++ is not so nice, and while this is totally possible to work in this fashion, we get into issues regarding name-space collisions, scope issues, multiple declarations, and code bloat. Ask in the lab if you would like to know more.

Anyway, Inside Ship.h get this written down:

```

1 #pragma once
2 #include <SFML/Graphics.hpp>
3
4 class Ship : public sf::Sprite {
5 protected:
6     sf::IntRect _sprite;
7     //Default constructor is hidden
8     Ship();
9 public:
10    //Constructor that takes a sprite
11    explicit Ship(sf::IntRect ir);
12    //Pure virtual destructor -- makes this an abstract class
13    virtual ~Ship() = 0;
14    //Update, virtual so can be overridden, but not pure virtual
15    virtual void Update(const float &dt);
16 };

```

Listing 3.7: Initial Ship.h

Create Ship.cpp Next to our ship.h, create ship.cpp

```

1 #include "ship.h"
2 using namespace sf;
3 using namespace std;
4
5 Ship::Ship() {};
6
7 Ship::Ship(IntRect ir) : Sprite() {
8     _sprite = ir;
9     setTexture(spriteSheet);
10    setTextureRect(_sprite);
11 };
12
13 void Ship::Update(const float &dt) {}
14
15 //Define the ship destructor.
16 //Although we set this to pure virtual, we still have to define it.
17 Ship::~Ship() = default;

```

Listing 3.8: Initial Ship.cpp

Access to global variables The code above needs access to some variables we have in our main.cpp (spritesheet). There are multiple ways to go about this. A rather simple yet hacky way is to have these variables as 'extern' in a header file. To do this, create another header, called "game.h" and insert:

```
1 #pragma once
2 #include <SFML/Graphics.hpp>
3 constexpr uint16_t gameWidth = 800;
4 constexpr uint16_t gameHeight = 600;
5 constexpr uint16_t invaders_rows = 5;
6 constexpr uint16_t invaders_columns = 12;
7
8 extern sf::Texture spritesheet;
```

Listing 3.9: game.h

We are defining some common variables here as constant, which is fine. The interesting bit is the 'extern spritesheet', this tells anyone that includes game.h that a sprite-sheet exists 'somewhere'. That somewhere is main.cpp, and the compiler will figure this out for us when we need to access it from ship.cpp.

Remember to reload CMake via Zero_check to add our new files to the build

Test out the code As Ship is an abstract class, we can't create one. Ee can only create a concrete class derived from it. We can reference it as pointer however, due to how c++ polymorphism works. Add the following to the top of your main.cpp

```
1 #include "ship.h"
2 // ...
3 std::vector<Ship *> ships;
```

Listing 3.10: main.cpp

This should compile without errors.

3.5 Making the Invader class

We could create a new invader.h and invader .cpp to house the invader class. Generally speaking separate files for separate classes is a good idea, although unlike Java we don't *have* to do this. In some situations when certain classes are very similar or just slightly different version of each other it makes sense to host them in the same Header file.

Add the following to code

```
1 class Invader : public Ship {
2 public:
3     Invader(sf::IntRect ir, sf::Vector2f pos);
4     Invader();
5     void Update(const float &dt) override;
6 };
```

Listing 3.11: Ship.h with initial Invader class

```

1 Invader::Invader() : Ship() {}
2
3 Invader::Invader(sf::IntRect ir, sf::Vector2f pos) : Ship(ir) {
4     setOrigin(16, 16);
5     setPosition(pos);
6 }
7
8 void Invader::Update(const float &dt) {
9     Ship::Update(dt);
10 }

```

Listing 3.12: Ship.cpp with initial Invader class

Now that we have a concrete implementation of a Ship we can create one.

```

1 Load() { ...
2 Invader* inv = new Invader(sf::IntRect(0, 0, 32, 32), {100,100});
3 ships.push_back(inv);

```

Listing 3.13: main.cpp

Important note, we used the New() operator here, which created the ship on the heap. If we wanted a stack version, we omit the new New and would use Invader 'inv = Invader()'.
 As we are storing the invader into a vector of ships, which will also later contain the player, this vector must be Ship Pointers. The way we have set this up we couldn't even create a vector<ship>, as that would try to construct an abstract class.

We need to call the update function of all our ships every frame, due to polymorphism this is very simple. Update() is a virtual function so when we call update() on a ship pointer that points to an invader, the invader's update() is called.

```

1 Update() { ...
2     for (auto &s : ships) {
3         s->Update(dt);
4     };

```

Listing 3.14: main.cpp

The same goes for rendering, as we have inherited from sprite, SFML can render our ships natively.

```

1 Render() { ...
2     for (const auto s : ships) {
3         window.draw(*s);
4     }

```

Listing 3.15: main.cpp

3.5.1 Invader movement

A quirk of space invaders is that all the invaders move as one, when any of the invaders touches the edge of the screen: all invaders drop down and reverse direction. When invaders are killed, the remaining invaders speed up. From this we can gather that we need some form of

communication medium between all the invaders so they can communicate when it's time to drop down and when to speed up. We are going to store these parameters as two variables: direction and speed. We could store these as properties in each invader, but as the contents will be identical for each invader we should do something better. The "something better" is static properties.

```
1 class Invader : public Ship {
2 public:
3     static bool direction;
4     static float speed;
5     ...
```

Listing 3.16: Ship.h

Top Hint: Any declared static variable **must** be defined somewhere. Which means we do the following in ship.cpp

```
1 bool Invader::direction;
2 float Invader::speed;
```

Listing 3.17: Ship.cpp

We can access these variables anywhere like so 'invader::speed = 20.f'.

Invader Update It's about time we had something moving on screen. We should modify the Invaders Update() to include some movement code.

```
1 void Invader::Update(const float &dt) {
2     Ship::Update(dt);
3
4     move(dt * (direction ? 1.0f : -1.0f) * speed, 0);
5
6     if ((direction && getPosition().x > gameWidth - 16) ||
7         (!direction && getPosition().x < 16)) {
8         direction = !direction;
9         for (int i = 0; i < ships.size(); ++i) {
10             ships[i]->move(0, 24);
11         }
12     }
13 }
```

Listing 3.18: Ship.h

The first two lines are simple, we call the base ship::update() to run any logic that is generic for all ships (none right now). Then we move either left or right, at the speed dictated by the static speed variable. The next few lines of code is the logic to detect whether it's time to drop and reverse. Direction is involved in the check to stop a feedback loop occurring of one invader triggering the reverse, then in the same frame another invader re-reversing it. So long as the invaders are updated sequentially (i.e not in threads) then this will work.

3.5.2 Spawning Invaders

Now we need to see this in action, lets create some more invaders. I'll start you off with this hint:

```

1 Load(){...
2     for (int r = 0; r < invaders_rows; ++r) {
3         auto rect = IntRect(...);
4         for (int c = 0; c < invaders_columns; ++c) {
5             Vector2f position = ...;
6             auto inv = new Invader(rect, position);
7             ships.push_back(inv);
8         }
9     }

```

Listing 3.19: main.cpp

3.6 The Player Class

Compared to the invader, the player is actually a very simple class. The only real logic it brings to the party is moving left and right based on keyboard inputs. Let's get to it by adding to the ship.h file

```

1 class Player : public Ship {
2 public:
3     Player();
4     void Update(const float &dt) override;
5 };

```

Listing 3.20: ship.h

Pretty basic. Over in the ship.cpp we now define this code.

```

1 Player::Player() : Ship(IntRect(160, 32, 32, 32)) {
2     setPosition({gameHeight * .5f, gameHeight - 32.f});
3 }
4
5 void Player::Update(const float &dt) {
6     Ship::Update(dt);
7     //Move left
8     ...
9     //Move Right
10    ..
11 }

```

Listing 3.21: ship.cpp

You should know how to add in the movement code, it's almost identical to pong. Bonus points for not allowing it to move off-screen. You should construct one player at load time and add it to the vector of ships.

3.7 Bullets

The game wouldn't be very difficult (or possible) without bullets firing around. Let's look at our requirements:

- Invaders shoot green bullets downwards
- The player shoots white bullets upwards
- The bullets explode any ship they touch
- After exploding the bullets disappear

If we look at our sprite-sheet we have two different bullet sprites. SFML can do some colour replacement, so if we wanted we could use the same white sprites for both bullet types and get SFML to colour them differently. However we want the two bullet types to look physically different so we will use two different sprites. So for whatever we decide to go with for our software design, we will be inheriting from `sf::Sprite` again.

That's rendering out of the way, now just movement and explosions to figure out. It would be tempting to do as we did with Ship and have two subclasses for invader and player bullets. But as they are both so similar, the only difference being the direction they travel and who they collide with, having a three class structure would be overkill. Sometimes rigorously following OO patterns isn't the best way forward. So instead we will build just one bullet class.

Here we go, create a `bullet.h` and `bullet.cpp`

```

1 #pragma once
2 #include <SFML/Graphics.hpp>
3
4 class Bullet : public sf::Sprite {
5 public:
6     void Update(const float &dt);
7     Bullet(const sf::Vector2f &pos, const bool mode);
8     ~Bullet()=default;
9 protected:
10    Bullet();
11    //false=player bullet, true=Enemy bullet
12    bool _mode;
13 };

```

Listing 3.22: `bullet.h`

```

1 #include "bullet.h"
2 #include "game.h"
3 using namespace sf;
4 using namespace std;
5
6 //Create definition for the constructor
7 //...
8
9 void Bullet::Update(const float &dt) {
10     move(0, dt * 200.0f * (_mode ? 1.0f : -1.0f));
11 }

```

Listing 3.23: `bullet.cpp`

3.7.1 Firing bullets

Alrighty, that's a barebones Bullet created, now to spawn one. The simplest way to do this would be to do something like this:

```
1 Player::Update(){...
2 if (Keyboard::isKeyPressed(...)) {
3     new Bullet(getPosition(), false);
4 }
```

Listing 3.24: ship.cpp player update

This is not a good idea however, there is three major problems.

Firstly, we will spawn thousands of bullets, we need a way to 'cooldown' the weapon of the player

Secondly, How do we update and render them? We should store our bullets somewhere.

Thirdly, and this is a big one, we put these bullets on the heap, and then forget about them, ayy'oh that's a **Memory Leak**.

3.7.2 Storing our bullets

Let's get our bullets at least updating and rendering before we worry about the other issues. What we could do is something like this:

```
1 Player::Update(){...
2     static vector<bullet*> bullets;
3     if (Keyboard::isKeyPressed(...)) {
4         bullets.push_back(new Bullet(getPosition(), false));
5     }
6     for (const auto s : bullets) {
7         bullets.Update(dt);
8     }
```

Listing 3.25: ship.cpp player update

So now the player is responsible for handling and keeping track of all the bullets it fires. We've stopped a runaway memory leak (for now, we still have to delete the bullets later). But how do we Render them? and while we're asking questions, won't this very get really, really big? We are going to fire a lot of bullets.

Yes, we will be firing loads of bullets, and we don't want to have keep track them all and delete them. In larger games this would cause performance issues. It won't here, but let's pretend we are running on original 80's hardware, we've gotta do better, or else the arcade will have to shut-down and the kids will be sad.

A different solution - Bullet Pools How about instead of creating bullets as and when we need them, we allocate a whole bunch at the start, and put them into a "pool of available bullets". When a player or an invader fires, an inactive bullet in the pool gets initialised to the correct position and mode and goes about it's bullet'y business. After this bullet has exploded or moved off-screen, it is moved back into the pool (or just set to "inactive").

This is a very common technique used in games with lots of expensive things coming into and out of existence. Almost every AAA UnityD game uses this with GameObjects – which take forever to allocate and construct. It’s much quicker to allocate loads at the start and re-use them.

Storing the Bullet Pool Each Ship could have it’s own pool of 3 or 4 bullets to re-use, but that’s a lot of code to refactor. Instead let’s store the bullet pool *inside* the bullet class.

```

1
2 class Bullet : public sf::Sprite {
3 ...
4 protected:
5 static unsigned char bulletPointer;
6 static Bullet bullets[256];
7 ...

```

Listing 3.26: bullet.h - “Yo dog I put a bullet inside your bullet”

We have statically allocated 256 bullets on the stack. We have brought along a sneaky unsigned char to do a clever trick to determine which bullet to use next. Unsigned chars go between 0 and 255, and then wrap round back to 0 and repeat. Therefore every time we Fire() a bullet we choose from the array like this “bullets[++bulletPointer]”. If there were ever more than 256 bullets on screen we will run into trouble, but I won’t worry about this if you don’t.

We will need to change our Firing mechanism, we now don’t want to ever construct a bullet, just Fire() one. We will have to change our class declaration around to suit this. Fire() will become a static function.

```

1 class Bullet : public sf::Sprite {
2 public:
3 //updates All bullets
4 static void Update(const float &dt);
5 //Render's All bullets
6 static void Render(sf::RenderWindow &window);
7 //Chose an inactive bullet and use it.
8 static Fire(const sf::Vector2f &pos, const bool mode);
9
10 ~Bullet()=default;
11 Protected:
12 static unsigned char bulletPointer;
13 static Bullet bullets[256];
14 //Called by the static Update()
15 void _Update(const float &dt);
16 //Never called by our code
17 Bullet();
18 //false=player bullet, true=Enemy bullet
19 bool _mode;
20 };

```

Listing 3.27: bullet.h

I’ll let you figure out the changes to the bullet.cpp. Keep in mind the differences between static-and non static functions. The _update() function is given in the next section.

3.8 Exploding Things

We will be using SFML to do the collision checks for us this time.

```

1 void Bullet::_Update(const float &dt) {
2     if (getPosition().y < -32 || getPosition().y > gameHeight + 32) ←
3     {
4         //off screen - do nothing
5         return;
6     } else {
7         move(0, dt * 200.0f * (_mode ? 1.0f : -1.0f));
8         const FloatRect boundingBox = getGlobalBounds();
9
10        for (auto s : ships) {
11            if (!_mode && s == player) {
12                //player bullets don't collide with player
13                continue;
14            }
15            if (_mode && s != player) {
16                //invader bullets don't collide with other invaders
17                continue;
18            }
19            if (!s->is_exploded() &&
20                s->getGlobalBounds().intersects(boundingBox)) {
21                //Explode the ship
22                s->Explode();
23                //warp bullet off-screen
24                setPosition(-100, -100);
25                return;
26            }
27        }
28    };

```

Listing 3.28: bullet.cpp

This code will require modification to our ship class. Also we need access to a pointer to the player ship so we can determine the types of collisions. My way of doing this would be to add it as another extern in game.h.

We need to introduce Explode behaviour into the ship classes. We will add the common functionality to the base Ship class - turning into the explosion sprite. The invader class will extend this by increasing the speed of other invaders, add removing the explosion sprite after a second. The player ship will end the game if explode is called on it. Which will trigger a game reset.

```

1 class Ship : public sf::Sprite {
2     ...
3     protected:
4         ...
5         bool _exploded;
6     public:
7         ...
8         bool is_exploded() const;
9         virtual void Explode();
10 };

```

Listing 3.29: ship.h

```

1 void Ship::Explode() {
2     setTextureRect(IntRect(128, 32, 32, 32));
3     _exploded = true;
4 }

```

Listing 3.30: bullet.cpp

3.9 Bullet Timing and Explosion fade

We noticed earlier that there is no limit to how fast a player could shoot – let's remedy that now.

My favourite way of doing this is keeping a 'cooldown' timer.

```

1 void Player::Update(const float &dt) {
2     ...
3     static float firetime = 0.0f;
4     firetime -= dt;
5     ...
6     if (firetime <= 0 && Keyboard::isKeyPressed(controls[2])) {
7         Bullet::fire(getPosition(), false);
8         firetime = 0.7f;
9     }
10 }

```

Listing 3.31: ship.cpp

Every time we fire, we put the timer up by .7 seconds. Every Update() we reduce this by dt. This means that we should only be able to fire from the player every .7 seconds. You could imagine some form of power-up that would modify this timer.

3.9.1 Invader shooting

Invaders should shoot somewhat randomly. How you do this is up to you, when it comes to something like this, it's usually a case of trying out magic numbers until you find something that looks good.

My hacky / beautiful solution was this:

```

1 void Invader::Update(const float &dt) {
2     ...
3     static float firetime = 0.0f;
4     firetime -= dt;
5     ...
6     if (firetime <= 0 && rand() % 100 == 0) {
7         Bullet::fire(getPosition(), true);
8         firetime = 4.0f + (rand() % 60);
9     }
10 }
```

Listing 3.32: ship.cpp

I've limited so an invader won't be able to fire more than once in four seconds. Bonus points for coming up with a solution wherein only the bottom row of invaders shoot, and as the invaders numbers dwindle, they fire more often.

3.9.2 Fading the Explosion sprite

At the moment our implementation turns a invader into the explosion sprite when it explodes, and the explosion remains in space. We need it to fade out over time. To do this we will use a similar technique as the bullet timer, where we will have a cooldown timer that starts when the ship explodes, and once the timer hits 0, the invader is moved off the screen or turned invisible.

3.10 Future

- Game over screen
- Restarting the Game
- animated sprites
- Green shield bases

Lesson 4

Tile Engine

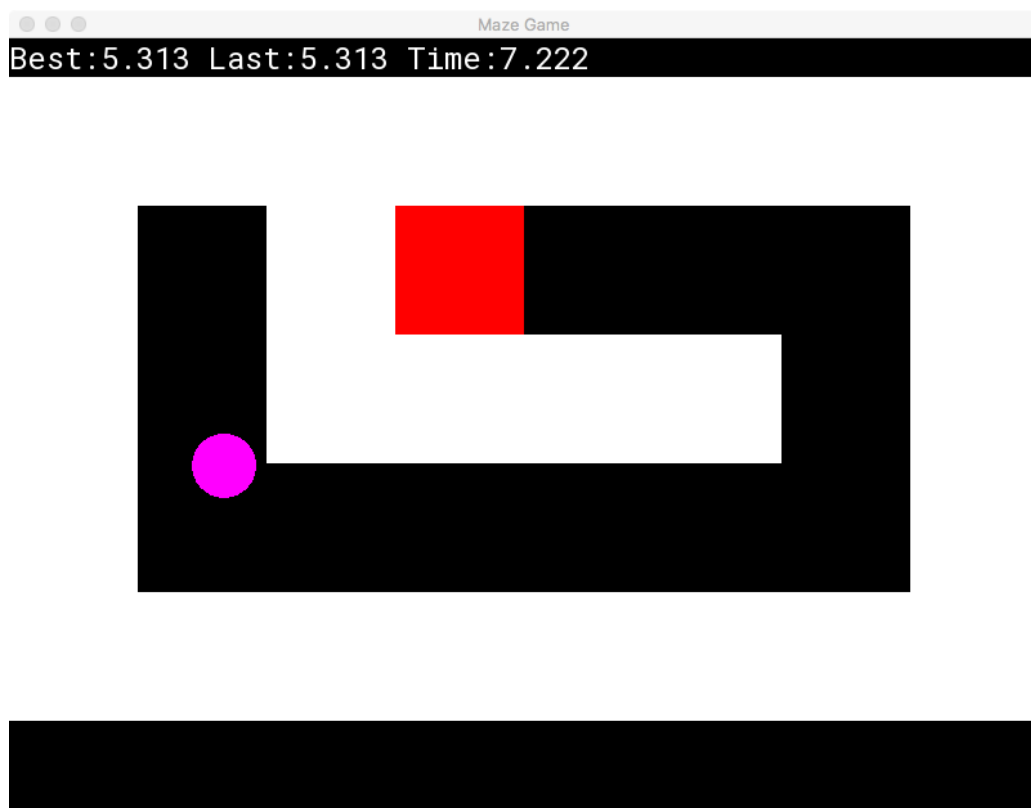


Figure 4.1: Completed Maze Game

This lab is design to introduce you to: Writing C++ Helper Libraries, Tile Based logic and 2D coordinate code.

4.1 Get Started

We will be starting this practical from the usual game loop basis. Create the main.cpp, and add the new project to CMake.

4.1.1 The Goal

The Game we are about to make is a maze game. The player moves a purple circle around from a starting point and tries to get to a determined end point in the shortest amount of time.

The Maze will be loaded from a text file with a super simple format. The logic for loading, rendering, and managing the maze data will be handled by a standalone "LevelSystem" library that we will build. This means we can use this code again in future projects. While we are building libraries, we will also make a small Maths helper library to cover some of the functions that SFML doesn't provide with its vector class.

The maze file, along with all other resources can be found in the Repo (section 1.0.1)

```
wwwwwwww
wswe    w
w  www  w
w       w
wwwwwwww
```

Listing 4.1: Maze file

4.2 Step One - Player Entity

While we won't have any need for complex inheritance or large software patterns, for this practical we are still going to follow the Entity Model. This will be a slight change from Space invaders in that we are not going to inherit from an SFML class.

4.2.1 Entity.h and Entity.cpp

For this game we will be working with `sf::shapes` rather than `sf::sprites`. They are both sibling classes that derive from `sf::drawable`, but are incompatible with each other (you can't allocate a shape with a sprite.)

Our base Entity class will be abstract, due to having a pure virtual `Render()` function.

The default constructor is also deleted, meaning the only way to construct it is through the constructor that takes a `sf::shape`. Meaning that all classes that derive from Entity must provide an `sf::shape` when they are constructed.

```

1 #pragma once
2
3 #include <SFML/Graphics.hpp>
4 #include <memory>
5
6 class Entity {
7 protected:
8     std::unique_ptr<sf::Shape> _shape;
9     sf::Vector2f _position;
10    Entity(std::unique_ptr<sf::Shape> shp);
11
12 public:
13    Entity() = delete;
14    virtual ~Entity() = default;
15
16    virtual void update(const double dt);
17    virtual void render(sf::RenderWindow &window) const = 0;
18
19    const sf::Vector2f getPosition();
20    void setPosition(const sf::Vector2f &pos);
21    void move(const sf::Vector2f &pos);
22 };

```

Listing 4.2: entity.h

Smart Pointers An important difference here is that the introduction of smart pointers (`std::unique_ptr`). So far we have been using "Raw" pointers, and creating them with `New()`, and deleting them with `Delete()`.

Smart pointers use reference counting to know where a pointer is stored. If it isn't stored anywhere, the reference count is 0 and the smart pointer deletes the memory associated with the pointer. This means that we don't have to call `Delete()` ourselves, as we would with raw pointers.

This is similar but different to "Garbage Collection" in Java. Smart pointers de-allocates memory when the last reference goes out of scope. This is deterministic, and so you can know when it will happen. With Java, the garbage collection process runs separately and deallocated memory based on internal algorithms – separate from your code.

Entity.cpp The definitions in the .cpp don't do anything fancy. We are just covering the basic movement functions that we no longer have from inhering from `sf::sprite`. Notice the Update function in particular. This is how we synchronise the state of the entity to SFML.

```
1 #include "entity.h"
2 using namespace std;
3 using namespace sf;
4
5 const Vector2f Entity::getPosition() { return _position;}
6
7 void Entity::setPosition(const Vector2f &pos) { _position = pos;}
8
9 void Entity::move(const Vector2f &pos) { _position += pos;}
10
11 void Entity::update(const double dt) {
12     _shape->setPosition(_position);
13 }
14
15 Entity::Entity(unique_ptr<Shape> s) : _shape(std::move(s)) {}
```

Listing 4.3: entity.cpp

4.2.2 Player.h and Player.cpp

Nothing really to see here for the player class, just a standard implementation of an Entity.

```

1 #pragma once
2 #include "entity.h"
3
4 class Player : public Entity {
5     private:
6         float _speed;
7
8     public:
9         void update(double dt) override;
10        Player();
11        void render(sf::RenderWindow &window) const override;
12 };

```

Listing 4.4: player.h

player.cpp For the .cpp, for now we will keep this basic and come back to it. Implement code that will move the player around on screen in the update.

```

1 #include "player.h"
2 using namespace sf;
3 using namespace std;
4
5 void Player::update(double dt) {
6     //Move in for directions based on keys
7     ...
8
9     Entity::update(dt);
10 }
11
12 Player::Player()
13     : _speed(200.0f), Entity(make_unique<CircleShape>(25.f)) {
14     _shape->setFillColor(Color::Magenta);
15     _shape->setOrigin(Vector2f(25.f, 25.f));
16 }
17
18 void Player::render(sf::RenderWindow &window) const {
19     window.draw(*_shape);
20 }

```

Listing 4.5: player.h

At this point you should have a magenta circle moving around a screen. Do not continue on if you haven't got everything working so far.

4.3 Writing Libraries

For our next piece of work, we are going to write code that we are going to want to use again in future games. Standard practise would be to use good software engineering to isolate all the logic required for our Level loader code to it's own files and minimize coupling between itself and game code. Another approach is to build a "helper class" which is completely separate from the code of the game, but included in the build as headers and .cpp's. We could then easily move this code to a new project by just bringing along the needed files. This is fairly common practise and most game programmers have a collection of small "helper" classes that they copy over from project to project.

The next step from this approach is to bundle up the code as a library. We are already using several libraries in our project - all the SFML components. Libraries are code that is compiled separately to your program and linked in during the link stage. The primary benefit of this is that we don't have to compile libraries again once they are compiled (imagine if we had to build SFML every time we needed to build our game code).

In certain situations you can download libraries pre-compiled from the internet. This isn't great for C++ as the compile settings need to be near identical for your application as for the downloaded library. Furthermore - we can't step down into source code when debugging. Providing a library with a well maintained CmakeLists.txt is by far the best way to distribute your code when building libraries for other programmers to use.

Static vs dynamic linking – .lib's and .dll's When we build a library - it will generate a .lib file. Depending on your build settings (Dynamic/Shared linking) it may also produce a .dll. The situation is more complicated but the simple explanation is that with dynamic linking" the code for our library lives inside the .dll (.so on linux/mac). When our application starts, it loads the code from the .dll into memory. This means that the .dll has to be somewhere the running program can access. We still need to link with a .lib file, this .lib will be an small file which only describes the .dll.

With static linking, the .lib is compiled into our executable. Meaning we don't need to bring any Dlls along. In this case the compiled .lib file contains all the code and will be significantly larger.

4.3.1 Setting this up

Finding and setting all the right settings in an IDE to set up building and linking libraries is a nightmare. With CMake it's laughably easier (and cross-platform!).

```

1 ## Tile loader lib
2 file(GLOB_RECURSE SOURCE_FILES
3     lib_tile_level_loader/*.cpp lib_tile_level_loader/*.h)
4 add_library(lib_tile_level_loader STATIC ${SOURCE_FILES})
5 target_include_directories(lib_tile_level_loader INTERFACE
6     "${CMAKE_SOURCE_DIR}/lib_tile_level_loader/" )
7 target_link_libraries(lib_tile_level_loader sfml-graphics)

```

Listing 4.6: Addition to CMakeLists.txt

The biggest difference here is the call to "add_library" rather than "add_executable"

From the CMake we can see that we need to put some code in a "lib_tile_level_loader" folder. Library code is exactly the same as wiring any other c++ file, but we don't need a Main() function.

4.4 Level System Code

Let's get started with our header.

```

1 #pragma once
2
3 #include <SFML/Graphics.hpp>
4 #include <memory>
5 #include <string>
6 #include <vector>
7
8 #define ls LevelSystem
9
10 class LevelSystem {
11 public:
12     enum TILE { EMPTY, START, END, WALL, ENEMY, WAYPOINT };
13
14     static void loadLevelFile(const std::string&, float tileSize=100.f);
15     static void render(sf::RenderWindow &window);
16     static sf::Color getColor(TILE t);
17     static void setColor(TILE t, sf::Color c);
18     //Get Tile at grid coordinate
19     static TILE getTile(sf::Vector2ul);
20     //Get Screenspace coordinate of tile
21     static sf::Vector2f getTilePosition(sf::Vector2ul);
22     //get the tile at screenspace pos
23     static TILE getTileAt(sf::Vector2f);
24
25 protected:
26     static std::unique_ptr<TILE[]> _tiles;
27     static size_t _width;
28     static size_t _height;
29     static float _tileSize;
30     static std::map<TILE, sf::Color> _colours;
31     static std::vector<std::unique_ptr<sf::RectangleShape>> _sprites;
32
33     static void buildSprites();
34
35 private:
36     LevelSystem() = delete;
37     ~LevelSystem() = delete;
38 };

```

Listing 4.7: levelsystem.h

That's quite a lot to begin with. pay attention to the public functions first. This is where we declare what our Library can do. The protected variables are internal state that we need for some calculation later on. The whole LevelSystem is a static class, everything is static so

we can access everything within it from anywhere (Downside: we can't inherit from it). I've thrown in a handy `#define` macro so we can access everything like `ls::render()`. `Vector2ul` will give you an error, this is something that doesn't exist yet, more on this later.

With our `Levelsystem` declared, let's get to defining it in `LevelSystem.cpp`

```

1 #include "LevelSystem.h"
2 #include <fstream>
3
4 using namespace std;
5 using namespace sf;
6
7 std::unique_ptr<LevelSystem::TILE[]> LevelSystem::_tiles;
8 size_t LevelSystem::_width;
9 size_t LevelSystem::_height;
10
11 float LevelSystem::_tileSize(100.f);
12 vector<std::unique_ptr<sf::RectangleShape>> LevelSystem::_sprites;
13
14 std::map<LevelSystem::TILE, sf::Color> LevelSystem::_colours{
15     {WALL, Color::White}, {END, Color::Red}};
16
17 sf::Color LevelSystem::getColor(LevelSystem::TILE t) {
18     auto it = _colours.find(t);
19     if (it == _colours.end()) {
20         _colours[t] = Color::Transparent;
21     }
22     return _colours[t];
23 }
24
25 void LevelSystem::setColor(LevelSystem::TILE t, sf::Color c) {
26     ...
27 }

```

Listing 4.8: levelsystem.cpp

We start off by defining all the static member variables declared in the header file. This brings in a C++ data structure that we’ve not dealt with before, the map. It’s statically initialised with two colours, more can be added by the game later. This map is read by the “getColor” function which will return a transparent colour if an allocation is not within the map.

You should complete the setColor function. It’s super simple, but you may have to look up the c++ docs on the std::map.

Next up, reading in and parsing the text file.

```

1 void LevelSystem::loadLevelFile(const std::string &path,
2                                 float tileSize) {
3     _tileSize = tileSize;
4     size_t w = 0, h = 0;
5     string buffer;
6
7     // Load in file to buffer
8     ifstream f(path);
9     if (f.good()) {
10         f.seekg(0, std::ios::end);
11         buffer.resize(f.tellg());
12         f.seekg(0);
13         f.read(&buffer[0], buffer.size());
14         f.close();
15     } else {
16         throw string("Couldn't open level file: ") + path;
17     }
18
19     std::vector<TILE> temp_tiles;
20     for (int i = 0; i < buffer.size(); ++i) {
21         const char c = buffer[i];
22         switch (c) {
23             case 'w':
24                 temp_tiles.push_back(WALL);
25                 break;
26             case 's':
27                 temp_tiles.push_back(START);
28                 break;
29             case 'e':
30                 temp_tiles.push_back(END);
31                 break;
32             case ' ':
33                 temp_tiles.push_back(EMPTY);
34                 break;
35             case '+':
36                 temp_tiles.push_back(WAYPOINT);
37                 break;
38             case 'n':
39                 temp_tiles.push_back(ENEMY);
40                 break;
41             case '\n': //end of line
42                 if (w == 0) { //if we haven't written width yet
43                     w = i; //set width
44                 }
45                 h++; //increment height
46                 break;
47             default:
48                 cout << c << endl; //Don't know what this tile type is
49         }
50     }
51     if (temp_tiles.size() != (w * h)) {
52         //something went wrong
53         throw string("Can't parse level file") + path;

```

```

54 }
55 //Now we know how big the level is, make an array.
56 _tiles = std::make_unique<TILE[]>(w * h);
57 _width = w; //set static class vars
58 _height = h;
59 std::copy(temp_tiles.begin(), temp_tiles.end(), &_tiles[0]);
60 cout << "Level " << path << " Loaded. " << w << "x" << h
61      << std::endl;
62 buildSprites();
63 }

```

Listing 4.9: levelsystem.cpp

If we had many more tile types we would switch out that switch statement for a loop of some kind, but for the limited tile types we need it will do.

The file handling code at the top is nothing special, we read the whole file into a string then close the open file. This may be a bad move if the level file was larger, but this where we can get away with saying "C++ is fast, it doesn't matter".

Once the level string has been parsed into a vector of tile types, an array is created with the final dimensions. Keeping within a vector could be valid, but we don't ever want to change the size of it, so an array seems a better fit.

Notice that while the level file is 2D, we store it in a 1D storage type. If we know the width of the level we can extrapolate a 2d position from the 1d array easily. We do this as C++ doesn't have a native 2D array type. We could create an array of arrays which would do the job, but makes the functions we need to write later slightly more difficult.

Our level loader library will do more than just parse in a text file, it will also render the level with SFML. To do this we will build a list of sf::shapes for each tile in our array. The colour of this shape will depend on the colour association stored in our map. We only need to build this list of shapes once, so this function is called at the end of loadLevelFile().

```

1
2 void LevelSystem::buildSprites() {
3     _sprites.clear();
4     for (size_t y = 0; y < LevelSystem::getHeight(); ++y) {
5         for (size_t x = 0; x < LevelSystem::getWidth(); ++x) {
6             auto s = make_unique<sf::RectangleShape>();
7             s->setPosition(getTilePosition({x, y}));
8             s->setSize(Vector2f(_tileSize, _tileSize));
9             s->setFillColor(getColor(getTile({x, y})));
10            _sprites.push_back(move(s));
11        }
12    }
13 }

```

Listing 4.10: levelsystem.cpp

Notive we need yet another function, the getTilePosition().

```

1 sf::Vector2f LevelSystem::getTilePosition(sf::Vector2u1 p) {
2     return (Vector2f(p.x, p.y) * _tileSize);
3 }

```

Listing 4.11: levelsystem.cpp

As we are just doing maths here we don't need to read into the tile array. We could add some validity checks to make sure the requested tile falls within our bounds, but I like my one-liner too much to bother with that.

There will be times when we need to retrieve the actual tile at a position, both screen-space and grid-space. This is where we must convert 2D coordinates to a single index in our tile array.

```

1 LevelSystem::TILE LevelSystem::getTile(sf::Vector2u1 p) {
2     if (p.x > _width || p.y > _height) {
3         throw string("Tile out of range: ") + to_string(p.x) + "," +
4             to_string(p.y) + ")";
5     }
6     return _tiles[(p.y * _width) + p.x];
7 }

```

Listing 4.12: levelsystem.cpp

Most of this function is taken up by a range check (Where we throw an exception, new thing!). The real calculation is in that last line. The secret is to multiply the Y coordinate by the length and add the X. Don't continue on unless you understand why and how this works, it gets more difficult from here on out.

Doing the same, but with a screen-space coordinate is not any different. However as we are dealing with floats now, we must check it's a positive number first, then we can convert to grid-space, and call our above function. Again, don't continue on unless you understand why and how this works.

```

1 LevelSystem::TILE LevelSystem::getTileAt(Vector2f v) {
2     auto a = v - _offset;
3     if (a.x < 0 || a.y < 0) {
4         throw string("Tile out of range ");
5     }
6     return getTile(Vector2u1((v - _offset) / (_tileSize)));
7 }

```

Listing 4.13: levelsystem.cpp

And finally - here lies our Render Function. Nice and Simple.

```

1 void LevelSystem::render(RenderWindow &window) {
2     for (size_t i = 0; i < _width * _height; ++i) {
3         window.draw(*_sprites[i]);
4     }
5 }

```

Listing 4.14: levelsystem.cpp

4.4.1 Linking our Library

While the library build by itself, that's rather useless to us. We need to link it into our lab code. Back to CMake:

```
1 target_link_libraries(... lib_tile_level_loader sfml-graphics)
```

Listing 4.15: CMakeLists.txt

You probably could have guessed this addition. Just add the library target name to your `link_libraries`.

Using the library Give it a test, Call some library functions from your lab code.

```
1 #include "LevelSystem.h"
2
3 ...
4
5 void load() {
6     ...
7     ls::loadLevelFile("res/maze_2.txt");
8
9     // Print the level to the console
10    for (size_t y = 0; y < ls::getHeight(); ++y) {
11        for (size_t x = 0; x < ls::getWidth(); ++x) {
12            cout << ls::getTile({x, y});
13        }
14        cout << endl;
15    }
16 }
17 ...
18 void render(RenderWindow &window) {
19     ls::render(window);
20     ...
21 }
```

Listing 4.16: main.cpp

4.5 Maths Library

Remember that Vector2ul type that doesn't exist? The vector maths functionality of SFML is quite lacking when compared to larger libraries like GLM. We could bring in GLM and write converter functions to allow it to interface with SFML. This would be a good idea if we needed to advanced thing like quaternions, but we don't. Instead we will build a small add-on helper library to add in the functions that SFML misses out.

CMake Firstly, like we did with our first library, add this to CMake.

```
1 ## Maths lib
2 add_library(lib_maths INTERFACE)
3 target_sources(lib_maths INTERFACE
4     "${CMAKE_SOURCE_DIR}/lib_maths/maths.h")
5 target_include_directories(lib_maths INTERFACE
6     "${CMAKE_SOURCE_DIR}/lib_maths" SYSTEM INTERFACE ${SFML_INCS})
```

Listing 4.17: Addition to CMakeLists.txt

This is slightly different to the level system library. This time we declare the library as INTERFACE. This changes some complex library and linker options that are beyond the scope of explanation here. The simplest explanation is an INTERFACE library target does not directly create build output, though it may have properties set on it and it may be installed, exported and imported. Meaning that in visual studio the library will look like it is part of our main lab code (except it isn't. Magic.)

There are many different way to create and link libraries, CMake allows us to change these options from a central point and not worry about digging through IDE options.

We need to link the maths library, against the level system library. edit the level systems cmake code to include lib_maths

```
1 target_link_libraries(lib_tile_level_loader lib_maths sfml-graphics)
```

Listing 4.18: Addition to CMakeLists.txt

As this is a static library - and doesn't produce a compiled output, everything will be in a header. To extend the functionality of sf::vectors we must first be within the same namespace. From here we can define code as if we were inside the sfml library code itself. Thing get a little strange if we want to change or override functions that already exist, but we don't here as we are only creating new functionality.

We start by creating a new vector type the 'Vector2ul' which will use size_t (i.e the largest unsigned integer type supported on the system) as the internal components. We will use this for the tile array coordinates.

From this we implement the standard vector maths functions that any self respecting game engine would have. Length, Normalization, and Rotation. I've left these incomplete so you will have to dredge up your vector maths skills to complete them.

Lastly, we override the `jj` stream operator to us do things like `"cout << vector"`. Useful for debugging.

```

1 #pragma once
2
3 #include <SFML/System.hpp>
4 #include <cmath>
5 #include <iostream>
6 #include <vector>
7
8 namespace sf {
9     //Create a definition for a sf::vector using size_t types
10    typedef Vector2<size_t> Vector2u1;
11    // Returns the length of a sf::vector
12    template <typename T> double length(const Vector2<T> &v) {
13        return sqrt(...);
14    }
15    // return normalized sf::vector
16    template <typename T> Vector2<T> normalize(const Vector2<T> &v) {
17        Vector2<T> vector;
18        double l = length(v);
19        if (l != 0) {
20            vector.x = ...
21            vector.y = ...
22        }
23        return vector;
24    }
25    //Allow casting from one sf::vector internal type to another
26    template <typename T, typename U>
27    Vector2<T> Vcast(const Vector2<U> &v) {
28        return Vector2<T>(static_cast<T>(v.x), static_cast<T>(v.y));
29    };
30    // Degrees to radians conversion
31    static double deg2rad(double degrees) {
32        return ...
33    }
34    //Rotate a sf::vector by an angle(degrees)
35    template <typename T>
36    Vector2<T> rotate(const Vector2<T> &v, const double degrees) {
37        const double theta = deg2rad(degrees);
38        const double cs = cos(theta);
39        const double sn = sin(theta);
40        return {(T)(v.x * cs - v.y * sn), (T)(v.x * sn + v.y * cs)};
41    }
42    //Allow sf::vectors to be cout'ed
43    template <typename T>
44    std::ostream &operator<<(std::ostream &os, const Vector2<T> &v) {
45        os << '(' << v.x << ', ' << v.y << ')';
46        return os;
47    }
48 }

```

Listing 4.19: maths.h

That should be all we need to successfully build both our libraries and our game. Give it a go. Build. Run. See if your hard work typing all this has paid off.

4.6 Making the Game a Game

Player Class Disallow the player from moving into a tile:

Hint:

```
1 bool validmove(Vector2f pos) {  
2     return (ls::getTileAt(pos) != ls::WALL);  
3 }
```

Listing 4.20: main.cpp

Start the Player from the "Start Tile"

End the game When the player hit's the end tile

Time how long it takes to complete the maze

Show current, previous and best times

Lesson 5

Pacman

Lesson 6

Physics

Lesson 7

AI: Steering and Pathfinding

Lesson 8

AI: Behaviours

Lesson 9

Deployment and Testing

Lesson 10

Performance Optimisation

Lesson 11

Scripting

Lesson 12

Networking

Appendix A

Appendix

A.1 Additional CMake scripts

Custom target dependency - for mac mac, sfml , and cmake do weird things to do with frameworks and R-paths.

```
1 ##### Target for copying resources to build dir####
2 if(APPLE)
3     add_custom_target(copy_resources ALL
4         COMMAND ${CMAKE_COMMAND} -E copy_directory
5             "${PROJECT_SOURCE_DIR}/res"
6             ${CMAKE_RUNTIME_OUTPUT_DIRECTORY}/res
7
8         COMMAND ${CMAKE_COMMAND} -E copy_directory
9             "${CMAKE_SOURCE_DIR}/lib/sfml/extlibs/libs-osx/Frameworks"
10            ${CMAKE_BINARY_DIR}/lib/sfml/Frameworks
11     )
12 else()
13     add_custom_target(copy_resources ALL COMMAND ${CMAKE_COMMAND} -E
14     copy_directory
15         "${PROJECT_SOURCE_DIR}/res"
16         ${CMAKE_RUNTIME_OUTPUT_DIRECTORY}/${<CONFIGURATION>/res
17     )
18 endif()
```

Listing A.1: custom target dependency (including mac)

A.2 C++ Header file tips

Don't forget Headers aren't magic or smart. The preprocessor just replaces every instance of "`#include file.h`" with everything that it's in `file.h`. Headers are nothing more than a copy and paste macro. If you are struggling to figure something out, consider what would be the effects of writing whatever is giving you an error in the `.h`, directly in all the `.cpp` files where you include the `.h`.

- Only Include what you need.
- Only declare items that other files will need.
- Never use "`using namespace`" in a header.
- Avoid defining functions in a header.
- Don't forget include guards "`#pragma once`"
- Don't forget to define declared static members
- Templates must be defined in a header.

A.2.1 Forward declaring - to avoid circular dependencies

In the case where class A in A.h needs to use and include class B in B.h, but class B also needs to use class A, we get a "circular dependency". We can't include both Headers within each other. We can avoid this by doing a forward declaration.

```

1  //----- A.h -----
2  class B; // forward declaration
3
4  class A
5  {
6  public:
7      B* myB;
8  };
9
10 //----- B.h -----
11 class A; // forward declaration
12
13 class B
14 {
15 public:
16 A* myA;
17 };

```

Listing A.2: Forward declare

Note we don't include the Headers of each other within each other. This is similar to the "extern keyword". This works only because we don't need to know anything about the class we are forward declaring, and we are storing it as a pointer. This is because we don't know how big a class B is, but we know how big a class B pointer is, it's just the standard 32/64 bits.

```

1  class B; // forward declaration
2
3  class A
4  {
5  public:
6  B* myBpointer; //works
7  B myB; //will not work.
8  };

```

Listing A.3: Forward declare