

**Department of Computer Science**

**Department of Multimedia**

Multimedia - Game Programming

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S19340

**Turn-based multiplayer strategy game**

Engineering thesis

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## Introduction

Inform about topic -> What is this thesis/diploma about ...

(Don't write it at the beginning (final version)

Explain …

List of goals:

(THIS part is written BEFORE You will start...) -> It defines how You wish to proceed...

(Do not give any answers to your problems)....

#KEYWORDS!!!!

List of technologies

## Project description

### Definitions

Game - …

Turn based game - …

Strategy game - ..

Multiplayer - …

Matchmaking - …

Player ranking - ...

### Game description

Chart, scatter chart

Description automatically generatedThe game is played between 2 players on a rectangular grid, usually 25 by 25 cells, but other sizes are also supported. Each turn a player places his unit (also called “dot”) on a vacant grid cell. All units are the identical and only differentiated by the color, signifying to which player they belong. If, after placement, by connecting player’s adjacent dots (either orthogonally or diagonally) a cycle can be formed that also surrounds one or more opponent’s dots, the player captures the opponent’s units.

Figure 1. Red units captured a blue unit.

Each captured dot grants the player 1 point, as well as effectively “disables” the enemy uint - it can no longer participate in forming cycles needed for capture. The goal of the game is to get more points then your opponent. The game is played until either one of the players resigns or there are no legal moves left.

### Multiplayer aspects

The game should also provide rich multiplayer aspects by having an automatic matchmaking system, where you can queue up to have a game with the next available player.

There also will be a ranking system to give each player a score that would describe their skill level. Ranking would be calculated based on the results of game’s played and updated according to the ELO system[1], similar to the ones used in online chess games. The rankings would also be used to match opponents with the closest skill levels during matchmaking.

### Game visuals

The two players are identified by their color: player 1 - red, player 2 - blue. The dots are rendered on cell grid intersections and match the color of the player who placed them.

Captured areas are denoted by connecting the dots that participated in the enclosure with a line and adding a semi-transparent fill over the enclosed area with a matching color.

Q: Should I include the game screenshots here?

## Project architecture

### Overview

The project can be split among two parts: the game client that uses Unity and is written in C#, and a backend server that maintains the game state. Between them there are several shared classes such as data models describing the game state and the moves made by players. The high level overview of the project structure is presented on Figure 2.

The backend server hosts a WebSocket API that game clients connect to. Choosing WebSockets as a transport layer provides us with an ability for two-way communication: game server can push updates to the clients and clients can send moves made by players. Also this increases the flexibility for the backend deployment as almost all hosting providers support WebSockets.

The backend server has a PostgreSQL database associated with it. It was chosen because relational databases are well supported by mainstream C# data-persistence frameworks, such as Entity Framework.

There’s also an additional test module hosting automated unit-tests for the core data models and algorithms.

Diagram

Description automatically generated

Figure 2. Project overview. TODO: Add the test module.

### C# build pipeline

One of the difficulties when sharing code with a Unity project is that Unity does not support multi-assembly builds. Meaning that all C# sources must be a part of a single C# project when compiling the game client. Also, C# project and solution files are auto generated, which means making any manual changes are unfeasible, as they would be lost next time Unity Editor is refreshed.

This poses a challenge, because a usual way to share code between the backend server and a client would be to introduce a third class-library project with shared classes, that two other projects depend upon. Since that’s not possible the only solution is two have two parallel project structures: one for the backend and the second one for the Unity build. The shared sources would be included in both structures and compiled separately.

Unity requires all C# sources to be placed inside “Assets” directory. This also includes the shared classes. This would force us to move away from then canonical project structure where each module resides in a separate directory on the top level. There were numerous attempts to go back to the flat structure utilizing filesystem symlinks. Unfortunately, Unity as well as C# build tools do not have good enough support for them, and often they were not recognized as a link to another directory.

Ultimately the following project structure was settled on:

* Backend project directory.
  + Backend “csproj” file.
  + Backend sources.
* Test project directory.
  + Test “csproj” file.
  + Test sources.
* Unity project directory.
  + Assets directory.
    - Unity assests.
    - Core project directory (shared sources).
      * Core “csproj” file.
  + Unity autogenerated “csproj” file.
  + Unity autogenerated solution file.
* Solution file for the backend and core projects.

### Dependency management

It wouldn’t make sense for every project to re-implement from scratch common standardized components such as serialization, networking and others. So, to speed-up and ease development we often rely on existing solutions and already developed libraries and frameworks. Initially, and often in older programming languages like C and C++, developers would copy the library into the source tree of the project.

This approach poses many problems, among which is difficulty of installation, as it must be performed manually. And the difficulty of configuration as there’s no enforced standard for how the reusable library code should be structured. Upgradability is also an issue: when a new version of the dependency gets released, developers would need to perform the same steps of copying the library code into their project’s codebase and configuring the compilation pipeline. The process gets even more difficult when transitive dependencies come into play. Transitive dependencies are dependencies if the library or package your project depends on directly.

To solve those issues package managers were created. Package manager is a tool responsible for installing and upgrading project dependencies and their transitive dependencies. Code is typically structured into packages that are identified by their unique name. Packages are versioned and the project’s manifest specifies what version of the package it requests to be installed. The most common versioning schema is “SemVer” (semantic versioning) [add reference].

SemVer versions consist of three integer parts: major, minor, and patch number. For example, 1.0.12 – would be a valid SemVer version. Each part has its own meaning to represent the type of changes that were introduced. The major number is incremented when breaking changes were introduced – changes that, after upgrade, would break existing code that depended on the previous version of that package. The minor version is incremented when new features were introduced, but in a backwards-compatible way, where it wouldn’t break the existing code after an upgrade. The patch number is reserved for bugfixes.

This type of versioning scheme allows developers to specify not concrete versions of their dependencies, but whole ranges of versions they are compatible with. Most commonly, developers allow minor and patch numbers to change up to the next major release. 2.4.12 <= x < 3.0.0 would be an example of such a range.

Such standards allow packages to be distributed easily and often package managers come with their own package repositories, where developers can publish their packages and others can download and install dependencies with a package manager. The installation usually is as easy as issuing a command to the package manager, to install a dependency, by specifying its name and the requested version. In such a setup, only the manifest file is committed to the VCS, and package files are excluded from source control, as every developer can easily recover them from the manifest using a package manager.

The de-facto package manager for C# (and the whole .NET ecosystem) is NuGet [add reference]. It comes with its own package repository hosted on <https://www.nuget.org/>. As of the time of writing, the repository contains over 280 thousand packages. Packages are versioned using SemVer.

This project uses NuGet to manage dependencies for the backend server. Among which is the JSON [add reference] serialization library and web-socket networking library. For Unity, a different package manager is used: Unity Package Manager (UPM for short).

UPM has a package distribution method. NuGet distributes packages in their compiled form: as a DLL (Dynamically Linked Library) [add reference]. This has the advantage of the source code already being compiled, which avoids any compilation errors in packages and reduces the size of installed dependencies. There’s however a disadvantage: assets including textures, models and prefabs cannot be distributed in such a way. UPM installs packages with their C# source code and assets. The package code is typically included in VCS.

The UPM ecosystem is quite young and there are often packages missing. While there’s no official support for NuGet in unity, there’s an open-source unofficial plugin to replicate NuGet package manager behaviour for Unity projects: https://github.com/GlitchEnzo/NuGetForUnity.

### Unit testing

The game state and associated algorithms outlined in the section 4 of the work can get quite complex and have many edge cases. Testing them manually is a very time-consuming and error-prone process. For those reasons an automated test suite is used to verify the correctness of the algorithms. A unit test suite is contained in the “CoreTest” submodule. It consists of a series of functions each executing a piece of game logic following a specific scenario and asserting that the output matches the expectation. The tests might contain general scenarios such as modifying game state by making moves or test concrete functions such as querying game state for cycles in the graph of units.

Since unit tests are set-up as individual methods, a test-runner is needed to orchestrate the test execution. It should execute each test methods, gathering the results or handling any thrown exception and then report the test execution result. NUnit is used for that purpose. It is widely adopted in the .NET ecosystem. Has IDE integrations and supports running subsets of tests or running individual tests with debugger enabled.

[TODO: Add illutaration of tests results in Rider]

Every unit test usually consists of three sections:

* Assemble – setting up the initial state of the tested module. For testing state transitions it might be the state before making a mutation.
* Act – run the code which is being tested. For example: make a move on the game board.
* Assert – assert that the result of the executions matches your expectations.

Graphical user interface, text, application, email

Description automatically generated

Figure 3. Example of a unit test.

In the unit test displayed on the Figure 3 the three stages are apparent. The “assemble” stage sets up the game state from a predefined scenario. In this case it’s a state just before a capture. Next step is to make a move by calling the API. The move is for the Red Player to place the final unit completing the cycle. This will mutate the board state in reaction to the move. In the final stage we assert that the game state after the move has recorded that capture.

To achieve good impact from unit-tests it’s important to have them cover edge cases and different branches in code. This might involve describing many different test cases, which increases the amount of code used for testing. Maintaining a large amount of test code can cause problems, so it’s important to optimize the test code size as much as possible.

In the example above a utility function is introduced – “ParseBoardState”. It is used to create an initial game state with a minimal amount of code. The way it is achieved is by parsing board state for a string. This also has a benefit of providing good visualization of the board state. The string format consists of a rectangular grid of characters separated by spaces. Each character corresponds to a cell on the grid. Grid size is determined automatically from the input string: by measuring the number of lines, and the number of characters in the first line. Only “.”, “R”, and “B” characters are allowed, specifying empty cell, cell occupied by the red player, and a cell occupied by the blue player respectively.

“TestUtils” class is used to host aforementioned and other utility functions. A different function can be used to generate a sequence of grid coordinates which is used for testing algorithms related to cycle search. In that case the similar string format is used, but instead grid cells have numbers which represent indexes of grid cells in the resulting array.

### Diagram Description automatically generatedDatabase schema

Figure 4. Database schema.

### Class diagram

### Deployment

TODO: digital ocean or heroku

## Game state

### Game state data structure

The game state consists of a 2-dimensional array describing each grid cell position as well as a list of captures that were performed during the game.

Each cell state consists of:

* Vacancy flag - whether this cell was claimed by the player.
* Their player that claimed this cell - only in case this cell is claimed.
* Captured flag - whether the dot placed in this cell is captured by the opponent.

A picture containing graphical user interface

Description automatically generatedEach capture entry in the list includes a player that made the capture as well as the list of grid coordinates of dots that participated in the enclosure of enemy units.

Figure 5. Board state

### Updating the game state with new move

With every move we perform a cycle search to find new enclosed areas. Dots placed on the square grid form an effective graph with their neighbors. A depth-first search algorithm is used to find cycles in this graph. Cycles are also validated to not be composed from multiple larger cycles.

After the cycle is found a variant of flood-fill algorithm is used to select all grid coordinates that are enclosed by this cycle. Then, if any of those contain enemy units, those units are marked captured, and the cycle is added to “captures” list.

### Representing cycles

One of the core data-structures used by the algorithm is a cycle. Cycle is closed sequence of distinct points on a grid. Each point must be adjacent to the previous and next points in the cycle either horizontally or diagonally. In-memory cycles are represented as arrays of grid coordinates (row and column).

There are many ways that a single set of points can be ordered in an array: different points can be chosen as the begging of the cycle, and the enumeration direction can be either clockwise or counter-clockwise. This makes it difficult to perform equality comparisons, as the algorithm would need to account for those variations. In the same way, it makes it difficult to build a stable hash function, which would be useful for performing efficient lookups in “Set” or “Map” data structures.

For those reasons cycles are always stored normalized. Normalized cycles must have their points ordered clockwise. And the starting point must be the one with the smallest row coordinate. If there are multiple points on the lowest row, the one with the smallest column coordinate is taken. As a reminder, rows and columns are counted from the bottom-left corner of the game board, starting from (0; 0). Figure 6 displays a normalized cycle. Numbers in points depict the index of said point in the internal array representing the cycle.

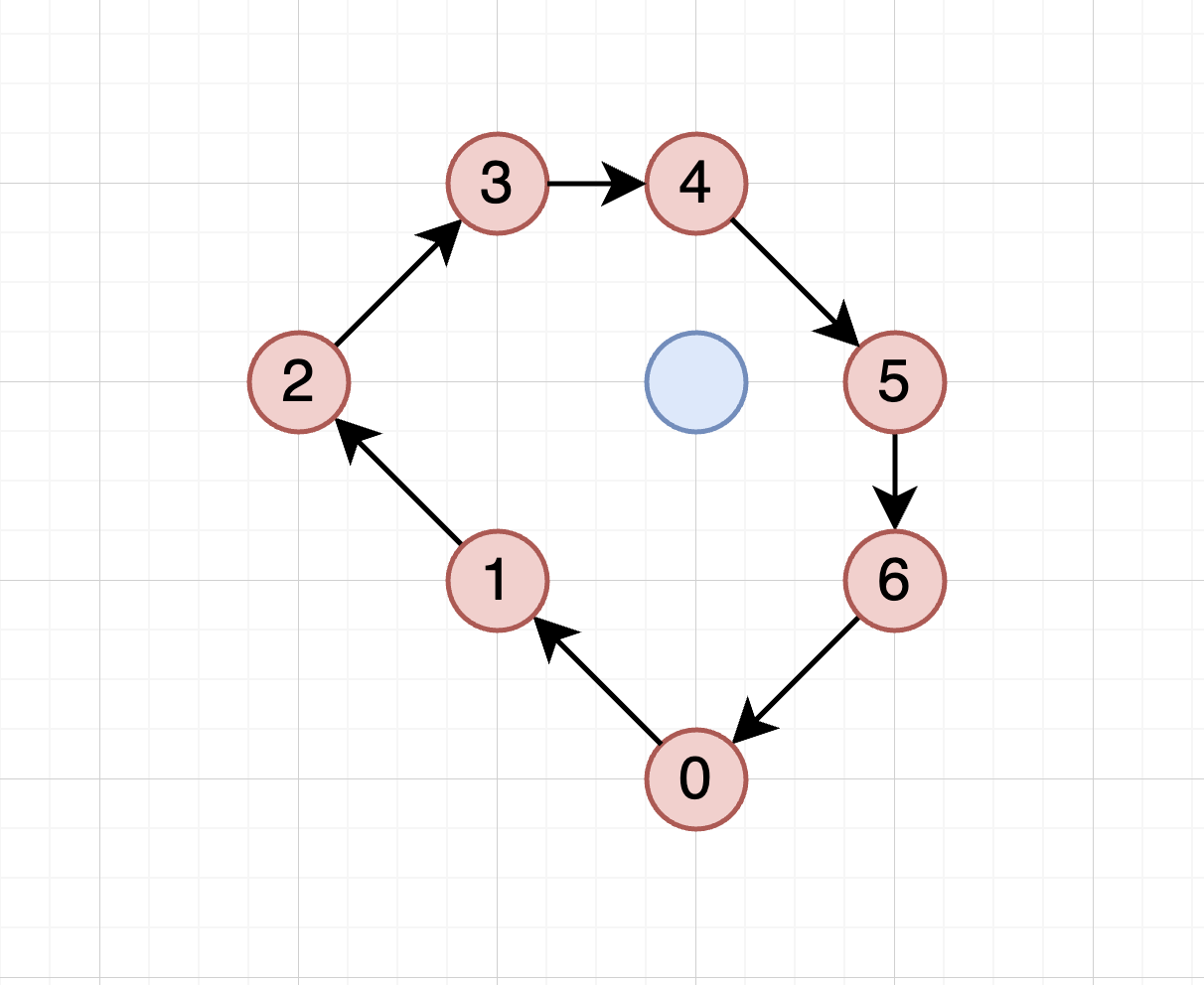


Figure 6. A cycle of 7 red points around a single blue one.

Normalization is performed using “Normalize” method in the “Cycle” class. It will mutate the instance it is called upon to have it be normalized. Normalization is done in two steps:

* Determining the current enumeration direction (clockwise or counter-clockwise) and reversing the array if the direction is counter-clockwise.
* Searching for the minimal point in the array (using aforementioned comparison rules) and rotating array elements so that the minimal point is at the index 0.

For the first stage, while reversing an array is easy using the standard library function, determining an enumeration direction can prove tricky. An operation similar to vector cross-product is used. Algorithm is as follows:

1. For each point in cycle, consider a vector pointing from the previous point in the cycle to the current one, and a vector pointing the current point to the next one in the cycle.
2. Normalize the two vectors so their lengths are equal to 1. This is required because diagonal connections will have a length of , while horizontal ones will have a length of 1. For the next steps it is important that all vectors are of equal length.
3. Extending the vector space to the third dimension, take a cross product of two vectors: . This vector is guaranteed to be parallel to the third-dimension basis.
4. The z coordinate (third dimension) of that vector will be positive if the curvature in that point of the cycle is clockwise, negative if it is counter-clockwise, and 0 if the line connecting cycle points is straight in that spot. Refer to Figure 7 for more details.
5. Summing up z coordinates calculated for each point in the cycle, we get a total metric for the entire cycle. It will be a positive number if ordering in the cycle is done counter-clockwise, and negative otherwise. This algorithm will also be resistant to any local fluctuations in the cycle boundary curvature, such as when the boundary shape is concave.

Chart, bubble chart

Description automatically generated

Figure 7. Examples of different curvatures at a given point in cycle boundary.

After obtaining the metric for the whole cycle it is just the matter of reversing the array if the current ordering is counter-clockwise. Next step in normalization is positioning the minimum point at the index 0. This is achieved by first, finding the current index of the minimum point by linearly searching the whole array. And second, copying all of the points to a newly allocated array of the same size. Copying is performed with an offset equal to the index if the minimum point, with indexes being calculated modulo array size. This could be done more efficiently by performing a series of swaps in-place, which would allow to get rid of extra array allocation, but performance boost gained is not significant in the context of this application.

There’s another, implicit, assumption: all cycles must not be self-intersecting. Meaning the only points allowed to be adjacent are the ones directly following each other in the cycle. The cycles that are self-intersecting can be split into two or more different cycles with some common points. This is not enforced in the “Cycle” class directly, but the following algorithms only operate on non-self-intersecting cycles. And self-intersecting ones are discarded immediately.

### Cycle search algorithm

Depth first search is used to find cycles in the graph. Search is always started from the dot placed on the current move. This optimization can be made because all cycles that were formed without the dot placed on the current move were already discovered when running the algorithm on previous moves.

To implement the algorithm a recursive approach is used with a stack to store a sequence of coordinates being currently processed. First a recursive function is executed on the starting point - the dot placed on the current move. It pushes the coordinates to the stack and then executes itself on all neighbors that can participate in capture. If a valid cycle is found, i.e. we reached the starting point, the sequence of points is stored as one of the cycle candidates. After all of the neighbors have been processed the current position is popped from the stack, and the execution flow is returned to the caller.

If during the execution we reach a neighbor of any point that already in the stack, but not the initial one, we terminate early, because that cycle could have been formed without the initial dot. And hence, was already processed on previous moves.

Text

Description automatically generated

Figure 8. Cycle search algorithm

TODO: Union find algorithm: <https://www.cs.princeton.edu/~rs/AlgsDS07/01UnionFind.pdf>

### Encircled unit search algorithm

When we detect a cycle, we can search all points inside that cycle to find out whether a capture was performed. To make the search a way to enumerated all points contained in the area bounded by the cycle is need. First a single point known to be inside that area is taken, and then a flood-fill algorithm is used to enumerate all points within that area. Each point is then examined to determine if it’s valid for capture.

The first step, calculating the starting point for flood-fill in the area bounded by the cycle, can be achieved using the same reasoning as for cycle normalization. We already defined a function to examine relative direction between neighbouring points. Assuming all cycles are normalized, their points must be enumerated clockwise. This means that, relative to the direction of the boundary, points inside the region would be to the right side, and outside the boundary – to the left. Picking a point on the cycle’s boundary and examining all of its neighbours to satisfy above conditions allows us to calculate the starting point for the flood-fill algorithm.

The flood-fill itself is an algorithm that recursively visits all neighbouring points from a given starting position. [add flood-fill reference] It is implemented using a queue and an array to mark visited points. Queue contains a list of points to be visited. It is bootstrapped with the initial point. The algorithm goes as follows:

1. Pop the point from the front of the queue. If the queue is empty algorithm is finished.
2. Set the visited flag for that point.
3. Perform any operations meant for visited points. In this case the point is checked for any potentially capturable units.
4. Enumerate all neighbours of the point. If they weren’t visited already, and satisfy conditions for flood-fill (not part of cycle boundary), push them to the back of the queue.
5. Go back to step 1 and repeat the algorithm until the queue is empty.

Figure 9 shows the C# code for the algorithm.

### Iterator methods in C#

In C# programming language there’s a feature called iterator methods. [add link to iterator methods docs] This is a special case of a method that instead of returning a single value, can generate a possibly infinite sequence of values. This is done by specifying the return type of that method as “IEnumerable<T>” and using “yield return” keyword. In this case the execution of the method will continue past the return statement, potentially allowing it to return multiple values. In practice this is achieved by returning a generator object, containing a suspendible version of the method code. This object can be repeatedly queried, for example using a “foreach” loop, to produce the next value in the sequence. Each query will run the portion of the method code up to the next “yield return” keyword. Then the execution will be suspended and method scope variables will be serialized.

There are numerous applications for such construct, but in this work it is used to optimize algorithms based on sequence manipulation. Consider this: many steps in the previously described algorithms can be considered either acting on a sequence of values. To find what units have been captured after a move we need to consider points in all new captured regions. To get all new captured regions, we first iterate over all cycles created by the newly placed point. To get all cycles we recursively iterate over neighbours of the starting point. Those seem like logical boundaries by which the algorithm can be decomposed into different functions. The problem here is that many of those functions return sequences or sets of values: getting neighbours of a given point returns a set of points. Enumerating cycles formed around a given point returns a set of cycles. Applying a flood-fill algorithm returns a set of points inside a given cycle. Using dynamically allocated containers such is array or Set here would have a drastic impact on performance, as there would be a big overhead in memory allocation. Also the entire resulting set would need to be pre-computed and stored in memory before returning from the function. This is often not needed, as the resulting elements are consumed one-by-one and access to the whole set at a time is not required.

Graphical user interface, text, application, email

Description automatically generated

Figure 9. Example of an iterator method.

This is where iterator methods are useful. They allow us to use the same principles for code decomposition, without sacrificing on performance. Figure 9 shows an example. This method enumerates all points inside a boundary of a given cycle using a flood-fill algorithm. “GetDirectNeighbours” is also an iterator method. Here it is consumed by a “foreach” loop.

## |Game rendering

### Board rendering

### Captured area rendering

With sprite-shape controller

## Client-server interaction

### Overview

Networking model is built around client-server architecture with JSON RPC protocol over a WebSocket transport. This allows for persistent sessions to be established with two-way asynchronous communication between game-client and server.

Instances communicate establishing a connection with an associated session and issuing Remote Procedure Call (RPC) [add reference] requests. Each request has an associated method and payload, which are forwarded to the handler which processes the request. Both client and server expose a set of supported RPC methods with respective request handlers. Handler can respond with an optional response to the request.

It is important to note that while there are distinct server and client roles, they are only used in the context of establishing the connection: client dials the server and originates a new session. After the session is established, both client and server can issue RPC requests to the other party.

### Web-sockets

Rationale for using web sockets.

API reference: JSON RPC

### JSON-RPC

### Making a move

Describe what path a move makes, from being created on the client, registered on the backend and then game state synchronized to the client.

### Backend server

### Database

### WebSockets API

### Authentication?

### ELO ranking

### Matchmaking

Show Your Struggle... and knowledge You had to get...

Theory - There is a knowledge You will have to accumulate... Explain it on Your OWN... (give good statement from where You got this knowledge... footnote.. ...page 47-85)

(You got all the pieces together here)...

Practice

You invoke knowledge form thery presenting Your SOLUTION...

(Always ask 2 questions... Why... and ... where.....)....

You do think about something.... Is it important for my work... for it's explanation...

Choose something for structure... Start general... then go to details/ or do opposite...

------------------------------------------------------------------------------------

## Conclusion

Answer Introduction...

- You where defining problem.. You where defining possible approaches You wish to follow...

Look at ALL YOUR SOLUTION (Main body)... tell what is the result... Summarize effects...

What Do You think about it....

Future improvements

------------------------------------------------------------------------------------

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