IP40: The Individual Project Module (U10834)

Chess Engine Project

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Abstract

This paper details the analysis, design, and testing of chess engines in general; and how I implemented my particular Chess_Engine_Project. Its purpose is to be used by chess enthusiasts to assist in analysing positions and giving recommendations for the best moves. To implement this, I looked over how different styles of engines work, such as Stockfish and AlphaZero. Although AlphaZero is analysed in this paper, no AI neural networks were implemented in this project. This is a more classical style of engine focusing on implementing pro chess concepts to analyse and evaluate positions.

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Introduction and Idea

Background to Problem

This project is about creating a chess engine that will be able to play a decent game of chess by the end. Chess players would typically use it to analyse positions for insight. It may also train players up to a specific Elo rating and, finally, play against another player for a bit of fun. It will be programmed in C# and will mainly run on a desktop computer, and if there is the time at the end of the project, it will also be available to access on the web.

To tackle this project, I will be using a test-driven development approach. I will be splitting the project into three parts; automated tests, the engine, and the GUI. I will be using Trello to manage the project, and although this will be a solo project, GitHub will be used to track changes to the project.

Justification to Task

I chose to take on this project not only because of my interest in the game itself; but also the personal growth and development I will get out of it as a programmer. It will be one of the most significant projects I have taken on solo. I will have to deep dive into some complex searches and evaluate algorithms that make up the main bulk of this project. The project is not only a task well suited to computers, but these algorithms' fundamental principles could be helpful in many other domains. Additionally, my time management and prioritisation skills will be tested due to the different moving parts of this project.

One of the main reasons I chose this project was the advanced understanding I will develop due to deep-diving into researching these fundamental computing algorithms and concepts. There is also an enormous scope of other domains that benefit from applying these algorithms. Examples of a few sectors which benefit from these algorithms include:

- Finance
- Chemical
- Gaming
- Databases and big data
- Travel

Project Analysis

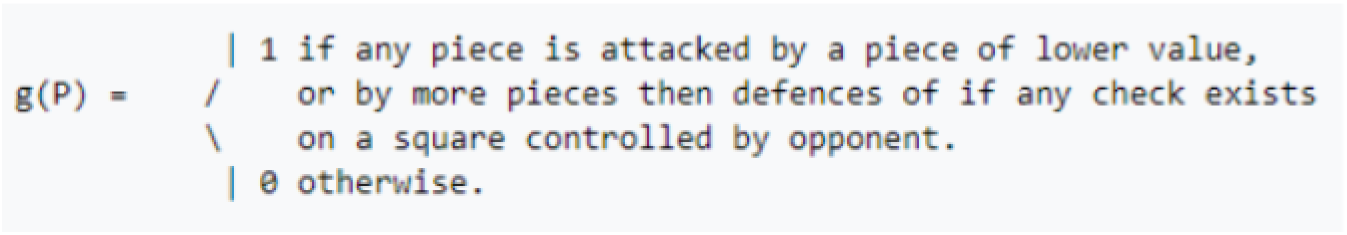
Traditionally most chess engines follow the exact blueprint:

- Finding all legal candidate moves
- Iterating through a tree of potential moves to a given depth
- Assessing the tree to find the best move

An engines quality is usually evaluated based on two criteria:

- Speed - How fast it finds a list of potential 'good' moves
- Accuracy - How fast it finds the best move out of these moves

Dietrich Prinz's (1951) implementation on a Ferranti Mark 1 at the University of Manchester was one of the first commercially available chess engines. The Ferranti Mark 1 lacked power, so it was limited because it could only find the best move when a position was two moves away from checkmate. The next engine the world saw was by a gentleman named Bernstein (1957). It was the first complete chess engine to run on a computer (IBM 704), which could play a game from start to finish, taking roughly 8 minutes to make a move. It was a type B implementation, a selective technique that attempts to cut processing times by examining variations as far as possible. Then only evaluate when a reasonable amount of instability in the position is detected. It then prunes unnecessary, redundant variations to cut processing times further. Finally, it is run through a function to evaluate the position's stability (e.g. en prise). See Figure 1 for a "Crude definition" of this type of algorithm. (Bernstein, 2022; Chessprogramming.org, 2022)



```
            | 1 if any piece is attacked by a piece of lower value,
g(P) =     /    or by more pieces then defences of if any check exists
           \    on a square controlled by opponent.
            | 0 otherwise.
```

Figure 1: A "Crude definition" of an en prise algorithm

Since then, engines have developed significantly with engines such as:

- AlphaZero
- Stockfish
- Leela Chess Zero
- Houdini

Each demonstrates a different approach to the classic problem. Three of these engines were written in C++, while AlphaZero was developed in Python. Leela Chess Zero, much like AlphaZero, relies on AI and the use of a self-taught neural network to evaluate and generate the best moves. The engine plays against itself millions of times to teach itself the best move generation. These engines focus much more on selection/evaluation on the 'winning routes' rather than the more typical brute force search we see in solutions like Stockfish. This project will look into more brute-force type algorithms with additional refining algorithms to 'trim' the search down. (Chess Engine | Top 10 Engines In The World, 2022)

Stockfish - Basics

Stockfish, one of the most potent and well-known engines available to the public, was developed over several decades with the input from several chess grandmasters and many other sources. It used to be a classical brute force implementation that analysed millions of positions per second for optimal moves, defined by countless human input. However, since the famous loss against AlphaZero spoke about below, they implemented AI and machine learning aspects to enhance the engine further and cut processing times. (Champion, 2022)

Stockfish stores the board in a bitboard fashion with an array of 64 bits, with each representing a square on the board (see figure 2). If the bit representing a square has a value of one, there is a piece occupying it. This way, it is easy to represent a moving piece through bitwise operations:

- One square forward: left shift of 8 bits
- One square left: left shift of 1 bit
- Retrieving all pieces currently on board: Logical OR of all the individual bitboards together
- Checking if a square is occupied: Logical AND of the bitboards with the positional mask of the selected square
- E.t.c...

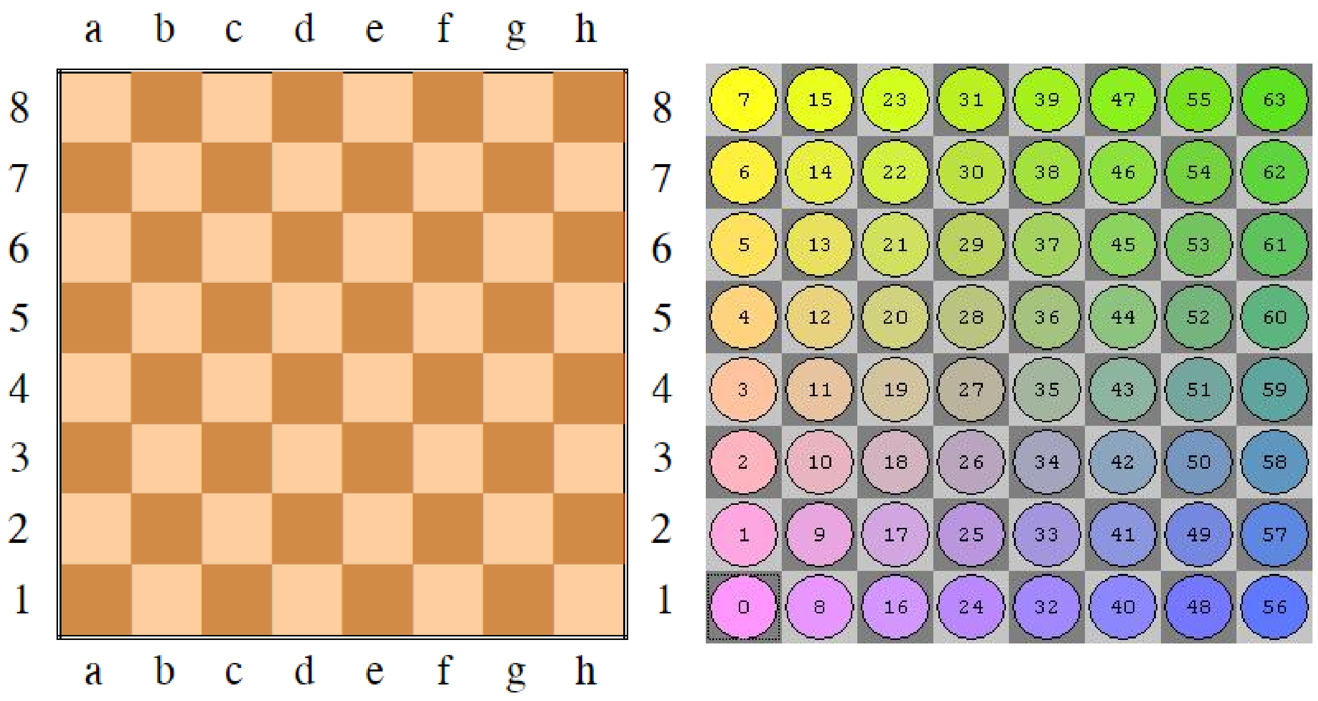
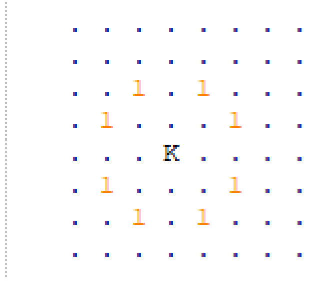


Figure 2: Little-Endian File-Rank Mapping

Stockfish - Move Generation

Next, I will go over how the engine generates its list of candidate moves. Some pieces, for example, the knight, have fixed candidate moves due to their movement, that being in an 'L' shape, with three squares forward and one square left (see Figure 3). (Champion, 2022)



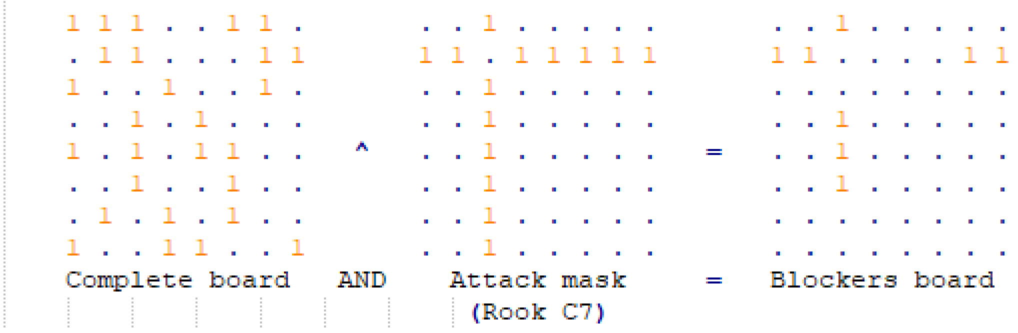
```
. . . . . . . .
. . . . . . . .
. . 1 . 1 . . .
. 1 . . . 1 . .
. . . K . . . .
. 1 . . . 1 . .
. . 1 . 1 . . .
. . . . . . . .
```

Figure 3: Knight piece movement example

Variables containing bitshift operations are stored for knights' movement; they contain all eight operations required to move the knight in any direction. This works for most knight movements except for those where it is near a side of the board. A mask is applied to ensure no moves where the piece lands off the board are generated in these circumstances. A safe destination method is run after generating all pseudo-legal candidate moves to eliminate those that are invalid off-board positions. Pseudo legal move generators look for all empty square moves possible given a board position. It ignores most scenarios listed below. Once the moves have been generated, it runs a 'bool Position::legal(move m)' method alongside 'position.cpp', which tests whether the moves generated are legal. (Champion, 2022) The method checks for scenarios such as:

- Blocking pieces
- Discovered checks
- Pinned pieces
- E.t.c...

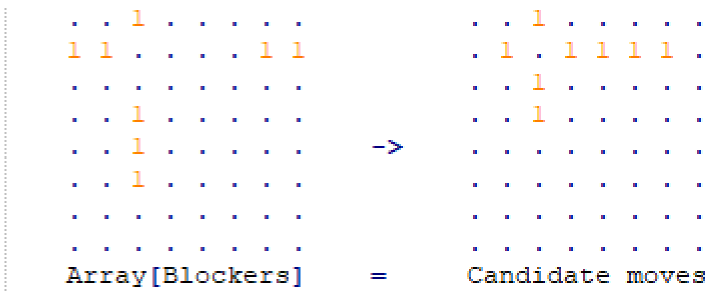
For the other sliding pieces: rooks, bishops, and the queen. Candidate moves are a bit more problematic due to the sliding nature of the pieces' movement; they can move an indefinite amount of squares in their available attacking rays depending on whether a piece is blocking. To accomplish move generation of these pieces, a combination of the chosen pieces attacking rays and the complete board representation needed to be AND'd together to find these blocking pieces (see figure 4). Although this can be done in run-time for each piece and each attacking ray direction they can move, it is computationally expensive to do so. Therefore Stockfish uses a slightly more efficient method by using the look-up method in an array containing all the candidate moves for the sliding piece. However, finding all blockers for the piece is still required. (Champion, 2022)



```
1 1 1 . . 1 1 .        . . 1 . . . . .        . . 1 . . . . .
. 1 1 . . . 1 1        1 1 . 1 1 1 1 1        1 1 . . . . 1 1
1 . . 1 . . 1 .        . . 1 . . . . .        . . . . . . . .
. . 1 . 1 . . .        . . 1 . . . . .        . . 1 . . . . .
1 . 1 . 1 1 . .   ^    . . 1 . . . . .   =    . . 1 . . . . .
. . 1 . . 1 . .        . . 1 . . . . .        . . 1 . . . . .
. 1 . 1 . 1 . .        . . 1 . . . . .        . . . . . . . .
1 . . 1 1 . . 1        . . 1 . . . . .        . . . . . . . .
Complete board   AND    Attack mask      =    Blockers board
                         (Rook C7)
```

Figure 4: Sliding piece move generation; blocking pieces

Once the blockers board has been found, Stockfish combines this with the existing array containing the candidate moves to generate the actual candidate moves for the piece (see figure 5 below).



```
. . 1 . . . . .        . . 1 . . . . .
1 1 . . . . 1 1        . 1 . 1 1 1 1 .
. . . . . . . .        . . 1 . . . . .
. . 1 . . . . .        . . 1 . . . . .
. . 1 . . . . .   ->   . . . . . . . .
. . 1 . . . . .        . . . . . . . .
. . . . . . . .        . . . . . . . .
. . . . . . . .        . . . . . . . .
Array[Blockers]   =    Candidate moves
```

Figure 5: Finding legal candidate moves for sliding pieces

However, this method has a problem because the blocker piece board is a 64-bit array. The array containing the candidate moves will have up to 264 elements. These combined works out at about one exabyte in size, much larger than any modern memory can hold at once. Stockfish uses a hashmap to store the candidate moves more memory efficiently to solve this issue. This brings the candidate move array down to only a few hundred kilobytes, easily handled by most modern computer systems. For a diagrammatic summary of all described above, see figure 6. (Champion, 2022)

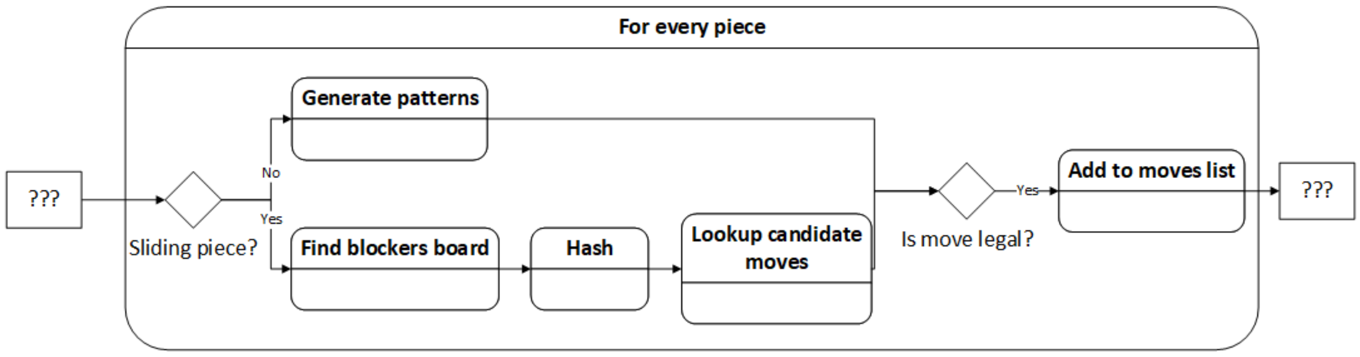


Figure 6: Summary of Stockfishes process to generating a move list

Stockfish - Move Evaluation

Once Stockfish has generated its set of possible legal moves, it needs to evaluate to return the best possible move for this set. Until 2018 when AlphaZero, spoken about below, drastically outperformed Stockfish, Stockfish relied solely on a classical evaluation of the position to retrieve the best move. Since then, they have integrated a neural network to assist in evaluations of more balanced positions to close the gap. However, for this next section, I will be focusing more on the classical evaluation and later look into the benefits brought by AI.

Without neural networks, Stockfish's classical evaluation relies on pro chess concepts such as:

- Tempo
- Material
- Space e.t.c

The evaluation function essentially combines chess concepts and strategies input by chess professionals and Grandmasters over several decades. It essentially evaluates things such as but not limited to the following parts along with examples:

- Material:
    - Imbalance - How many pieces left
    - Advantage - Strength of pieces, e.g. bishop pair
    - Positional - How vital the pieces are in the current position
- Strategy
    - Advantage for pawns, e.g., Doubled pawns, isolated pawns, connected pawns, supported pawn structure, attacked pawns e.t.c
    - Advantage for pieces, e.g., Blocked pieces, bishop x-ray attacks, bishops on long diagonals such as C4 for light-squared bishop, trapping pieces, rook, and queen battery, keeping rooks on open files, forking pieces, e.t.c
- Space - Controlling more squares than the opponent
- King Safety - Looking out for incoming checks, keeping king 'sheltered,' e.g. castling

This will make up the bulk of what makes up these engines and what differentiates them from others; it essentially makes up the 'personality' of the engine and how it plays. Due to Stockfish's open-source nature, there have been countless pull requests just editing some of the weights and scores of some of these functions, which usually entails minor Elo rating improvements. (Champion, 2022)

Benefits of AI Neural Networks

Historically some of the most potent engines have implemented aspects of AI, for instance, Google's AlphaZero, which introduced neural networks to the chess programming world. AI demonstrated its supremacy over other engines when it emerged victorious in its hundred-game match against the well-known Stockfish 8. At the time of this match, Stockfish could beat even the top players in the world. This matchup was played with three hours of playtime with a 15-second increment. Both engines had time to evaluate positions thoroughly and to the best of their abilities, making any arguments of time limitations playing to either of the engine's disadvantages obsolete. (Pete, 2022)

AlphaZero even soundly won against the traditional engine in a series of time-odds matchups with a surprising time odds of 10:1. AlphaZero even won with ten times less time than Stockfish (see figure 4). Furthermore, to take it further, the machine-learning engine even won matchups with a version of Stockfish with a "strong opening book". It did win a substantial number more games when AlphaZero was playing as black. However, it was not nearly enough to win the overall match (see Figure 5 for results). These victories over the strongest of traditional chess engines show just how powerful AI can be in both:

- Evaluating moves
- Searching for moves

DeepMind released information suggesting AlphaZero uses a Monte Carlo tree search algorithm to examine around 60,000 positions per second. Compared to Stockfishes, 60 million per second, demonstrating its much higher efficiency in generating its move set. (Pete, 2022)

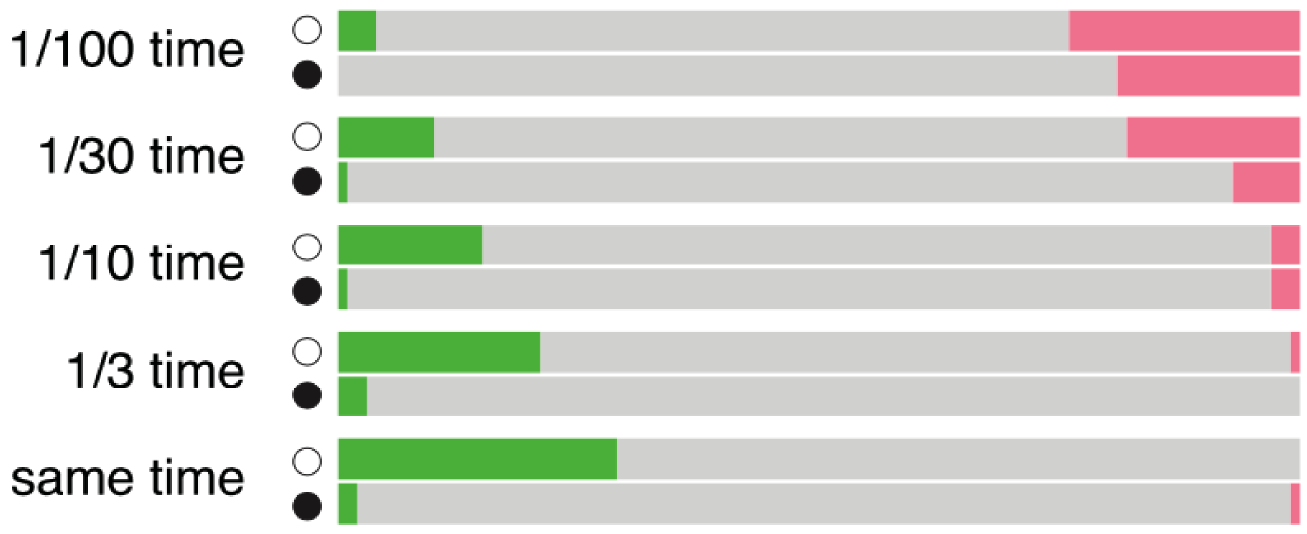


Figure 7: AlphaZero's results in time odds match against Stockfish engine

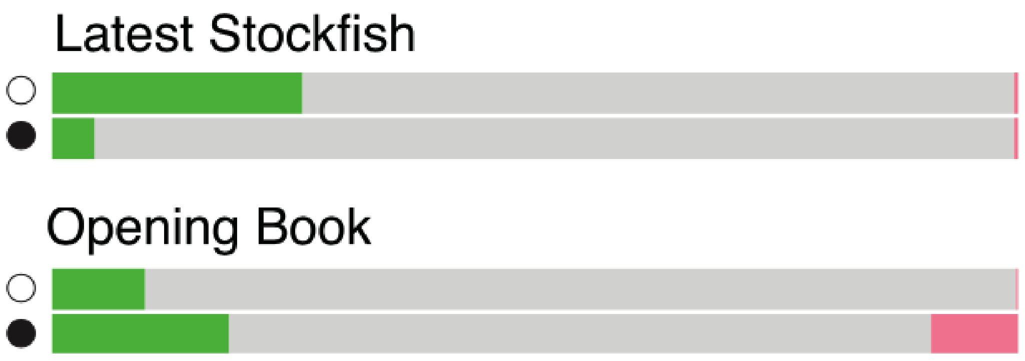


Figure 8: AlphaZero's matchup results against Stockfish with a "strong opening book". Image by DeepMind.

These results safely conclude that AI and machine learning are superior to traditional engines and have solidified their place in the game and engines today. (Pete, 2022)

Resource Estimation

Time Complexity

Take a starting chessboard, for example (see figure 9); for white, there are 20 total possible starting moves they can take. 2 possible moves for each of the pawns and 2 for both the knights ((8x2) + (2x2) = 20) then same for black. After both players make their first move, there are 400 different possible positional outcomes.

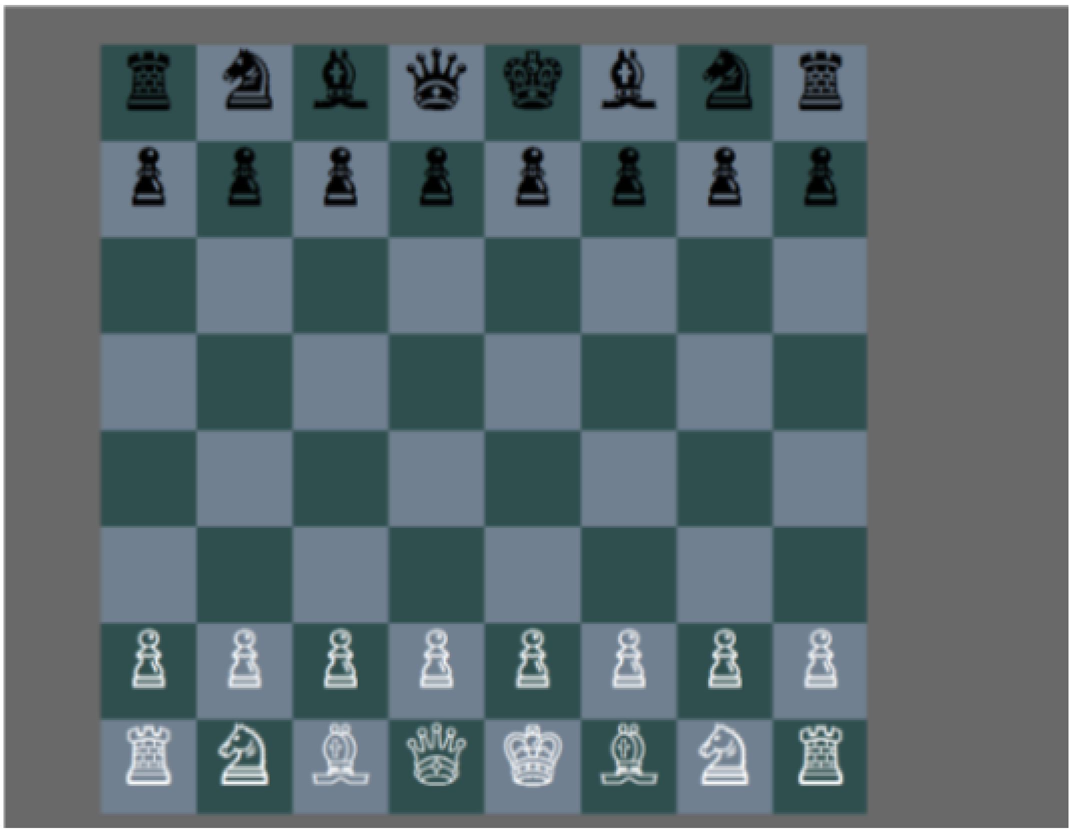
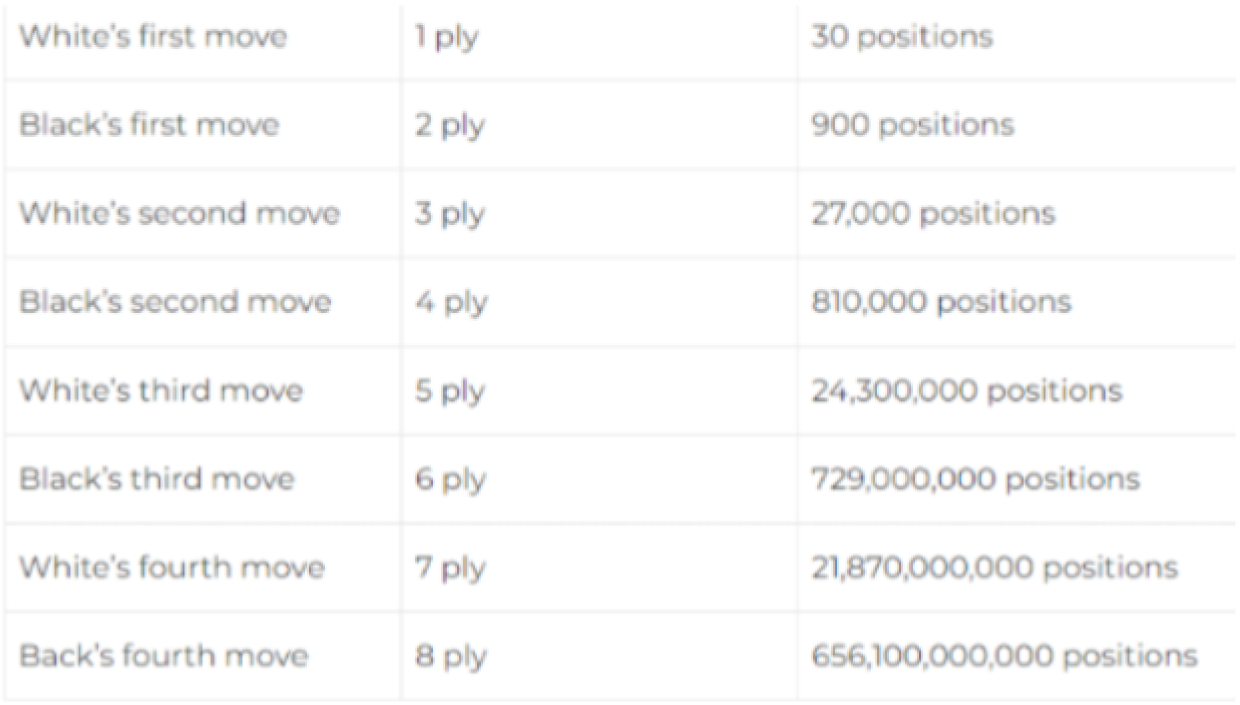


Figure 9: Starting chess position

After each move, there are more and more possibilities for where each player can move their pieces. The number of possible positions grows exponentially; to put this into perspective, see figure 10. Hence, we create trees to hold all the available moves down a given path. (Hercules, A., 2022)



White's first move	1 ply	30 positions
Black's first move	2 ply	900 positions
White's second move	3 ply	27,000 positions
Black's second move	4 ply	810,000 positions
White's third move	5 ply	24,300,000 positions
Black's third move	6 ply	729,000,000 positions
White's fourth move	7 ply	21,870,000,000 positions
Back's fourth move	8 ply	656,100,000,000 positions

Figure 10: Number of variations with incrementing the half-ply count

With these figures, it is possible to estimate how long the system will be able to calculate the best moves for a position x number of half-plys. For the following calculations, the assumptions are that only one core running at 3GHz is being used to analyse a position. Roughly 1,000 instructions are being sent to the CPU to evaluate each position fully.

- 2 ply : ~ 0.0003s
- 3 ply : ~ 0.009s
- 4 ply : ~ 0.27s
- 5 ply : ~ 8.1s
- 6 ply : ~ 243s / 4m 3s
- 7 ply : ~ 7,290s / 2hrs 1m 30s
- 8 ply : ~ 218,700s / 60hrs 45m

Memory Requirements

Memory requirements are small for this project because the algorithms used only usually keep one branch of a search tree in memory at any one time. Most modern systems now, usually having gigabytes of RAM, will not have any problems housing the entire transposition table, depending on the depth of the search used. (Search - Chessprogramming wiki, 2022)

Board Representation

There are many ways to approach the board representation in this project, such as:

- Piece Centric
    - Piece-Lists
    - Piece-Sets
    - Bitboards

These implementations typically hold a collection of pieces still on the board with information such as square occupied, typically held in lists or arrays. Doing it this way comes with the benefit of avoiding scanning the board for move generation purposes saving processing time.

- Square Centric
    - Mailbox Approach
        - 8x8 Board
        - 10x12 Board
        - Vector attacks
        - 0x88

These implementations typically hold the opposite of piece-centric approaches in how they hold pieces of information on squares on the board. For example, an array of squares on the board is created to hold information on whether there is a piece occupying it or if it is empty.

- Hybrid Solutions

As discussed above, some of these implementations may also use elements of both of these types of implementation hence the 'hybrid'. Different search and evaluation functions favour a specific representation; however, it is still common to see both in today's solutions.

Search Algorithm

Types of Search Algorithm

For search algorithms, according to Claude Shannon, there are two types:

- Type A - More brute-force style of an algorithm, looks at every possible variation to a given depth.
- Type B - More particular style approach only searching what it classes as a more 'important' branch of moves.

Until the late 1970s, most chess engines focused on type B implementations. However, today, due to an increase in average processing power, they tilt more towards type A implementations; for this project, I will be developing a type A implementation to generate the move list.

Depth-first searches are often used in searching a transposition tree/table. They work by starting at the root node (The starting position) and exploring as far as possible or to the specified depth before backtracking and exploring the next branch. Additionally, these searches are typically embedded within an iterative deepening blueprint algorithm. These essentially work by starting with a one-ply search and then incrementing the search depth until a set timer goes off. In the event of the timer finishing, before the current search is finished, it reverts to the results of the previous depth. (Search - Chessprogramming wiki, 2022; Iterative Deepening - Chessprogramming wiki, 2022)

Search Trees

The search algorithm works by utilising a search tree which consists of nodes and edges representing alternating sides to moves and the connecting edges being the moves made by either side. The root of the search tree represents the current position to be searched and evaluated to find the best move. (Search Tree - Chessprogramming wiki, 2022)

Cycles

Different variations of moves often end up at the same node, even in cases where they are from differing amounts of moves made, aka cycles. Due to the repetition rule, cycles are usually cut from the search tree, resulting in the search tree being more of a directed acrylic graph (See Figure 11 below). (Search Tree - Chessprogramming wiki, 2022)

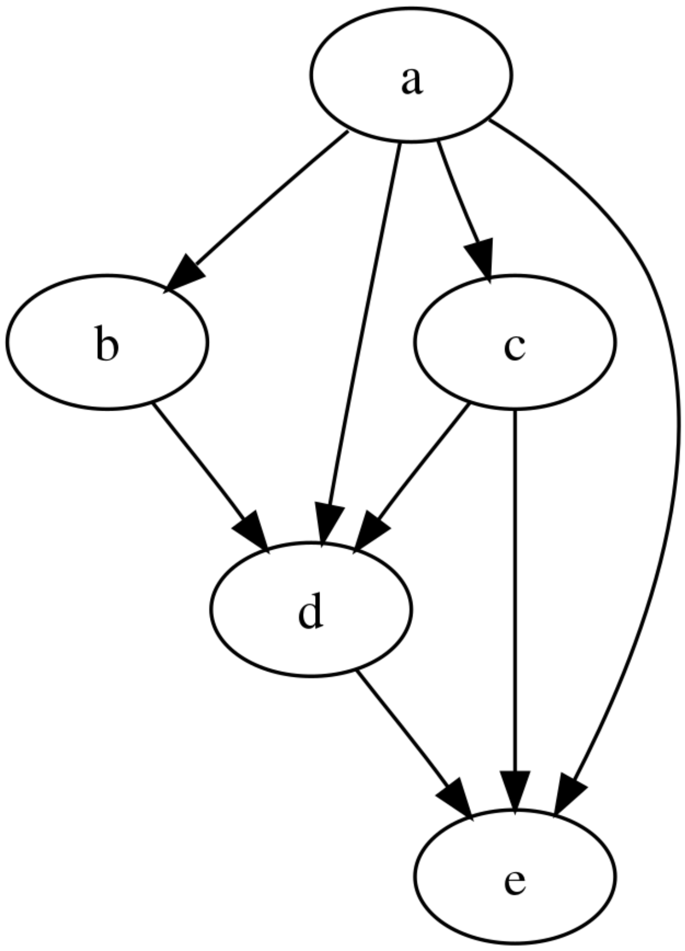


Figure 11: Directed acrylic graph example

Transposition Table

Transposition tables are used alongside search functions; they are stored as hash tables which store information on all branches of variations previously explored and their results. This is so these searches do not have to keep being re-done, saving computation time. In cases where the depth of the information kept in the table is not enough, it still provides valuable insight, especially when it comes to move-ordering. The main reason for implementing these is to save considerable search time.

Standard hashing functions used alongside these tables include:

- Zobrist Hashing
- BCH Hashing

After a search has been run, these hash tables store information on:

- Best move from position
- Depth of search
- Evaluation Score
- Age

All of which are potentially extremely useful when searching again. (Transposition Table - Chessprogramming wiki, 2022)

Alpha-Beta Algorithm

Alpha-beta algorithms provide significant enhancements to the minimax algorithm by eliminating big sections of the game tree. It maintains two values for each branch; alpha and beta. These represent the minimum score that the current colour side can acquire and the maximum score. This works by taking, for example, its white's turn to play and were using a depth of 2;

- Consider all possible white moves
- Consider all possible response moves to each move

Firstly, we pick one of the white candidate moves, then we consider every possible response by black and come up with an evaluation score for each. For example, it comes back with a lower bound evaluation score of even (~0) in one variation. Then another black wins a rook; we can safely cut this move from the search tree as this is obviously not as good a move as the previous. This can be done without analysing any further possible responses from black due to the lower bound retrieved from the first transposition we evaluated being even and the following losing a rook. As you can imagine, from the previously discussed resource estimation section, this comes with considerable time 'savings' due to it no longer having to analyse every single move and counter move. (Alpha-Beta - Chessprogramming wiki, 2022)

Alpha-beta algorithms often utilise the following things to work:

- Iterative deepening (See Glossary)
- Transposition Table
- Aspiration Windows (See Glossary)

Keeping a Minimal Search Tree

Minimising a search tree is primarily dependent on how good the move ordering of a search algorithm is. When best moves variations are searched for first, there is often no need to store any other variations because they are usually followed by 'weaker' moves. Alpha-beta pruning algorithm paired with the evaluation function attempts to solve this problem by utilising endgame tablebases. These are essentially big tables of precalculated moves generated by exhaustive retrograde analysis (See glossary). During an engine's search & evaluation, if it notices certain material combinations, it can effectively query this table to determine the outcomes of these positions definitively and act as a helper by providing optimal moves. (Endgame Tablebases - Chessprogramming wiki, 2022; Search Tree - Chessprogramming wiki, 2022)

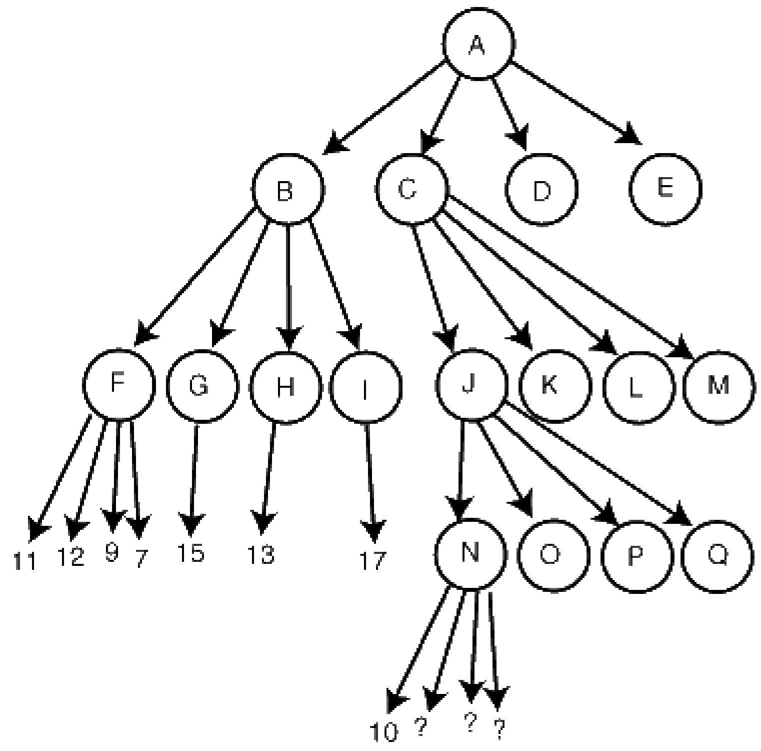


Figure 12: Alpha-Beta Search Tree example

Evaluate Algorithm

Basics

Evaluation algorithms are typically heuristic functions that attempt to calculate a particular position's evaluation score for the player. This score essentially represents each player's chance at winning. The score generated is usually between 1 to -1, 1 being that white will undoubtedly win the game, -1 being that black will undoubtedly win the game, and 0 being a draw. If chess engines could 'see' a winning route from any position, this would either be a 1, -1 or a 0. Unfortunately, this 'score' in practice is not known; therefore, we must make the best approximation using pro chess concepts and comparing positions.

There are two main ways of building these algorithms:

- Traditional Pro Chess Concept Evaluation
- Multi-Layered Neural Network Evaluation

The most significant aspect of most traditional engines evaluation scores comes from the following:

- Material Balance
- Piece-Square Tables
- Pawn Structure
- Evaluation of Pieces
- Mobility
- Center Control
- Connectivity
- Trapped Pieces
- King Safety
- Space
- Tempo

The first evaluation function ever written was by a man previously mentioned, Claude Shannon, in 1949. It essentially provides:

- A symmetric evaluation from the side to move perspective
- Score of the resulting position, NOT the actual move

Looks something like Figure 13 below.

```
f(p) = 200(K-K')
       + 9(Q-Q')
       + 5(R-R')
       + 3(B-B' + N-N')
       + 1(P-P')
       - 0.5(D-D' + S-S' + I-I')
       + 0.1(M-M') + ...

KQRBNP = number of kings, queens, rooks, bishops, knights and pawns
D,S,I = doubled, blocked and isolated pawns
M = Mobility (the number of legal moves)
```

Figure 13: Claude Shannon Symmetric Evaluation Function

From this, we can take that it essentially sums up all the pieces on the board compared with the opponent and multiplies them by their respective weighting for importance: king being most important, followed by queen, rook, bishops & knights (some engines value bishops higher), then finally pawns. After doing this, it considers other essential factors such as: doubled, blocked, and isolated pawns, and finally, the mobility of pieces is measured by the number of available legal moves. For an example of this, see Figure 14 below.

```
materialScore = kingWt  * (wK-bK)
              + queenWt * (wQ-bQ)
              + rookWt  * (wR-bR)
              + knightWt* (wN-bN)
              + bishopWt* (wB-bB)
              + pawnWt  * (wP-bP)

mobilityScore = mobilityWt * (wMobility-bMobility)
```

Figure 14: Basic Complete Evaluation Function

We need to ensure that the function looks from the perspective of the right side for this evaluation style to work. For example, take the above evaluation function(Figure 14), then apply a side_to_move variable (+1 for white, -1 for black) to return the correct eval score (See figure 15 below).

```
Eval  = (materialScore + mobilityScore) * who2Move
```

Figure 15: Eval Score taking into account side to move

(Evaluation - Chessprogramming wiki, 2022)

Piece-Square Tables

One of the more straightforward implementations of the eval function is utilising piece-square tables. Implementing this is essentially just creating a table for each piece and colour, with values assigned to each square to represent 'good' squares. This scheme is beneficial as it can be:

- Incrementally updated as moves are made/unmade
- Hold scores for early game, mid-game, and late game (See figure 16 below)

```
// knight
-50,-40,-30,-30,-30,-30,-40,-50,
-40,-20,  0,  0,  0,  0,-20,-40,
-30,  0, 10, 15, 15, 10,  0,-30,
-30,  5, 15, 20, 20, 15,  5,-30,
-30,  0, 15, 20, 20, 15,  0,-30,
-30,  5, 10, 15, 15, 10,  5,-30,
-40,-20,  0,  5,  5,  0,-20,-40,
-50,-40,-30,-30,-30,-30,-40,-50,
```

Figure 16: Knight Piece-Square Table. Higher value = More valuable square for the piece to occupy.

As you can see, it is generally not a good idea to have knights on the edges of the board from the knight's piece-square values. They are best off in the middle of the board for higher coverage, represented by higher scoring toward the centre. As can also be seen from the famous quote, "knight on the rim is grim".

This technique is handy due to the dynamic nature of the tables; for example, a pawn can have a higher value later in the game than in the early game. Additionally, Utilising these piece-square tables is enough to play a semi-decent game of chess. (Piece-Square Tables - Chessprogramming wiki, 2022)

Board Notation

Board notations attempt to represent board states; there are two main chessboard notations:

- Forsyth–Edwards Notation, a.k.a. FEN
- Portable Game Notation, a.k.a. PGN

Each has its unique way of representing the board, each with its advantages and disadvantages.

FEN

Advantages:

- Holds all information on a specific position
- Position of pieces
- Whose move it is
- Castling rights
- En-passant target
- Half-ply count
- Full-ply count
- Smaller in size compared to PGN, with one string of a maximum of 712 bits

Disadvantages:

- Only holds this information for one position, has no history of moves
- Does not hold any information on threefold repetition

```
rnbqkbnr/pppppppp/8/8/8/8/PPPPPPPP/RNBQKBNR w KQkq - 0 1
```

Figure 17: FEN String Example

PGN

Advantages:

- It is easy to read
- Holds information on an entire game; moves made, names of players, winner/loser, and even the date the game was played.

Disadvantages:

- Does not specifically hold information the same as FEN. You have to work it out from the moves played. Ie, castle rights, en-passant target e.t.c
- File sizes are much larger due to the increase in data needed

Example:

```
[Event "Chess.com Staff Tournament #2"]
[Site "Chess.com"]
[Date "2010.10.26"]
[White "ACEChess"]
[Black "piotr"]
[Result "1-0"]
[WhiteElo "2037"]
[BlackElo "2125"]
[TimeControl "1 in 3 days"]
[Termination "ACEChess won by resignation"]

1.e4 d5 2.exd5 Nf6 3.d4 Nxd5 4.c4 Nb6 5.Nc3 g6 6.Be3 Bg7 7.h3 O-O 8.Qd2 Nc6 9.Nf3
e5 10.d5 Ne7 11.g4 f5 12.O-O-O e4 13.Ng5 h6 14.Ne6 Bxe6 15.dxe6 Qxd2+ 16.Rxd2 Rad8
17.Bc5 Rxd2 18.Kxd2 Rd8+ 19.Kc2 Nc6 20.gxf5 Nd4+ 21.Bxd4 Rxd4 22.Rg1 g5 23.c5 Nc4
24.Bxc4 Rxc4 25.Rd1 Bf6 26.Kb3 Rxc5 27.Nxe4 Rxf5 28.Nxf6+ Kf8 29.Ng4 h5 30.Ne3 Rf3
31.Rd5 g4 32.hxg4 1-0
```

Figure 18: PGN example from Chess.com archives

Alternatives

Alternatives to normal FEN include PGN, compressed FEN, and ųFEN. Alternatively, a custom conversion script to convert FENs to a human-readable text created a chessboard with ASCII pieces to clearly show the state to the user. This would probably be the least efficient way to go about it; however, it gives the project ease of readability. Therefore, testing will become a lot easier. (Keiter, 2015)

Compressed FEN could be good for saving bytes and be more memory efficient in the system. However, it does not meet project goals. It arguably is worse for humans to read than normal FEN, which is the purpose of this alternate board state storage. (Keiter, 2015)

ųFEN could be interesting as it considers a single square and its different states. There are 14 states with the different pieces, empty squares, and the blocker piece. This means the board could be represented in (4bits x 64 squares) 256bits. Compared with normal FEN, which has a worst-case scenario of 712 bits (r1b1k1n1/1p1p1p1p/p1p1p1p1/1n1q1b1r/R1B1P1N1/1P1P1P1P/P1P1K1P1/1N1Q1B1R w KQkq e3 999 999), almost 3 times less efficient. However, in practice, without compression techniques, which I do not wish to go into in this project, it is less memory efficient than compressed FEN. (Keiter, 2015)

PGN will need to be stored regardless, mainly to complete the functionality of the 'Next' and 'Back' buttons. This will be implemented through a stack of all the moves made in the game or a list. Then when a user wishes to go back to a position, it will simply pop the top move off of the stack/list, which will be the last move played due to the stack's nature in storing data.

Design

Language Choice

The language I will be using to produce the engine will be C#. This is for many reasons, although the main advantages C# gives over other languages are listed below, such as:

- Portability
- Object-oriented nature
- Static language

Which due to the reasons listed above, it is easier to find errors, understand the code, and write it than a language such as python for example. C#'s main advantage is that it is an object-oriented language; this makes the code

- Highly efficient
- Reusable
- Flexible
- Scalable
- Easy to maintain

Additionally, the chess programming world is primarily dominated by C and C++ languages, meaning a vast community of developers and resources are available. Some of the most robust engines written in other languages were eventually revised and developed in C. For example, Booot, written by Alex Morozov in Delphi, was rewritten due to running into too many 64-bit bugs. It is also commonly used for web and windows applications which fits the project's needs.

The main difference between statically typed and dynamically typed languages is variables and how each handles them. With static languages, all variables and their types are already known at run time as the programmer, as I will have already declared and defined them down to specific data type. This is advantageous as it means a lot of more trivial hard to detect bugs are caught early on.

On the other hand, dynamically typed languages do not know the types associated with run-time values/variables/fields, e.t.c. They are allowing programmers to skip the process of thinking about the type of each variable used. Although many dynamically typed languages also allow you to provide type information if required, for example, to take care of a bug. Finding bugs inside more significant projects can be much more difficult. Hence, dynamic languages are mainly used as scripting languages due to their usefulness in developing solutions quickly and the much smaller nature of scripts compared to more significant projects, the main reason why I chose a static language such as C#. (Lynn, 2021)

Design Pattern

To develop this project, I chose to use MVC Architecture, which was for several reasons which provide a significant advantage when developing this solution. It is often referred to as a design pattern; I have referred to it as an architectural pattern due to its application to structure my solution. It also helps:

- Creates a solid structure
- Helps reduce repetition

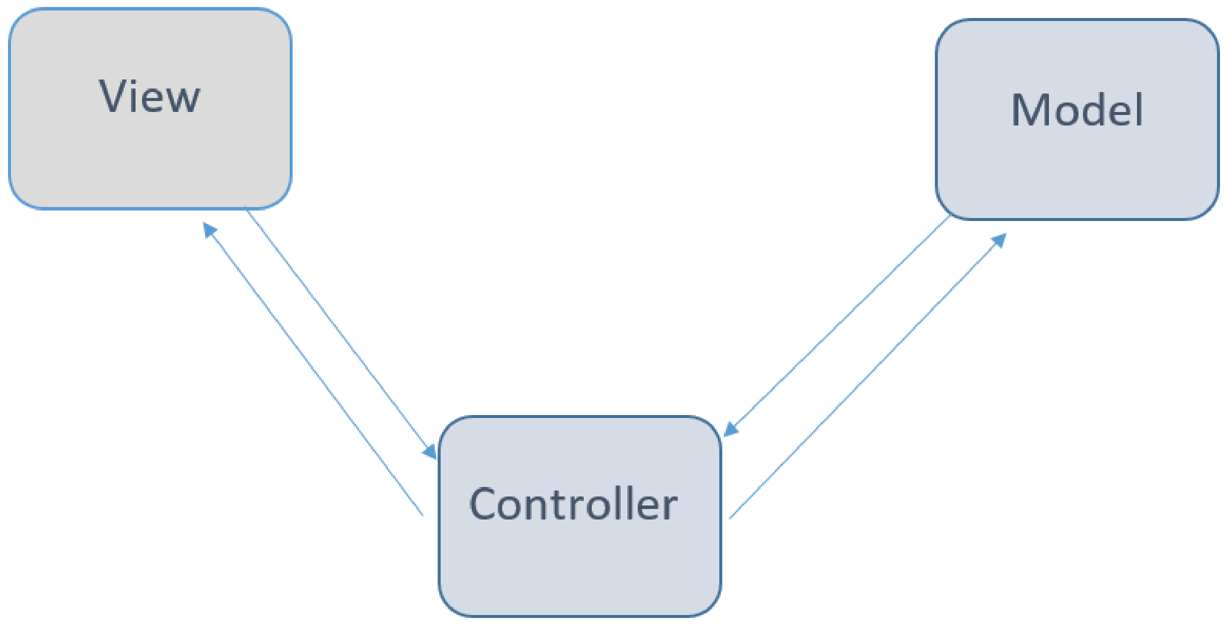


Figure 19: MVC Architecture

It comprises three parts: model, view, and controller—each with particular purposes and responsibilities.

- Model

  This section is responsible for handling and maintaining the data involved with the solution. In addition, it is the model that will typically connect to any databases/sources utilised within the solution.

- View

  This section displays the information from the model layer to the user. Developers often write the view in a friendly and easy to understand way. This layer also allows users to interact and change data for the controller to pass to the model to update the back-end and then vice versa.

- Controller

  Finally, as previously mentioned this section is responsible for the data flow between the model and view components. It takes any changes from the view and passes them to the model to update and vice versa.

(Svirca, 2019; TutorialsPoint, 2022)

To make this project more manageable, instead of creating one titanic project, I split it up into three separate parts:

- Testing

  Testing is the part of the project that is responsible for ensuring the code stays bug/error-free. It is vital to write bug-free code at the start of a project. Or there will likely be problems when implementing the search and evaluation functions later down the line. It will be an automated test routine which will run every time the project is run to ensure everything is working as expected.

- Engine

  Responsible for the 'brains' of the solution. The engine project section will make up the model/controller part of the solution and the main bulk of code. I refer to it as both the model and controller here as it will be responsible for keeping the data on the GUI accurate when the engine makes a move and vice versa for when the player makes a move from the GUI. It will be responsible for handling all the data involved in the solution, such as moves, pieces, 50 ply count, e.t.c. It will implement most of the things discussed in the project analysis section. It will be home to the Search & Evaluate functions which are responsible for finding all moves and then filtering them down to the 'best move' in a given chess position (See Appendices B & C for roughly how this will work)

- GUI

  This project section is self-explanatory, the 'View' section of the MVC architecture mentioned above. It is essentially just the project's graphical user interface. It gives the user control over the solution and allows them to interact with the engine quickly and easily.

The segmentation of these projects made me concentrate a lot more on what each section is supposed to achieve. Ultimately this led to:

- Much less duplicated code
- Highly modularised code
- Fewer anti-patterns in code

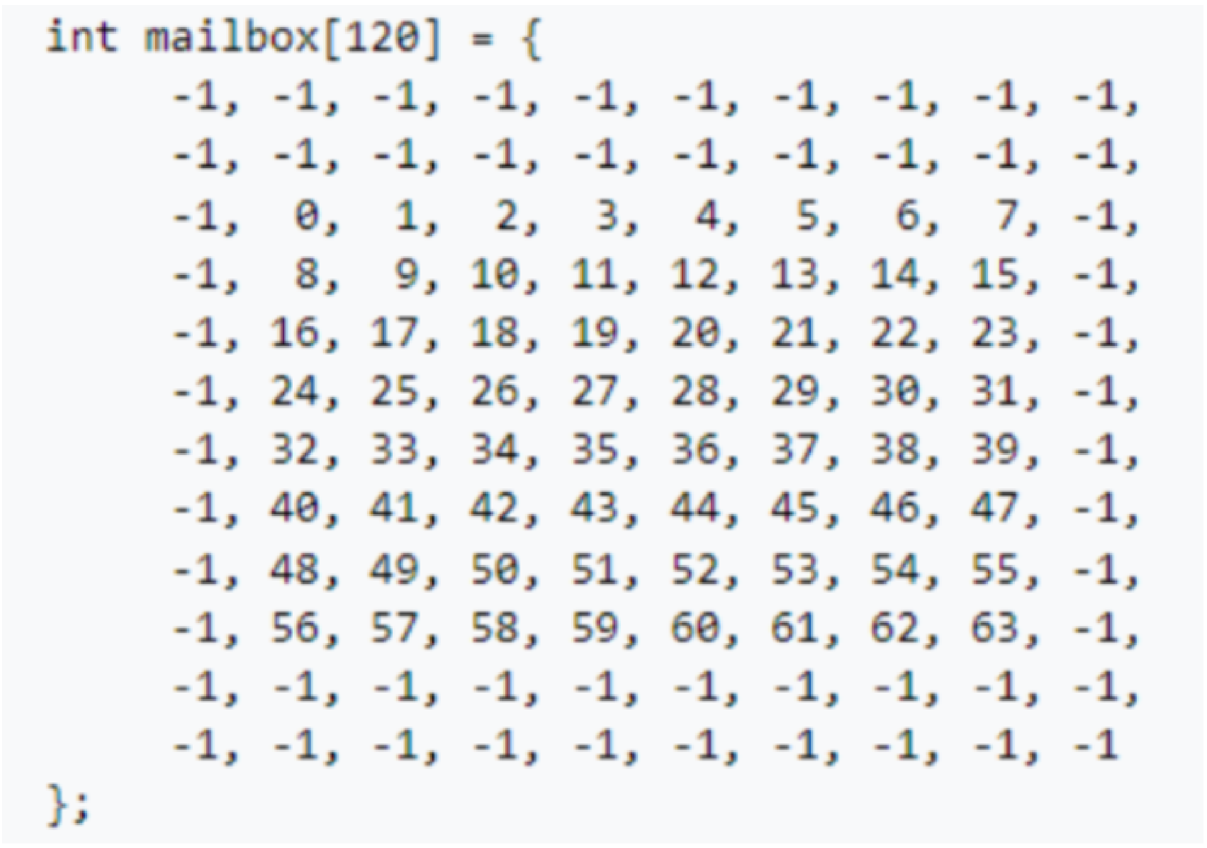
The use of this alongside the TDD approach, spoken about below, helped me split code up into appropriate objects avoiding the 'God object' anti-pattern. The 'God Object' anti-pattern is when a programmer puts too many functions/methods inside one class or object. It is an object that attempts to solve every problem, hence the name 'God Object'. This is a problem as it makes it hard to:

- Test
- Maintain
- Document

Another anti-pattern this choice of software architecture will help tackle on the other side of the spectrum is useless/poltergeist classes. These are just classes with no responsibility, often just empty classes with a function call from another class or some other unnecessary level of abstraction. This may not sound like a huge problem. However, it adds complexity where it is not needed and makes code less readable. Structuring my solution in this way will hopefully help tackle this as each section has its responsibilities and actions. (Saba, 2015)

Board Representation

I have chosen to represent the board in memory with the 0x12 mailbox approach. This is a 2D array of 120 slots in size; 64 positions in the middle of the array represent the board squares and pieces, and the remaining surrounding files and ranks represent sentinel pieces (see figure 20).



```
int mailbox[120] = {
     -1, -1, -1, -1, -1, -1, -1, -1, -1, -1,
     -1, -1, -1, -1, -1, -1, -1, -1, -1, -1,
     -1,  0,  1,  2,  3,  4,  5,  6,  7, -1,
     -1,  8,  9, 10, 11, 12, 13, 14, 15, -1,
     -1, 16, 17, 18, 19, 20, 21, 22, 23, -1,
     -1, 24, 25, 26, 27, 28, 29, 30, 31, -1,
     -1, 32, 33, 34, 35, 36, 37, 38, 39, -1,
     -1, 40, 41, 42, 43, 44, 45, 46, 47, -1,
     -1, 48, 49, 50, 51, 52, 53, 54, 55, -1,
     -1, 56, 57, 58, 59, 60, 61, 62, 63, -1,
     -1, -1, -1, -1, -1, -1, -1, -1, -1, -1,
     -1, -1, -1, -1, -1, -1, -1, -1, -1, -1
};
```

Figure 20: 10x12 Mailbox approach example

I chose to do it this way rather than the traditional 8x8 approach to ensure all knight jumps, even from the very corner of the board, end up on valid array positions. For example, when a knight is on square A8, it can only jump to squares B6 and B7. Otherwise, it would end up in positions highlighted in red squares in figure 21, not on the board. Every knight's move ends with it still on a valid array index; this is useful as it will avoid errors in the engine's search and evaluate algorithms where knights are on bordering squares. The code will need to check that the index the knight lands on is not '-1' as this is a blocker piece. The knight cannot land there if it is, as it is not a legal move. (Chessprogramming.org. 2022)

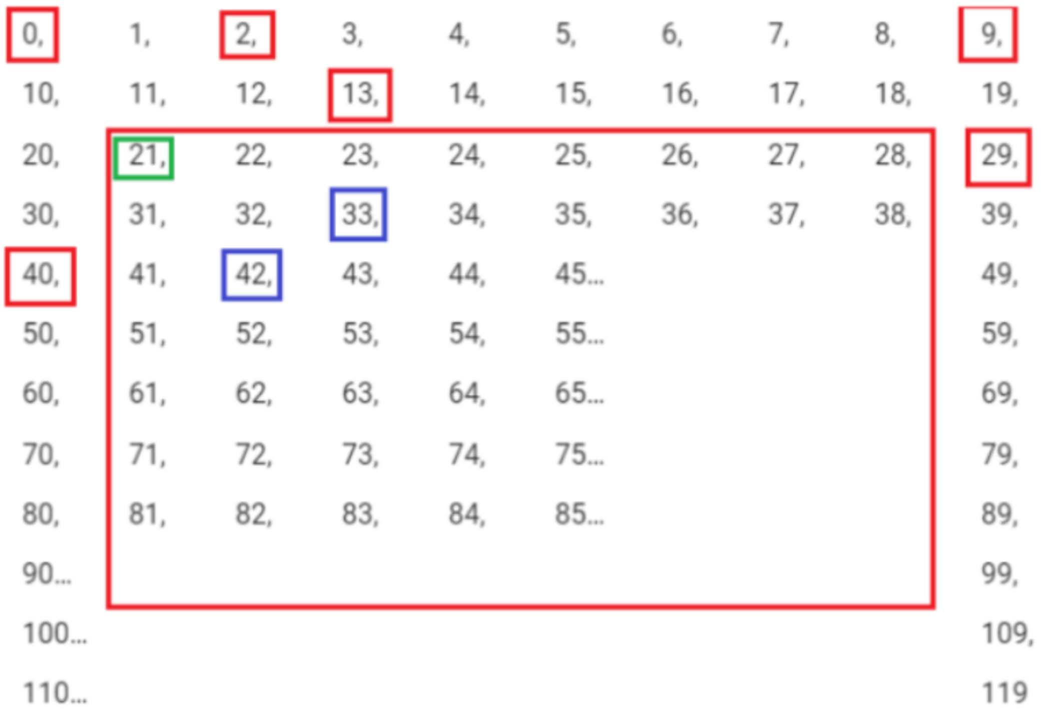


Figure 21: Extreme knight movement example: Red squares represent invalid pseudo-legal moves, blue represents legal moves, and the green represents knight's current square position.

This implementation is beneficial as it removes the need to catch index out of bounds errors when generating moves for all pieces. The most significant piece is the knight due to its 'L' shaped jumps, as mentioned previously, always landing on a valid array index. This is beneficial as move generation becomes computationally less expensive and saves much time evaluating the best move.

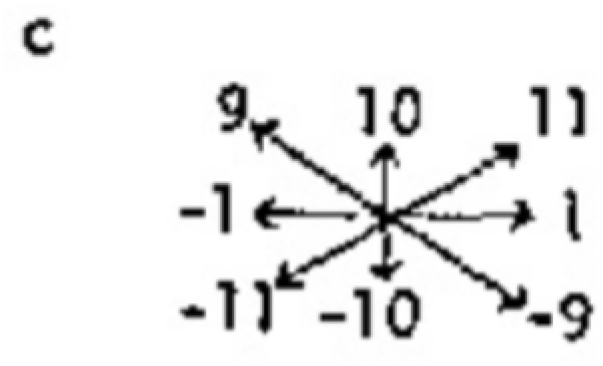


Figure 22: Movement vectors for 10x12 array representations example

Program Flow

Now that I have worked out the language, structure, and board representation, I need to work out the flow of the different solutions.

Engine

Firstly, thinking about the engine flow of things is the most difficult because it is more likely not a continuously running solution. However, if it were, it would look something like seen in Appendix A: Figure 28. The main functionality of the engine needs to have is the following:

1. Take custom state input (E.g. FEN or PGN)
2. Search for all possible moves given a position
3. Evaluate for the best possible move

As mentioned previously, PGN is less suitable for inputting custom states. Therefore, I decided to utilise the FEN's superior format for recording game details that you would otherwise have to work out from PGN notation. This meant that the program would be able to take in a FEN string and directly convert that into object variables.

Other than taking custom FEN input, the engine needs to:

- Generate valid move lists
- Evaluate move lists for the best move
- Update GUI with info

Which I will futher explore the flow of in the sections below.

Search Algorithm

To design the search algorithm flow was relatively simple as it is a pretty linear function. It is simply passed a board position. It assigns it as the root node on the search tree and then proceeds to check the transposition table for previous search results for move ordering purposes. It then evaluates each position in order of 'importance' and compares it with the successive prioritised variations. It does this by comparing the resulting positions lower bound evaluation score, cutting off if the score is lower than the previous positions. As previously mentioned in the alpha-beta section, if the lower bound is higher than the next variation lower bound, it stops there and returns the best move found. If not, the algorithm will check the subsequent variations for a better resulting position for whichever side it is searching currently. (See Appendix B: Figure 29 for flowchart)

Evaluate Algorithm

The evaluate functions flow is pretty similar in that it is a pretty linear function that simply checks the position against specific criteria. First, it will need to check material balance as this is arguably one of the best ways to tell who is winning a match. Next, we will check things like piece-square tables and space/mobility. The only other functionality the evaluate function needs is to work out the upper and lower bounds of certain variations the search algorithm throws at it. This is for alpha-beta enhancements I will be attempting to implement into this solution. (See Appendix C: Figure 30 for flowchart)

GUI Interface

GUI program flow was slightly more tricky due to the number of possible interactions with it than the other parts of the solution. The GUI needs to allow the user to:

- Input state, i.e. FEN
- Change state, i.e. Next/Back buttons in-game
- Move pieces and interact with the board

We need to evaluate these individually to investigate each parts flow. For example, take inputting states, to work out the program flow we need to first think about what checks need to be done. Inputting state requires a check as to whether the FEN string provided is valid. If it is not valid, the program needs to return a message to the user and wait for further interaction. If valid, the program needs to call and pass the FEN string to the FEN handler to deconstruct and convert into program code to represent board attributes(See Appendix D: Figure 31).

Next, make the change of state feature, specifically the back button. For this to work, we need to check if the current program state has any data available for the last state of the board. If it does not just return the current board state, update the GUI, and finally return to the waiting state for further interactions. The next button will do the previous steps again but check for future positions in the board's object state. Again, update the GUI and return to the wait state if none are held.

Finally, there do not need to be many checks for moving pieces and other GUI functions due to how the GUI will interact with the engine to receive valid moves before a user inputs their move. This will essentially block users from inputting invalid moves from the GUI picture box displayed to the user. This will work by users clicking the piece they wish to move; the piece will then be highlighted then a call to the engine valid moves function will be made. The GUI will then convert this into dark circles visible on the board for users to see. Users will then click where they want to go or click on another piece and pass this info onto the engine to update its back-end data.

Testing

Development Lifecycle Choice

Due to the choice of development approach, being test-driven development, I used a mixture of automated unit testing and manual UI acceptance testing to test this project. Unit tests to ensure the basic functionality of my code stays bug-free throughout development, something that is extremely important with chess engines in particular. At the same time, the manual UI acceptance testing was used on the project GUI side to ensure that it stayed as user friendly as possible throughout development.

I used test-driven development for several reasons listed below:

- Reduces duplicated code
- Keeps code bug free
- Makes writing the code simpler

Due to this project including many different methods and functions, it will sometimes become hard to manage and keep bug-free. Using this development approach will provide significant advantages in managing this by forcing myself to think about each method's actual required functionality before writing it. It essentially consists of these five steps:

- Write a test
- Run tests
- Write some code
- Run tests & if code fails, refactor it
- Repeat

(See figure 23)

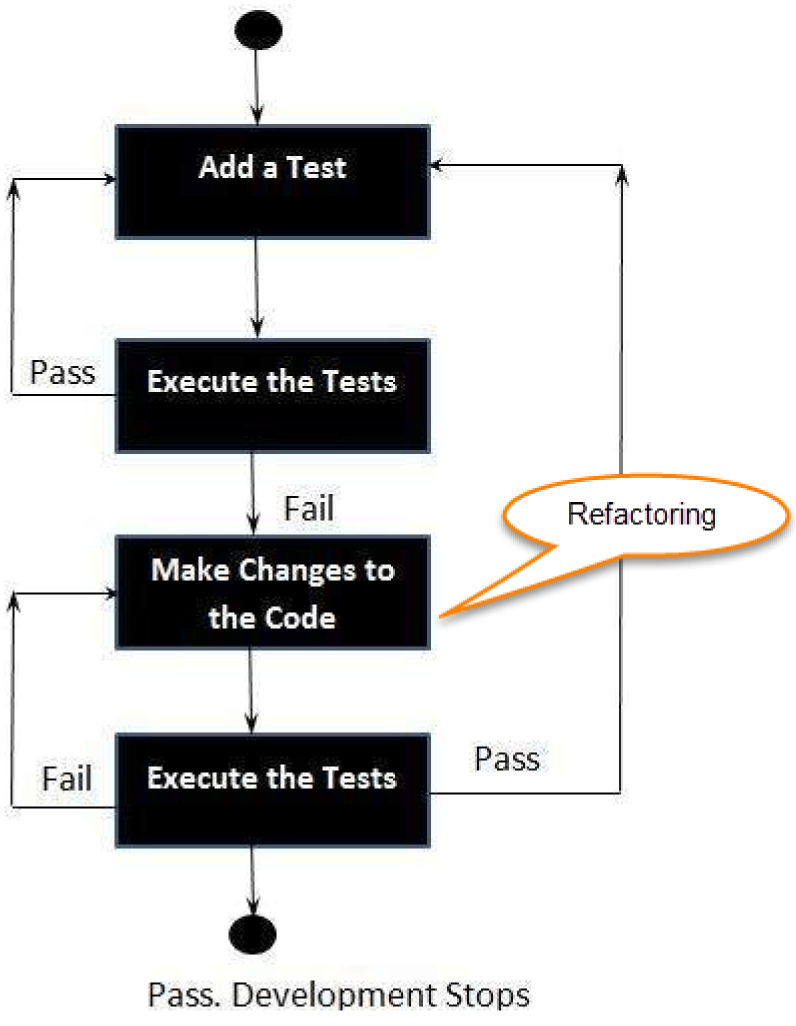


Figure 23: Test-driven development steps

(Hamilton, 2022)

Testing Strategy

As explained previously, testing is a vital part of this project, progressing into development and ensuring the code stays bug/error-free for the most part. The main parts of the program I needed to think about, and test were:

- Board Representation
- Piece Movement
- Board Functions e.g. make_move, unmake_move, e.t.c
- GUI

Engine

To test the engine side of the project, I chose to use C# unit tests for several reasons, such as:

- Speed - When using unit tests, the development process becomes a lot simpler due to you, the programmer having to affectively 'define' its functionality first and what/if it needs to return anything. This makes the development process a lot faster and easier as you know the exact functionality required before you start developing the solution.

- Quality of code - The code quality when utilising unit testing becomes a lot better; this is because you can define unit tests very specifically and test every part of the function down to tiny details.
- Find bugs easily - This is as the unit tests allow you to run through and debug code line by line seeing the state of all objects/variables after each line.
- Facilitates change - Since unit tests test each component of a solution individually. Finding and changing the defective section of code is much simpler, if there are any problems.
- Design - Forces developers to think about the design of a component before implementing it. This helps keep the focus on the functionality of that specific component and its responsibilities. (PerformanceLab, 2022)

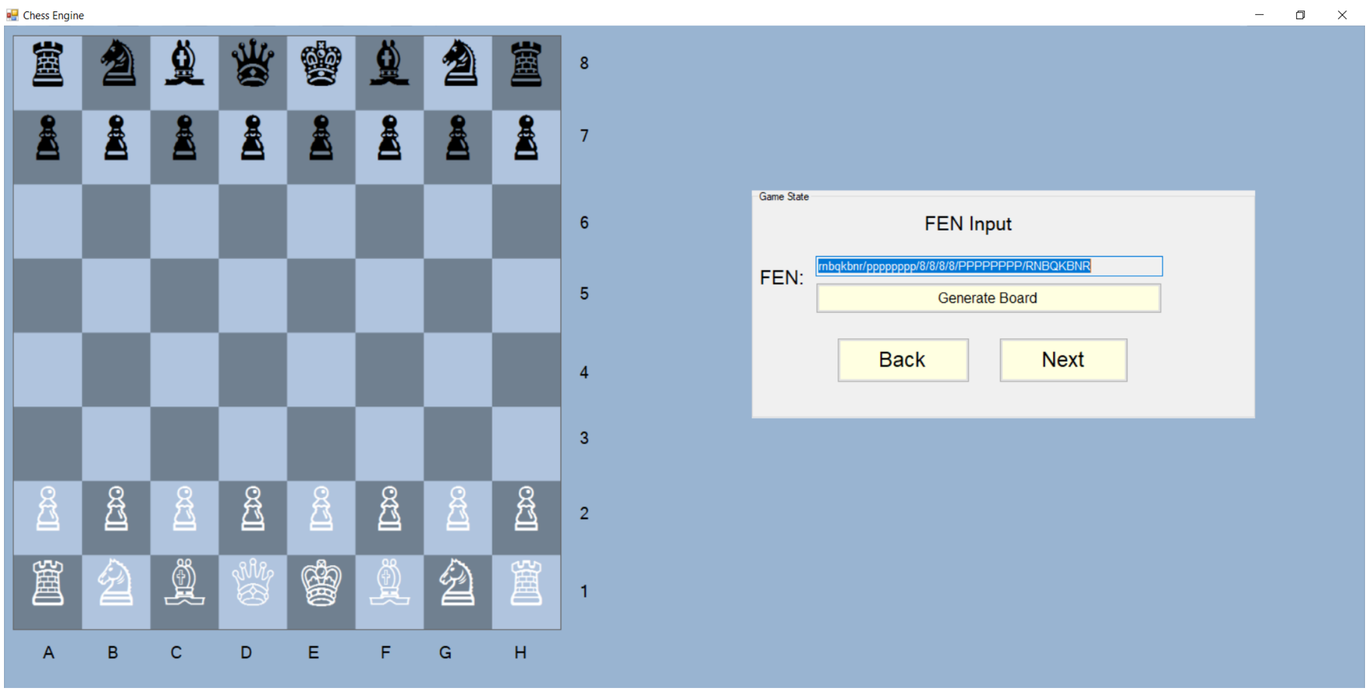
To test the board representation and the FEN handler at the same time, I wrote the tests seen in Appendix G: Figure 34. These essentially passed through valid FEN strings into the FEN_Handler to convert into a board and properties. As can be seen from the appendix mentioned previously, I first create a string representation of what the board should look like and create and set all the local variables to the expected board properties after it has been passed the FEN. The FEN is then passed into the functions for the solution to convert to actual board properties. Then the existing board properties are tested against the expected outputs. If they all match, the test should pass; if not, they will fail. Additionally, this tests board representation due to it populating the board array, this is also one of the checks for the test to pass.

Next, to test piece movement, I first had to test the engine's ability to generate valid legal moves. To do this, I created a string representation of the board and passed it into the function to convert. I would next manually calculate how many moves the pieces could get from the square. Once I had the squares, I would first check the count of moves returned to see if it is as expected; then, if it passes, check that the moves are precisely the anticipated moves. This was mainly fine to write; however, it got quite confusing to reference each square due to squares being indexes in the board array. To combat this, I created a Square enum in the board class to hold every square and its array index for ease in testing (See Appendix H: Figure 36). This allowed me to parse squares to their array index by simply calling an enum parser; this made testing much more straightforward to understand.

Due to the lack of progression in the project I never got round to creating tests for the rest of the functionality. However, if I were to go about testing the rest of the projects functionality, I know that due to the 'helper' functions I have created such as the square enum and the ASCII converter; it will be a lot easier to create the tests than they would have been.

GUI

To test the GUI, I mainly just used user acceptance testing by giving random people my solution and seeing if they would be able to work out how to use my GUI solution. As a result, 9/10 of my tested users knew how to operate the program off the bat with no previous information except one, which did not understand what FEN was. Hence, they did not know much about chess and my GUI. Although based on their responses after explaining a bit about it they understood how to use it easily.



FEN: rnbqkbnr/pppppppp/8/8/8/8/PPPPPPPP/RNBQKBNR

Figure 24: Project GUI Example

Project Management

For the project management, I chose to use GitHub to keep an online copy of and track any changes to the code. Then I chose to use Trello for the project management side of things, an interactive board used to keep a hold of and track necessary functionality or features the project needs to implement.

Project Links

- GITHUB
- TRELLO BOARD

Trello

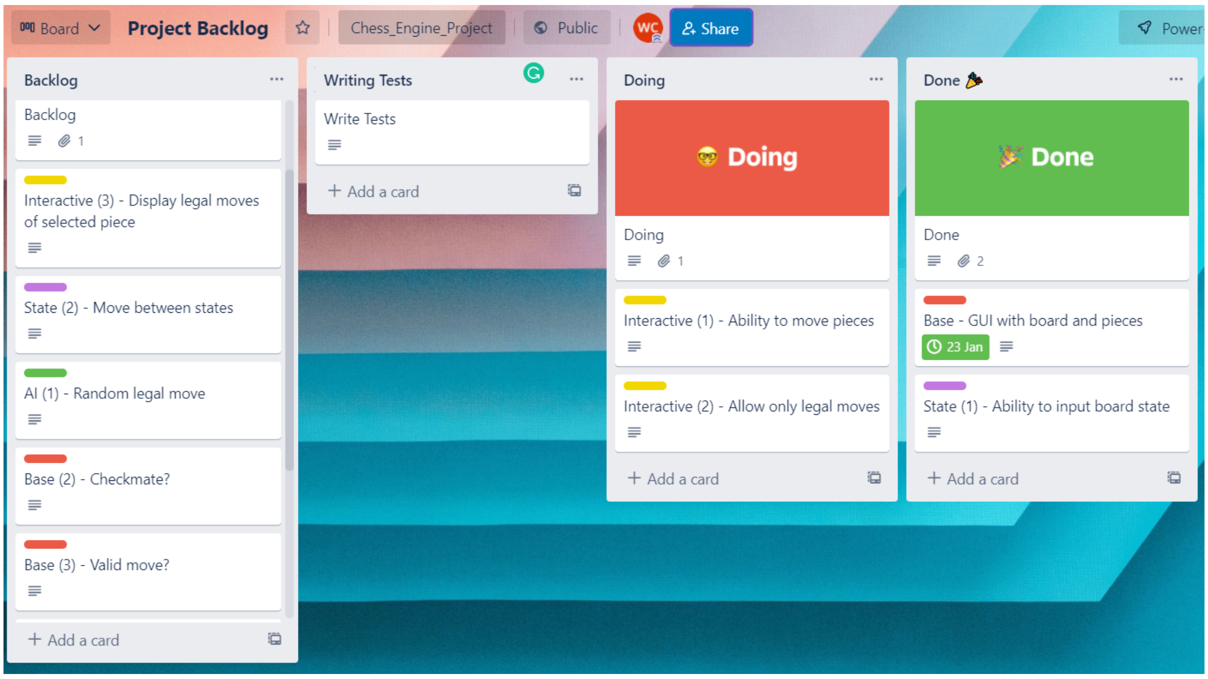
I decided to use Trello for several reasons:

- Ease of use
- Free to use
- Kanban-style of structure
- Easy to add and manage tasks to do, doing and done

One slightly annoying disadvantage is that Trello does not come with any burndown/Ghantt chart functionality. However, this was not a massive problem as it just meant I needed to add to an external mermaid Gantt chart instead, which was not a huge problem.

Trello allowed me to create tickets with numbers for importance/priority easily, so once I finished on a ticket, I could easily see what I had next on the list of importance(See Figure 24 below). Slightly similar to the kanban structure. However, I moved testing first due to my choice of the development approach. Tickets marked with a score of 1 are most important, while larger scoring tickets come later as they are less critical to the project's success. Tickets are also split up into different sections based on what section of the MVC architecture I am working on currently. For example:

- Base - Model side of things, part of the engine part of the project and makes up the basic structure of the chess engine and its features required.
- AI - Model section, again, will be a part of the engine section of the project. It will be responsible for generating move lists and evaluating them and if the user is playing against the engine, update the GUI with the engine's reply.
- Interactive - View side of the project; this will be how the GUI users interact with the chess engine/player.
- State - Controller side of the project; this will be responsible for handling the state of the current chess game/position being analysed.



Backlog
- Backlog
- Interactive (3) - Display legal moves of selected piece
- State (2) - Move between states
- AI (1) - Random legal move
- Base (2) - Checkmate?
- Base (3) - Valid move?

Writing Tests
- Write Tests

Doing
- Doing
- Interactive (1) - Ability to move pieces
- Interactive (2) - Allow only legal moves

Done
- Done
- Base - GUI with board and pieces (23 Jan)
- State (1) - Ability to input board state

Figure 25: Trello Project Management Board

When I was developing a solution for each ticket, I would move it first into the 'Writing Tests' section to determine the functionality required of this code section, then move along to the 'Doing' section. This section was for when I was working on implementing the feature of the code. Once that ticket is complete and fully functional, it will be moved to the 'Done' section.

Additionally, whenver I came accross a ticket that required some kind of experimentation in the project. I would first give the ticket a number, for example, #001; then I would proceed to branch off the main branch calling it the ticket name plus ticket number. This made it clear for each branch which feature I was specifically working on. This made the project a lot easier to manage and clear on what was going on with it at any point.

GitHub

I chose GitHub to track code for many reasons, such as those listed below:

- Used in the industry: The industry standard for tracking projects and versioning.
- Online repository: Code is accessible and saved online, meaning any locally corrupt files without GitHub would cause catastrophic delays; can easily be overwritten with previous versions.
- Developer documentation: This allows me to easily add a project readme beneath the project for any essential information other developers would need to carry on with the project.
- Tracks changes: Any commits that cause significant breakages in other code sections can easily be 'backtracked' onto a previous commit where the code worked.
- Integration options: This comes with integration options for many common platforms such as Google Cloud, Amazon, and even GitHub pages. GitHub Pages will be beneficial if there is the time to make the engine available to access the web at the end of the project.
- Collaboration: As stated before, this will be a solo project. However, it is a commonly used solution to aid in collaborative projects in the industry due to features such as merging. (Novoseltseva, 2020)

Initially, in the project, I created a separate branch called 'development' to work on any changes I was working on, then merged to main/master upon completing any features. However, this was not only redundant as it meant all changes were going onto one branch, but unnecessary and confusing due to its naming scheme. To tackle this, I decided to merge all my branches, then only branch off from the main/master when there was a particular ticket that required some experimentation with the code to complete. I did this as it meant I could experiment and commit code without it affecting the main branches currently functional code.

The ticket names would be assigned with a brief title of the feature followed by a ticket number, e.g. #001, #002, e.t.c. This made it much more straightforward and also meant a log of the changes made to implement each feature was taken down. Useful for anytime I needed to look back at a particular code block to reuse a similar piece of functionality or syntax reminder. Also, particularly useful for future use when looking to improve each part of the solution; allows you to quickly see how each feature was done. This also significantly increased the quality of my code as each branch was clear about what feature/code I needed to implement on that branch by the name.

Gantt Chart

As mentioned previously, Trello comes with no options to create/generate any burn down or gantt charts from the board. Therefore I created a rough expectation of how the project will progress(See Figure 26). I chose to develop the GUI roughly alongside the Engine as obviously many features are kind of linked with each other, this would force me to think about the GUI integration aswell when developing these sections of code.

However, due to problems during the first part of project it ended up looking like a much more squished version with development only starting around January/February.

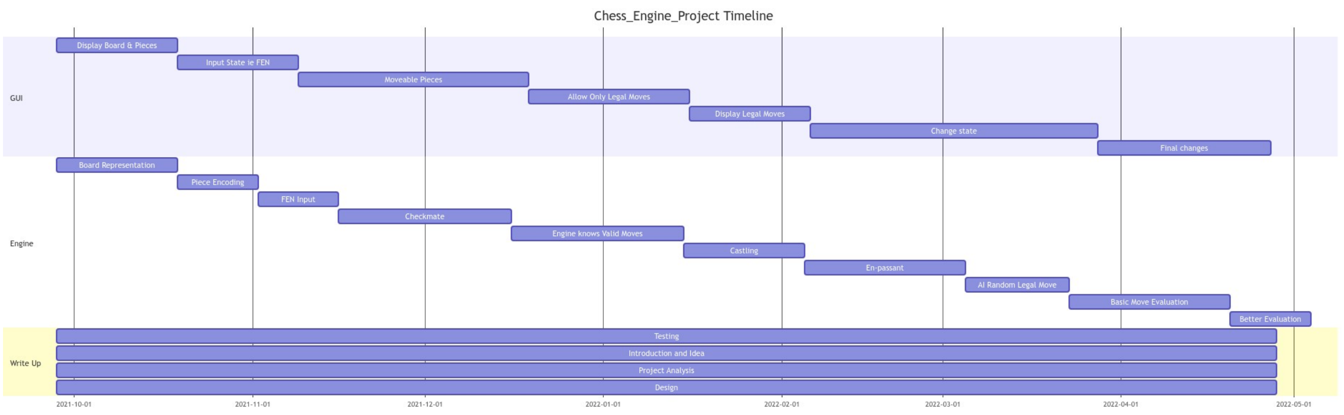


Figure 26: Gantt Chart of expected project progression

Conclusion

In conclusion, this was an extremely worthwhile project for me due to the personal growth and development gained from taking on a project of this size. It introduced me to many a problem which can often come up in industry and issues in taking on bigger projects such as this, e.g. importance of following a software lifecycle, analysis paralysis, magic numbers, and poltergeist classes, to name a few. It got me thinking about developing software from an industry perspective, developing solutions to developer problems which ultimately saved much time in coding some of these sections. For example, the ASCII board converter and the square enum previously mentioned and further gone into a bit more detail in the following evalutation section.

Critique of Work

One of the main critiques I would have to make would be the rushing of the development of my solution. Due to problems arising in my personal life, development did not get started until the second semester. This put significant setbacks and pressure on all parts of the project. Ultimately due to it needing to be done in such a short time. This eventually led to analysis paralysis, further slowing the production of the solution. To tackle this, if I were to do this project again, I would have researched and analysed the problem to break it down a lot more and then started developing a lot earlier than I did.

I also made a few mistakes following the development lifecycle during the development process. These being:

- Not writing any tests before developing

This mistake was mainly due to inexperience, panic and the desire to get too much functionality done too quickly. Due to a lack of research, I struggled to see the path to the end goal when starting the project. I was starting on a blank canvas; due to this, I lacked the knowledge of what tests I would even need to write to get started. This resulted in not only sloppy initial code I had quickly tried to develop due to time running out. But also a bit of analysis paralysis when thinking about the unit tests required. Instead of trying to write some functional tests forcing myself to think about the functionality before, I ended up writing a load of code which I would need to later test leading to my next mistake.

- Writing too many tests before developing/refactoring

This partly links in with my previous mistake in the way it lead into this mistake; writing way too many tests before refactoring code. This wasted a lot of development time having to go back and forth not only refactoring code but also the tests due to changes made in the engine's structure after finally refactoring some code. One of these was when I implemented the Move class to hold all the information about making a move in the game. Before this, I had written the tests and method to take in all the parameters individually but later down the line found benefits in creating one move object for keeping the code concise and more easily readable.

Due to these reasons tied in with other issues, meant not much functionality of the solution was actually implemented. It was essentially hitting very few of my project goals, as seen from the Trello board (Figure 25) and the online repository.

Short Comings

Overall, there are several shortcomings of the project that I wanted to address, these being:

- GUI Interaction - There was minimal GUI interaction implemented into the final solution, which was disappointing overall. I wanted to implement moving pieces around the board at least. However, this never got around to being implemented due to development struggles mentioned. The only interaction implemented was the change of board state with FEN strings. It would have been good to have pieces being able to be moved, and even when selected, showing legal moves.
- Engine Search & Evaluate - This was another section of the project I never really got fully round to completing. Another big shame as this was what was going to make up the main bulk and complexity of the project. I partly got around to coding a function to return valid moves for a piece. However, because it was a last-minute rush, I did not manage to get fully functional(Only partially works for sliding pieces and knights only when blocked by friendly pieces).
- Testing - Even in testing, there were several shortcomings, those being minimal tests written and passed all checks. This is mainly due to the lack of functionality implemented into the solution. It meant none of the function calls in the tests for the pieces altered the board state, meaning no checks would work as expected regardless.

Evaluation

This development lifecycle taught me many lessons and the importance of writing tests first during development. Especially in cases where it seemed to be just a minor feature to implement. In most of these cases where I decided to cowboy it and develop without testing, it usually burned me due to some unexplained errors popping up later into production. For example, when the GUI and engine were confusing piece colours with each other. This was annoying as it brought up unexpected board array indexes as valid moves for each side's pawn piece's.

Due to the way I encoded pieces and the board in general, I encountered a few issues while writing the tests. Each piece from each side was assigned a numeric identifier, and the board array was 120 in length. It proved challenging to populate these arrays (See Figure 27 below) manually, Mainly when setting up custom board positions to test. To combat this, I wrote a custom function within the code to take in a string representation of a chessboard and convert it to an actual board array in memory (See Appendix F: Figure 33). This meant that I could set up simple custom board positions to test code functionality more easily using a string representation of the board.

```
        [TestMethod]
        public void FEN_Handler_Default()
        {
            // Arrange
            // Initialising Test Var's
            int[] default_board = new int[120]
            {
                -1, -1, -1, -1, -1, -1, -1, -1, -1, -1,
                -1, -1, -1, -1, -1, -1, -1, -1, -1, -1,
                -1, 8, 4, 6, 10, 12, 6, 4, 8, -1,
                -1, 2, 2, 2, 2, 2, 2, 2, 2, -1,
                -1, 0, 0, 0, 0, 0, 0, 0, 0, -1,
                -1, 0, 0, 0, 0, 0, 0, 0, 0, -1,
                -1, 0, 0, 0, 0, 0, 0, 0, 0, -1,
                -1, 0, 0, 0, 0, 0, 0, 0, 0, -1,
                -1, 1, 1, 1, 1, 1, 1, 1, 1, -1,
                -1, 7, 3, 5, 9, 11, 5, 3, 7, -1,
                -1, -1, -1, -1, -1, -1, -1, -1, -1, -1,
                -1, -1, -1, -1, -1, -1, -1, -1, -1, -1
            };
```

Figure 27: Manually populating 120 element array

This choice of development came in handy in a few cases throughout development. One of these is during the writing of the Get_Valid_Legal_Moves function. This function was complicated to write due to it needing to:

1. Return valid moves
2. Be called for any piece

First, I had to write tests for each piece going into the function to check that valid moves returned are the same as expected; then write the code to return these moves. This scenario is perfect for TDD as it meant I could write the test for a specific piece, write the code for that piece or type of piece, and then write the next test. To do this, I first tried to test the piece with the most precise movement, e.g. the knight (See Appendix H: Figure 35). Then once I had gotten that bit working, I would write code for sliding pieces, e.g. bishops, queens, rooks, and then finally, pawns due to their more complex movement rules. After this, it would just be 'special' moves such as promotions, castling, en-passant, checks, pins, e.t.c. As you can see from the small increments of functionality, this scenario is a perfect example of where TDD can benefit development.

Future Work

There is much potential future work for this project in most aspects of it due to the lack of code I managed to get done in all areas—for example, testing, the GUI, and the engine itself. If I had more time, I would try to get the GUI as interactive as possible with the possibility of moving pieces, fixing up the engine's code to search, and finally the evaluate function to display the results of the best move to the user. The main noteworthy future work that would provide significant advantages to the project would be using CI/CD pipelines with the automated tests I created, which I will go into below.

Testing could have been taken a lot further while also considering aspects of CI. For example, all unit tests could have been set up on Github actions, so all tests are automatically run against the code for every commit. This would be tremendously valuable as it would allow us to see the commit and the developer working on that commit (Blame) that caused an error or threw up a failed test. Isolating the complete source of any faults makes them a lot simpler to fix, creating a faster mean time to resolve problems. As well to this fault isolation, the use of this CI in-turn gives the following advantages:

- Faster Mean Time to Resolution

  This fault isolation makes finding resolutions easier due to all the fault details provided to you by the test results, including even the developer responsible, as mentioned previously.

- Higher Code Reliability

  Using CI in this way would drastically increase the code's reliability, as only smaller code chunks are implemented at a time. In addition, fixing specific issues or adding functionality means more accurate positive/negative test results can be acquired.

- Faster Development

As code now has fewer faults and is more reliable due to the points made previously, it means faster release dates can be met.

- Customer/User Satisfaction

  CI/CD brings advantages to the business in an organisation's scope as it ultimately brings better solutions for customers to use. If the customer is happy, then the business is as happy customers means you retain them for future business and spread due to word-of-mouth from your satisfied clients bringing you new customers.

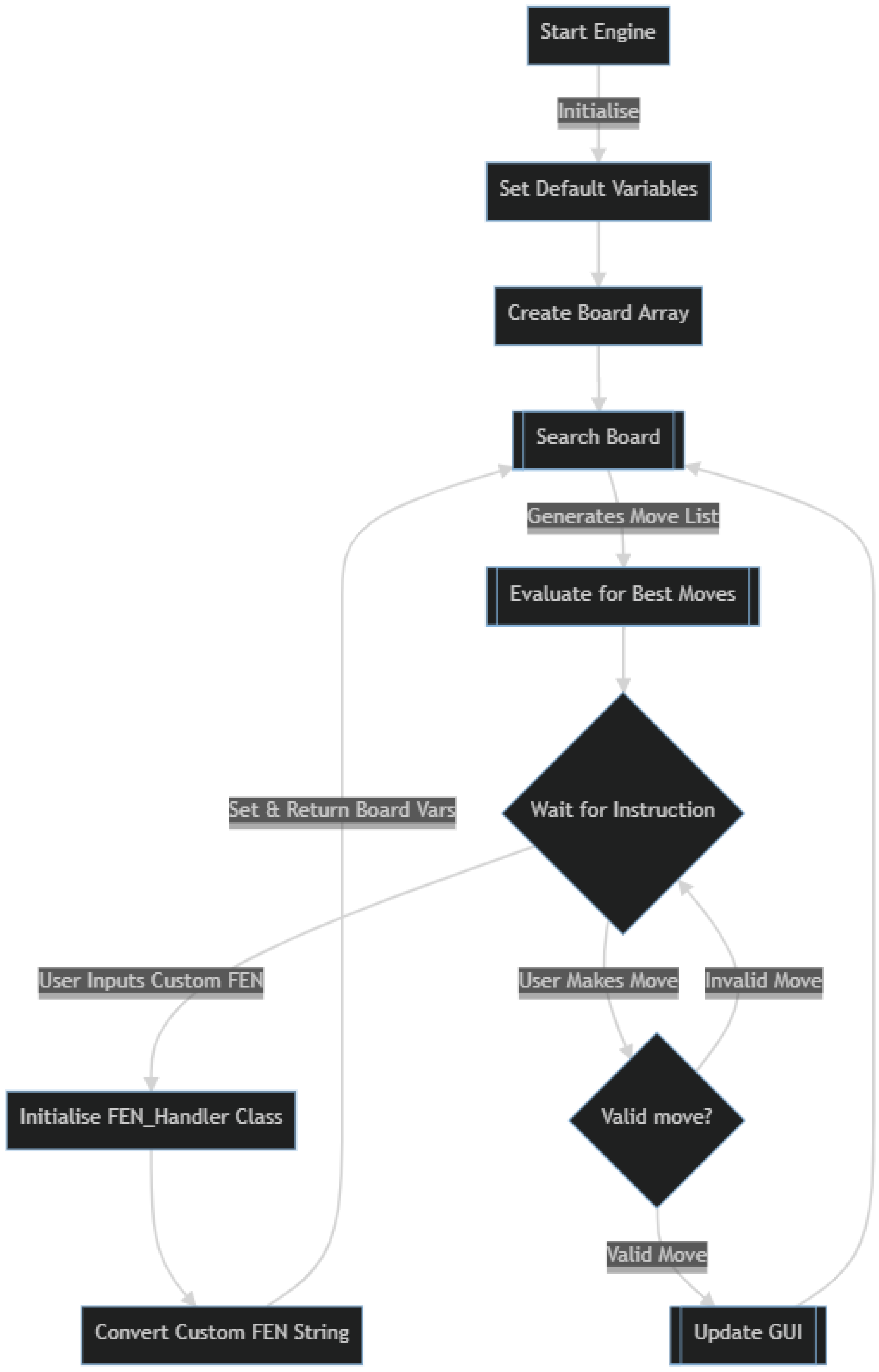
- Reduces Costs

  Ultimately reducing mean time to resolution and code reliability will bring down the business's costs. This is because someone has to fix these faults taking time and, therefore, money. Using the CI/CD pipeline for this project would mean less time is spent on making any changes due to faults/bugs appearing in the code. (Top 10 Benefits of Continuous Integration & Continuous Delivery, 2022)

Appendix

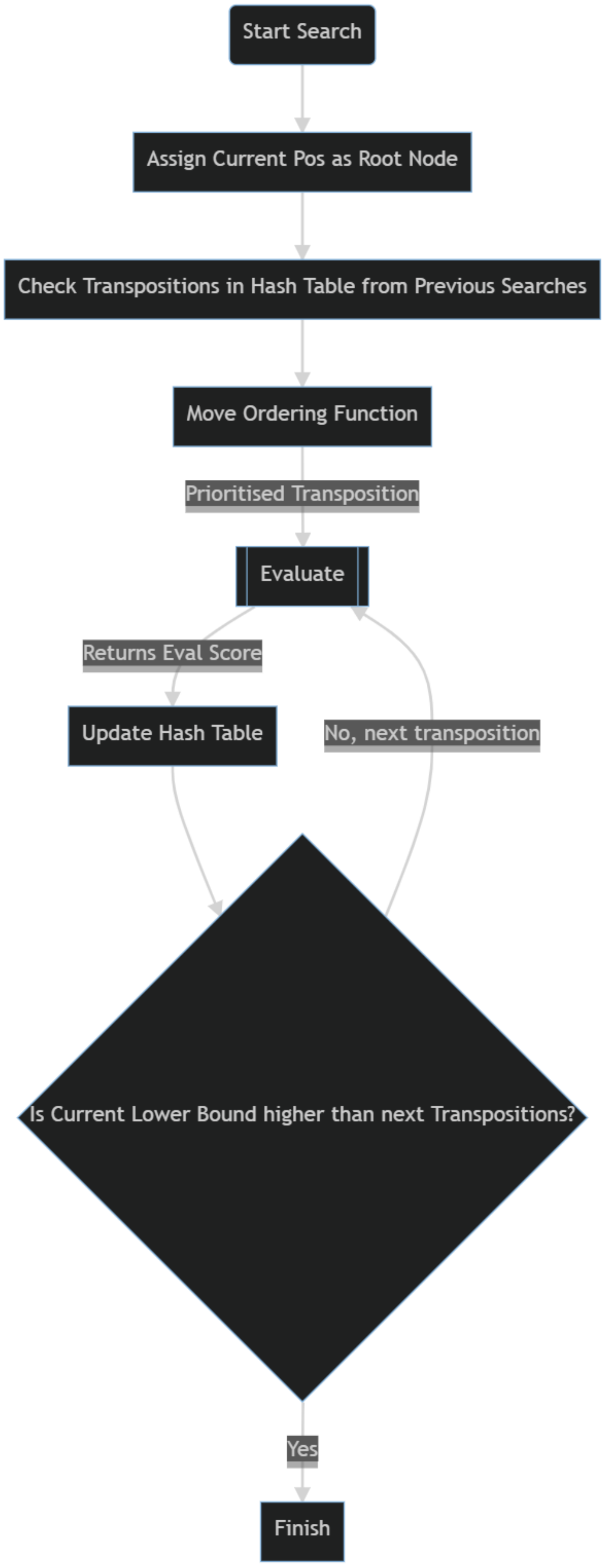
Appendix A: Engine Framework Flowchart

Figure 28: Chess Engine Program Flowchart



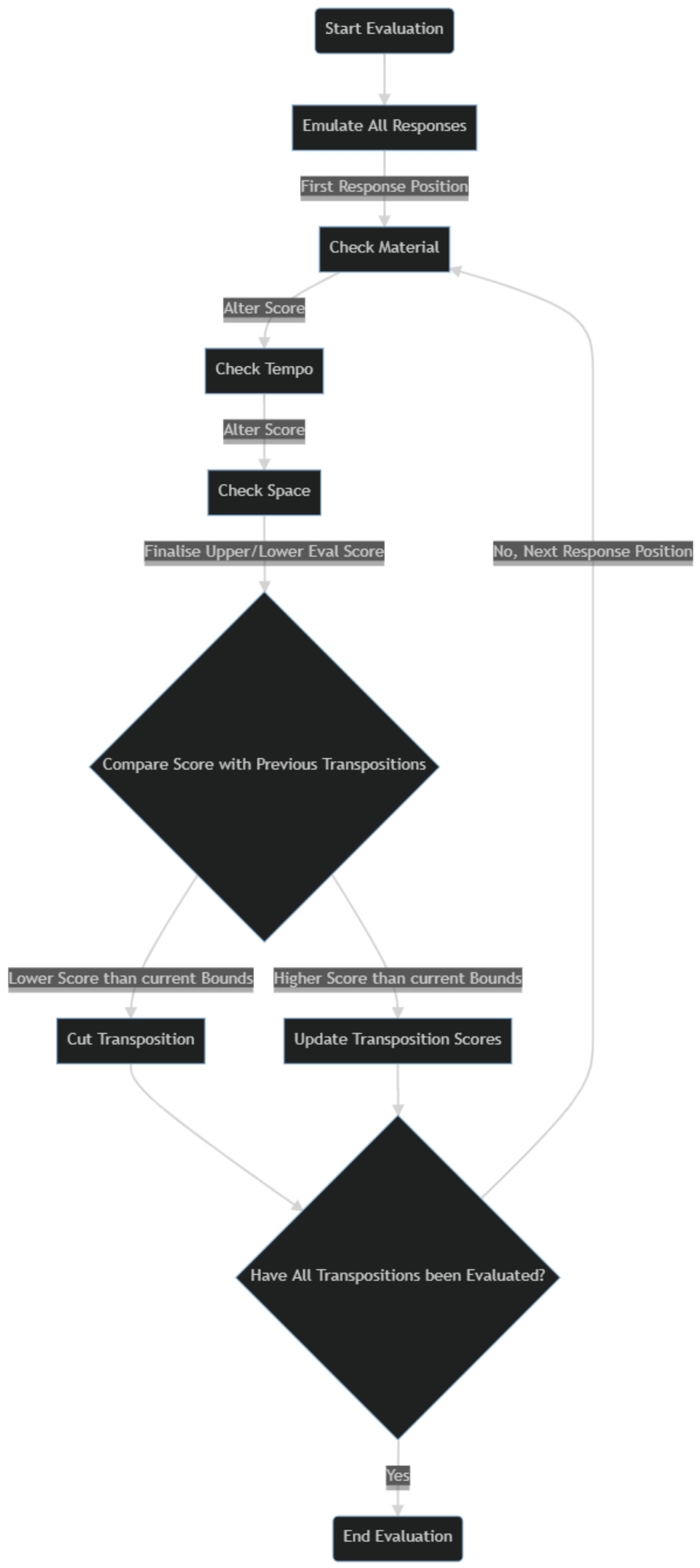
Appendix B: Engine Search Algorithm Flowchart

Figure 29: Chess Engine Search Board Function Flowchart


Start Search
Assign Current Pos as Root Node
Check Transpositions in Hash Table from Previous Searches
Move Ordering Function
Prioritised Transposition
Evaluate
Returns Eval Score
Update Hash Table
No, next transposition
Is Current Lower Bound higher than next Transpositions?
Yes
Finish

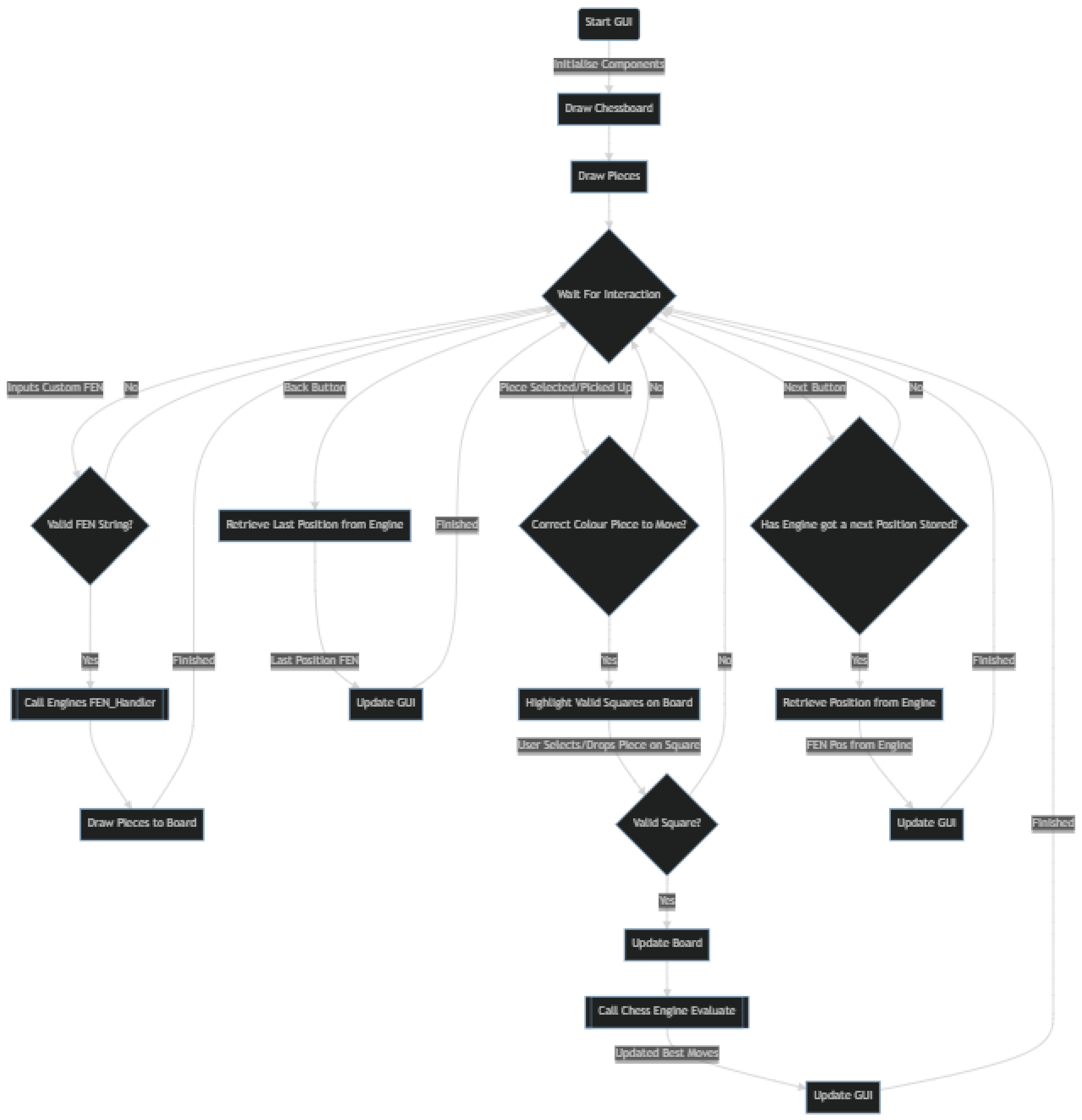
Appendix C: Engine Evaluate Algorithm Flowchart

Figure 30: Evaluate function Flowchart


Start Evaluation
Emulate All Responses
First Response Position
Check Material
Alter Score
Check Tempo
Alter Score
Check Space
Finalise Upper/Lower Eval Score
No, Next Response Position
Compare Score with Previous Transpositions
Lower Score than current Bounds
Higher Score than current Bounds
Cut Transposition
Update Transposition Scores
Have All Transpositions been Evaluated?
Yes
End Evaluation

Appendix D: Graphical User Interface Project Flowchart

Figure 31: Project GUI Flowchart

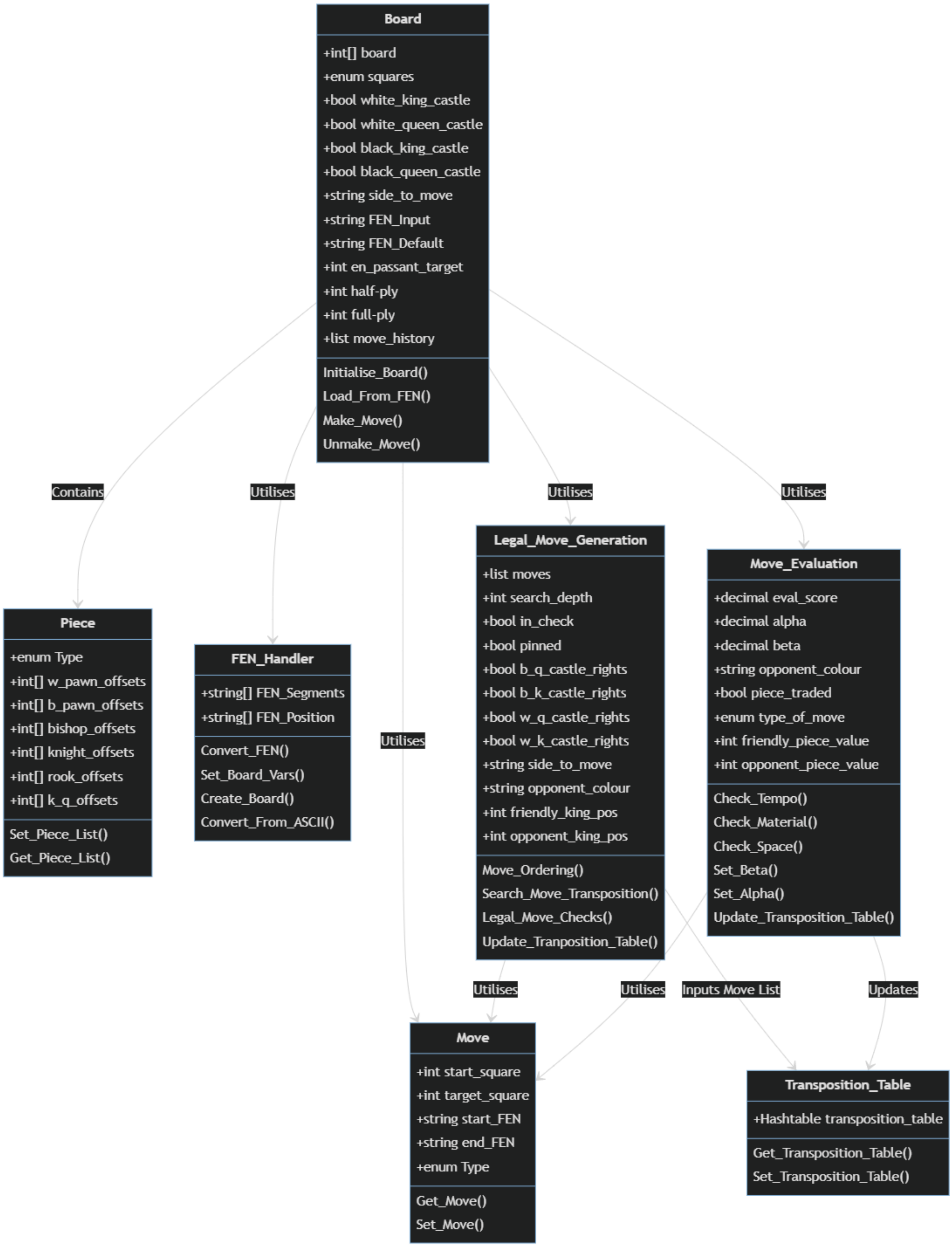


Mermaid Code to view properly:

```
graph TD
    A(Start GUI) -->|Initialise Components| B[Draw Chessboard]
    B --> C[Draw Pieces]
    C --> D{Wait For Interaction}
    D -->|Inputs Custom FEN| E{Valid FEN String?}
    E -->|Yes| F[[Call Engines FEN_Handler]]
    F --> G[Draw Pieces to Board]
    G -->|Finished| D
    E -->|No| D
    D -->|Piece Selected/Picked Up| H{Correct Colour Piece to Move?}
    H -->|No| D
    H -->|Yes| I[Highlight Valid Squares on Board]
    I -->|User Selects/Drops Piece on Square| J{Valid Square?}
    J -->|Yes| K[Update Board]
    K --> L[[Call Chess Engine Evaluate]]
    L -->|Updated Best Moves| M[Update GUI]
    M -->|Finished| D
    J -->|No| D
    D -->|Back Button| N[Retrieve Last Position from Engine]
    N -->|Last Position FEN| O[Update GUI]
    O -->|Finished| D
    D -->|Next Button| P{Has Engine got a next Position Stored?}
    P -->|No| D
    P -->|Yes| Q[Retrieve Position from Engine]
    Q -->|FEN Pos from Engine| R[Update GUI]
    R -->|Finished| D
```

Appendix E: Engine Class Diagram

Figure 32: Engine's Class Diagram



Appendix F: Custom Text to Board Converter

Figure 33: Code block for the function

```
public int[] Convert_From_ASCII(string ASCII_Board)
        {
            // init vars
            int x = 21;
            string[] ranks = ASCII_Board.Split('\n');           // split into
ranks
            // convert to board
            foreach (string rank in ranks)
            {
                foreach (char piece in rank)
                {
                    switch (piece)
                    {
                        case '^':
                            board[x] = (int)Piece.Type.empty;
                            break;
                        case '♙':
                            board[x] = (int)Piece.Type.w_pawn;
                            break;
                        case '♟':
                            board[x] = (int)Piece.Type.b_pawn;
                            break;
                        case '♘':
                            board[x] = (int)Piece.Type.w_knight;
                            break;
                        case '♞':
                            board[x] = (int)Piece.Type.b_knight;
                            break;
                        case '♗':
                            board[x] = (int)Piece.Type.w_bishop;
                            break;
                        case '♝':
                            board[x] = (int)Piece.Type.b_bishop;
                            break;
                        case '♖':
                            board[x] = (int)Piece.Type.w_rook;
                            break;
                        case '♜':
                            board[x] = (int)Piece.Type.b_rook;
                            break;
                        case '♕':
                            board[x] = (int)Piece.Type.w_queen;
                            break;
                        case '♛':
                            board[x] = (int)Piece.Type.b_queen;
                            break;
                        case '♔':
                            board[x] = (int)Piece.Type.w_king;
                            break;
                        case '♚':
                            board[x] = (int)Piece.Type.b_king;
                            break;
                    }
                    x += 1;
                }
                x += 2;         // skip blocker pieces
            }
            return board;
        }
```

Appendix G: Example of a Unit test

Figure 34: FEN_Handler Test

```
        /// <summary>
        /// Method to test the default board position along with its attributes
        /// </summary>
        [TestMethod]
        public void FEN_Handler_Default()
        {
            // Arrange
            // Initialising Test Var's
            string board = @"♖♘♗♕♔♗♘♖
♙♙♙♙♙♙♙♙
^^^^^^^^
^^^^^^^^
^^^^^^^^
^^^^^^^^
♟♟♟♟♟♟♟♟
♜♞♝♛♚♝♞♜";
            int[] default_board = new int[120];
            int en_passant_target = 0;
            int half_ply = 0;
            int full_ply = 1;
            bool w_k_castle = true;
            bool w_q_castle = true;
            bool b_k_castle = true;
            bool b_q_castle = true;
            char side_to_move = 'w';

            // Act
            // Creating board object to test
            Board b_test = new Board();
            default_board = b_test.Convert_From_ASCII(board);

            // Assert
            Assert.IsTrue(Enumerable.SequenceEqual(b_test.board, default_board),
"Test Failed: board array is not as expected");
            Assert.IsTrue(b_test.en_passant_target == en_passant_target, "Test
Failed: En_Passant target not correct");
            Assert.IsTrue(b_test.half_ply == half_ply);
            Assert.IsTrue(b_test.full_ply == full_ply);
            Assert.IsTrue(b_test.w_k_castle == w_k_castle);
            Assert.IsTrue(b_test.w_q_castle == w_q_castle);
            Assert.IsTrue(b_test.b_k_castle == b_k_castle);
            Assert.IsTrue(b_test.b_q_castle == b_q_castle);
            Assert.IsTrue(b_test.side_to_move == side_to_move);
        }
```

Appendix H: Knight Valid Moves Function Test

Figure 35: Unit test for Get_Valid_Moves function for knight piece

```
[TestMethod]
        public void Get_Valid_Knight_Moves()
        {
            // Arrange
            List<int> move_list = new List<int>();
            Piece.Type piece;
            string board = @"^^^^^^^^
                            ^^^^^♘^
                            ^^^^^^^^
                            ^^^♘^^^^
                            ^^^^^^^^
                            ^^^^^^^^
                            ^^^^^^^^
                            ^^^^^^^^"; // d5
            b = new Board();
            b.Convert_From_ASCII(board);
            // square got when user clicks board
            piece = b.Get_Piece_From_Square("a7");

            // Act
            move_list = b.Get_Valid_Moves(piece, "d5");

            // Assert
            Assert.IsTrue(move_list.Count == 7, "Test Failed: Returned more than
expected move count");
            foreach (int move in move_list)
                Assert.IsTrue(move == (int)Enum.Parse(typeof(Board.Square), "f6")
                    || move == (int)Enum.Parse(typeof(Board.Square), "f4")
                    || move == (int)Enum.Parse(typeof(Board.Square), "e3")
                    || move == (int)Enum.Parse(typeof(Board.Square), "c3")
                    || move == (int)Enum.Parse(typeof(Board.Square), "b4")
                    || move == (int)Enum.Parse(typeof(Board.Square), "b6")
                    || move == (int)Enum.Parse(typeof(Board.Square), "c7")
                    , "Test Failed: Unexpected move returned");
        }
```

Figure 36: Square enum

```
public enum Square
        {
            a8 = 21,
            a7 = 31,
            a6 = 41,
            a5 = 51,
            a4 = 61,
            a3 = 71,
            a2 = 81,
            a1 = 91,
            b8 = 22,
            b7 = 32,
            b6 = 42,
            b5 = 52,
            b4 = 62,
            b3 = 72,
            b2 = 82,
            b1 = 92,
            c8 = 23,
            c7 = 33,
            c6 = 43,
            c5 = 53,
            c4 = 63,
            c3 = 73,
            c2 = 83,
            c1 = 93,
            d8 = 24,
            d7 = 34,
            d6 = 44,
            d5 = 54,
            d4 = 64,
            d3 = 74,
            d2 = 84,
            d1 = 94,
            e8 = 25,
            e7 = 35,
            e6 = 45,
            e5 = 55,
            e4 = 65,
            e3 = 75,
            e2 = 85,
            e1 = 95,
            f8 = 26,
            f7 = 36,
            f6 = 46,
            f5 = 56,
            f4 = 66,
            f3 = 76,
            f2 = 86,
            f1 = 96,
            g8 = 27,
            g7 = 37,
            g6 = 47,
            g5 = 57,
            g4 = 67,
            g3 = 77,
            g2 = 87,
            g1 = 97,
            h8 = 28,
            h7 = 38,
            h6 = 48,
            h5 = 58,
            h4 = 68,
            h3 = 78,
            h2 = 88,
            h1 = 98
        }
```

Glossary

Key:

Word - Meaning

Iterative deepening - A search technique which takes advantage of both the completeness of breadth-first searches and the memory efficiency of depth-first search. It works similar to DFS but instead of exploring a brannch all the way out first it assesses its child nodes from left to right first to see if a solution can be found earlier.

Aspiration Window - Essentially applies a tighter window around the upper and lower bounds of an evaluation meaning more cut-offs are achieved, also meaning search time is reduced. The main drawback to this is if the true score is outside of the window then another search must be done with slightly expanded window. Typical window sizes are 1/2 pawn piece value.

Retrograde Analysis - A technique used within chess engines used to determine what moves were played to get to a certain position, analysing a chess position backwards essentially.

Transposition - A transposition is essentially two or more variations of moves, that may or may not be equal in number of moves, that end up in the same position.

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I would also like to extend my sincere thanks to Chess Programming Wiki for which this project would not have been possible without.

References

Champion, A., 2022. Dissecting Stockfish Part 1: In-Depth look at a chess engine. [online] Medium. Available at: https://towardsdatascience.com/dissecting-stockfish-part-1-in-depth-look-at-a-chess-engine-7fddd1d83579#:~:text=Stockfish is actually performing the,blocking pieces or discovered checks. [Accessed 29 April 2022].

Champion, A., 2022. Dissecting Stockfish Part 2: In-Depth look at a chess engine. [online] Medium. Available at: https://towardsdatascience.com/dissecting-stockfish-part-2-in-depth-look-at-a-chess-engine-2643cdc35c9a [Accessed 29 April 2022].

Chess.com. 2022. Chess Engine | Top 10 Engines In The World. [online] Available at: https://www.chess.com/terms/chess-engine [Accessed 11 February 2022]. (the_real_greco), A., 2022. Understanding AlphaZero: A Basic Chess Neural Network. [online]

Chess.com. Available at: https://www.chess.com/blog/the_real_greco/understanding-alphazero-a-basic-chess-neural-network#:~:text=This just means that a,be used in an engine. [Accessed 11 February 2022].

Chessprogramming.org. 2022. Alpha-Beta - Chessprogramming wiki. [online] Available at: https://www.chessprogramming.org/Alpha-Beta [Accessed 17 May 2022].

Chessprogramming.org. 2022. Evaluation - Chessprogramming wiki. [online] Available at: https://www.chessprogramming.org/Evaluation [Accessed 18 May 2022].

Chessprogramming.org. 2022. Endgame Tablebases - Chessprogramming wiki. [online] Available at: https://www.chessprogramming.org/Endgame_Tablebases [Accessed 17 May 2022].

Chessprogramming.org. 2022. Iterative Deepening - Chessprogramming wiki. [online] Available at: https://www.chessprogramming.org/Iterative_Deepening [Accessed 17 May 2022].

Chessprogramming.org. 2022. Languages - Chessprogramming wiki. [online] Available at: https://www.chessprogramming.org/Languages#:~:text=Chess programming is dominated by,bugs in the Delphi compiler. [Accessed 14 February 2022].

Chessprogramming.org. 2022. Piece-Square Tables - Chessprogramming wiki. [online] Available at: https://www.chessprogramming.org/Piece-Square_Tables [Accessed 18 May 2022].

Chessprogramming.org. 2022. Search - Chessprogramming wiki. [online] Available at: https://www.chessprogramming.org/Search#The_Search_Tree [Accessed 17 May 2022].

Chessprogramming.org. 2022. Search Tree - Chessprogramming wiki. [online] Available at: https://www.chessprogramming.org/Search_Tree [Accessed 17 May 2022].

Chessprogramming.org. 2022. Transposition Table - Chessprogramming wiki. [online] Available at: https://www.chessprogramming.org/Transposition_Table [Accessed 18 May 2022].

Chessprogramming.org. 2022. Type B Strategy - Chessprogramming wiki. [online] Available at: https://www.chessprogramming.org/Type_B_Strategy [Accessed 11 February 2022].

Chessprogramming.org. 2022. 10x12 Board - Chessprogramming wiki. [online] Available at: https://www.chessprogramming.org/10x12_Board [Accessed 21 March 2022].

En.wikipedia.org. 2022. Forsyth–Edwards Notation - Wikipedia. [online] Available at: https://en.wikipedia.org/wiki/Forsyth–Edwards_Notation [Accessed 6 March 2022].

Hamilton, T., 2022. What is Test Driven Development (TDD)? Tutorial with Example. [online] Guru99. Available at: https://www.guru99.com/test-driven-development.html [Accessed 16 May 2022].

Hercules, A., 2022. How Does A Chess Engine Work? A Guide To How Computers Play Chess - Hercules Chess. [online] Hercules Chess. Available at: https://herculeschess.com/how-does-a-chess-engine-work/#:~:text=So how does a chess,with no graphics or windowing. [Accessed 14 February 2022].

Historyofinformation.com. 2022. Alex Bernstein & Colleagues Program an IBM 704 Computer to Defeat an Inexperienced Human Opponent : History of Information. [online] Available at: https://www.historyofinformation.com/detail.php?id=5508 [Accessed 11 February 2022].

Katalon.com. 2022. Top 10 Benefits of Continuous Integration & Continuous Delivery. [online] Available at: https://katalon.com/resources-center/blog/benefits-continuous-integration-delivery [Accessed 20 May 2022].

Keiter, H., 2015. Alternatives to the FEN notation. [online] Chess Stack Exchange. Available at: https://chess.stackexchange.com/questions/8500/alternatives-to-the-fen-notation [Accessed 18 May 2022].

Lynn, E., 2021. What is the difference between statically typed and dynamically typed languages?. [online] Stack Overflow. Available at: https://stackoverflow.com/questions/1517582/what-is-the-difference-between-statically-typed-and-dynamically-typed-languages#:~:text=Statically typed languages%3A each variable,already known at compile time.&text=Dynamically typed languages%3A variables can,is defined at run time. [Accessed 19 May 2022].

Novoseltseva, E., 2020. Top 7 benefits you get by using Github | Apiumhub. [online] Apiumhub. Available at: https://apiumhub.com/tech-blog-barcelona/using-github/ [Accessed 17 May 2022].

PerformanceLab, 2022. [online] Available at: https://performancelabus.com/unit-testing-importance/ [Accessed 22 May 2022].

(Pete), P., 2022. AlphaZero Crushes Stockfish In New 1,000-Game Match. [online] Chess.com. Available at: https://www.chess.com/news/view/updated-alphazero-crushes-stockfish-in-new-1-000-game-match#games [Accessed 29 April 2022].

Saba, S., 2015. 9 Anti-Patterns Every Programmer Should Be Aware Of. [online] Sahandsaba.com. Available at: https://sahandsaba.com/nine-anti-patterns-every-programmer-should-be-aware-of-with-examples.html [Accessed 19 May 2022].

Svirca, Z., 2019. Everything you need to know about MVC architecture. [online] Medium. Available at: https://towardsdatascience.com/everything-you-need-to-know-about-mvc-architecture-3c827930b4c1 [Accessed 15 May 2022].

TutorialsPoint, 2022. MVC Framework - Introduction. [online] Tutorialspoint.com. Available at: https://www.tutorialspoint.com/mvc_framework/mvc_framework_introduction.htm [Accessed 15 May 2022].