

Yolah Board Game

Building a Two-Player Perfect-Information Game with AI
Players

Pascal Garcia

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MrCoder

C'est en forgeant qu'on devient
forgeron

À Sarah, Hugo et Célya ❤️

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Chapter 1

Introduction

1.1 The Yolah Game

I created the Yolah game to illustrate effective techniques for implementing board games and artificial intelligences for my students. I was inspired by the Pingouins game, whose box you can see in Figure 1.1 (I highly recommend it ☺)



Figure 1.1: The Pingouins game box

Important

I have done my best with my current knowledge (*ars longa, vita brevis*) to implement my game and the associated AIs. But like any good scientist, you should look at my work with a critical eye. I wrote the book in French (easier for me) and asked an AI assistant (Claude [1]) to translate it for me.

I will now describe the rules of the game, then I will explain why I chose these rules, I will give an example of a game between two AIs and then I will present the rest of the book.

1.1.1 Game Rules

The Yolah game board is shown in Figure 1.2. You can see four black pieces and four white pieces placed symmetrically. Black starts by choosing one of their four

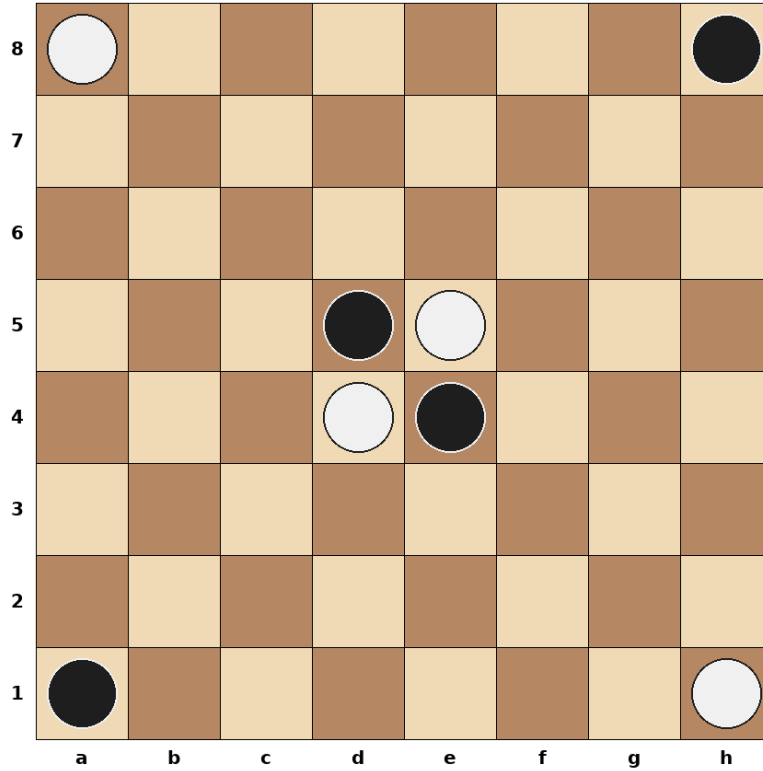


Figure 1.2: The initial configuration of the Yolah game

pieces. A piece can never disappear from the board because Yolah is a game without captures. A piece moves in all eight directions as far as it wishes as long as it is not blocked by another piece or a hole (a concept we will soon discuss). For example, if black chooses to move their piece located at d5, the squares where it can land are indicated by small black crosses in Figure 1.3.

Now, if the black piece at d5 moves to b7, which we will denote as d5:b7, we get the configuration shown in Figure 1.4. Notice that the starting square of the black piece disappears and becomes a hole! This square (this hole) becomes inaccessible and impassable for the rest of the game! This will create opportunities to block the opponent and try to create areas where the opponent cannot go.

A move earns one point for the player who just moved. For example, in the configuration of Figure 1.4, the black player has one point and the white player who has not yet moved has zero points. The goal of the game is quite simple to summarize: you must move longer than your opponent!

Now it is white's turn to play. They must decide which white piece they will move. Suppose it is the piece at e5. The possible moves for this white piece are shown in Figure 1.5. If white decides to make the move e5:f5, we end up in the configuration of Figure 1.6 and the score is one point each (each player has played one move).

To summarize, the rules of Yolah are as follows:

- The game is a two-player game (black and white) played in turns.

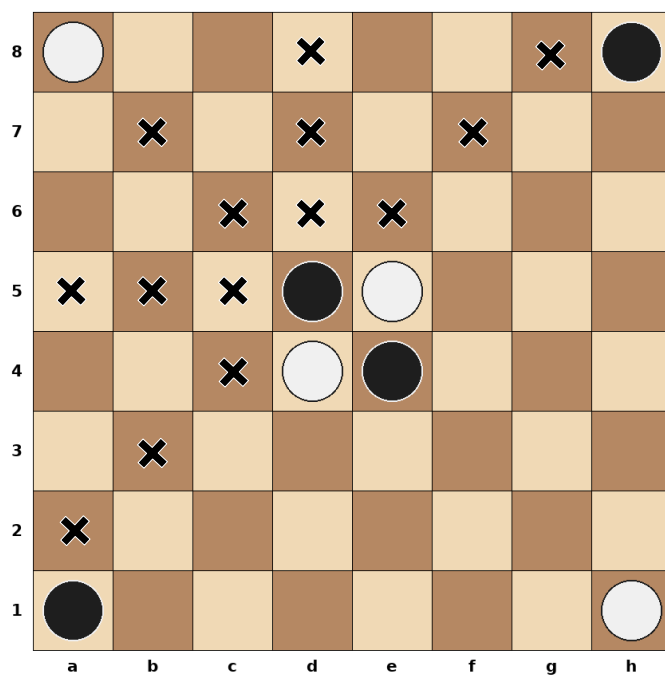


Figure 1.3: Possible moves (small black crosses) for the black piece located on square d5

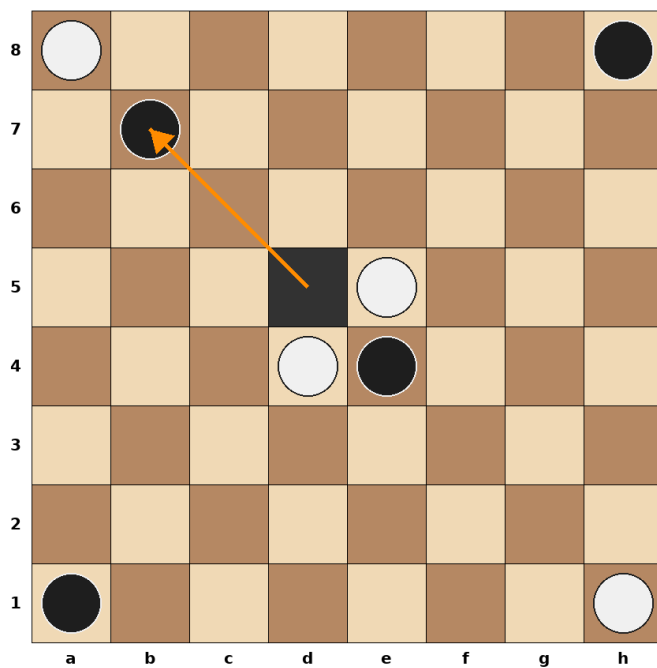


Figure 1.4: Black just moved from d5 to b7. The starting square d5 becomes inaccessible and impassable for the rest of the game

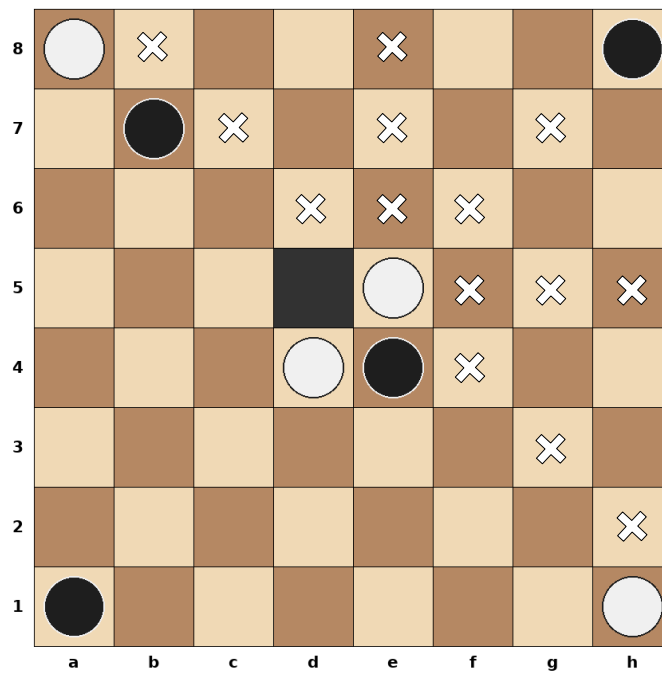


Figure 1.5: Possible moves (small white crosses) for the white piece located on square e5

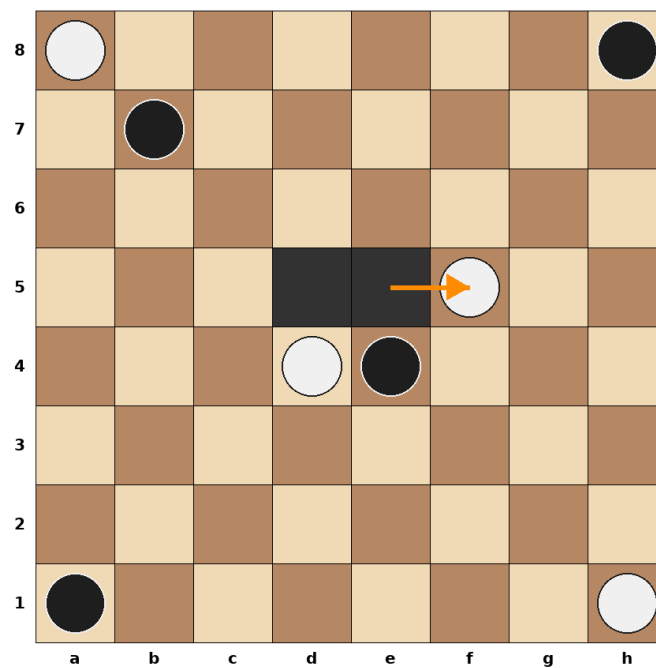


Figure 1.6: White just moved from e5 to f5. The starting square e5 becomes inaccessible and impassable for the rest of the game. The score is one point each (each player has moved once)

- Each player has four pieces.
- On their turn, the player chooses one of the pieces that can still move; if no piece can move, they pass their turn (we will denote by the move `a1:a1` to skip one's turn).
- They must move the chosen piece in one of the eight directions, as many squares as desired, but must not land on or be blocked by a piece or a hole.
- After moving the chosen piece, the starting square of the move becomes a hole and can no longer be crossed or landed on.
- After each move, the player earns one point.
- The game ends when both players can no longer move.
- The player with the most points wins the game.
- If both players have the same number of points, the game is declared a draw.

1.1.2 Interesting Characteristics of Yolah for Developing AIs

I chose the above rules for Yolah, on the one hand because I liked the dynamics of the Penguin game, but also because there are no cycles in the game, so there is no need for special rules to prevent a game from never ending. The number of moves available to each player is quite large at the beginning (but reasonable)¹, but it will decrease little by little with the appearance of holes². This allows the AIs to look ahead a fairly large number of moves.

I also wanted to be able to reuse concepts used for the efficient implementation of chess, and the size of the board and the movement of the pieces (same way of moving as a Queen in chess) allow me to do that.

1.1.3 Game Example

To get an idea of how a Yolah game unfolds, we will have two artificial intelligences play against each other. The first AI will be based on Monte Carlo Tree Search and the second will be based on Minimax with a neural network. We will study both of these AIs later in the book. The second AI is stronger and you will see its zone isolation strategy in action!

The progression of the game is described in Figures 1.7, 1.8 and 1.9.

The white AI estimates that it is winning starting from move 10 (see Figure 1.7k). We can see at move 30 (see Figure 1.8k) that it has successfully isolated a zone where black can no longer access. At move 32 (see Figure 1.8m) it moves one of its pieces out of the isolated zone because the other piece will be able to collect all the points from

¹56 possible moves for the black player at the start of the game.

²The number of possible moves does not necessarily decrease after each move; there are configurations where the player has more than 56 available moves.

that zone. It is more useful to use the other piece to gather points elsewhere. Note that starting from move 47 (see Figure 1.9h onward), black has no more available moves and must therefore pass their turn.

The game is won by the white player 32 to 24, which is a very good score because the Yolah game seems to favor black.

1.1.4 What's Next

In the next chapter, we will study the implementation of the Yolah game in [2]. This implementation is designed to be efficient because it will be important for the AIs to be able to play many games per second; their level of play will depend on it.

Chapter 3 describes the common interface for our different AIs. Chapter 4 presents a very simple AI based on Monte Carlo search. The next AI, described in Chapter ??, is an evolution of the previous one and will allow, unlike the Monte Carlo AI, the development of a game tree. Note that these two AIs will not require heuristics provided by humans and only need the rules of the game. Chapter 6 presents an AI based on minimax tree search with heuristics provided by humans. The heuristic used by the AI is a linear combination of the heuristics provided by humans; the weights of each heuristic in this linear combination are learned using a genetic algorithm. Our last and strongest AI is presented in Chapter 7. A neural network is used instead of heuristics. This neural network is trained on a set of games played by the previous AI.

Chapter 8 then evaluates all these AIs by having them compete in a tournament. We will then conclude and propose different directions for creating other artificial players.

Happy reading!

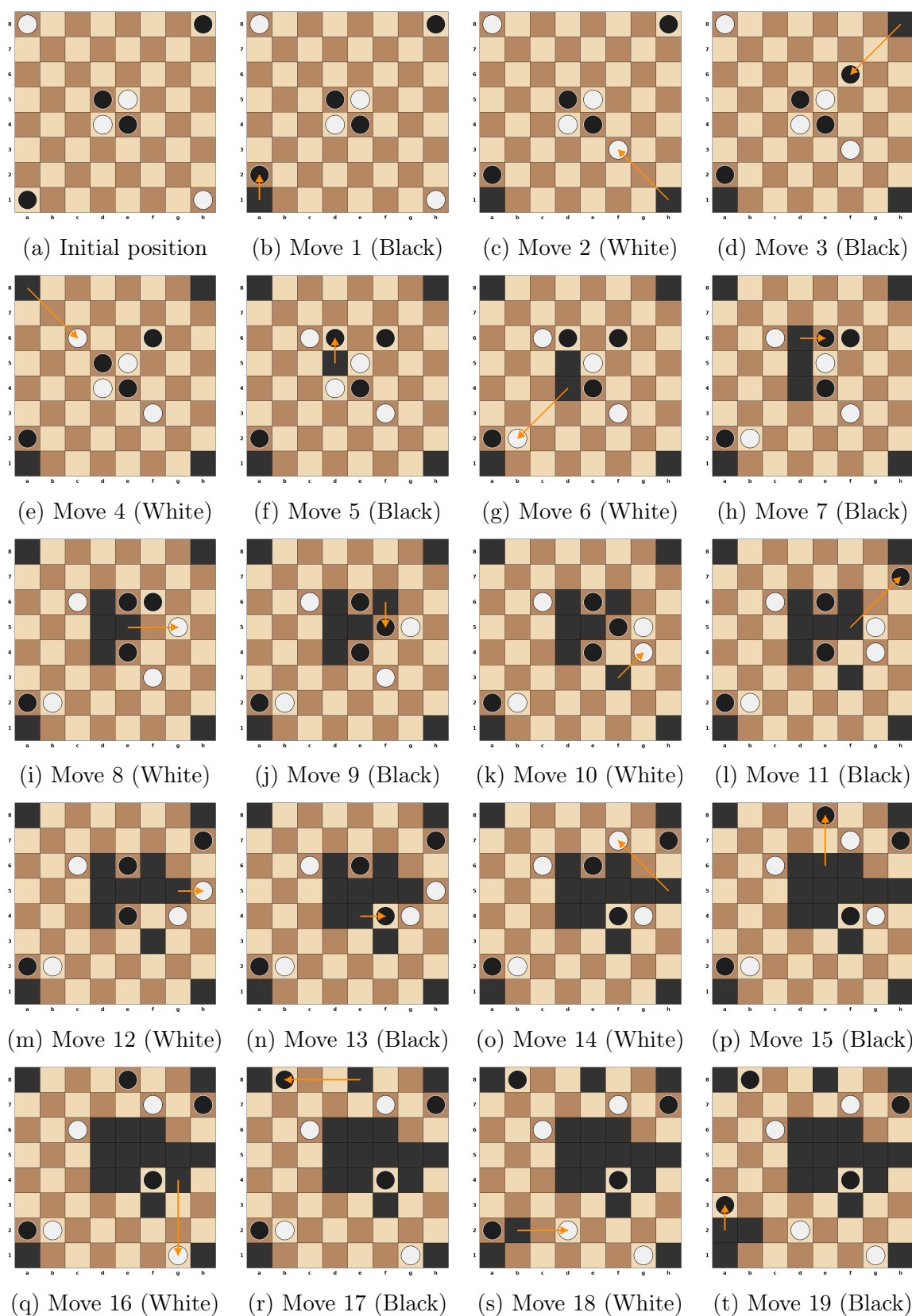


Figure 1.7: Game example between two AIs - moves 1 to 19

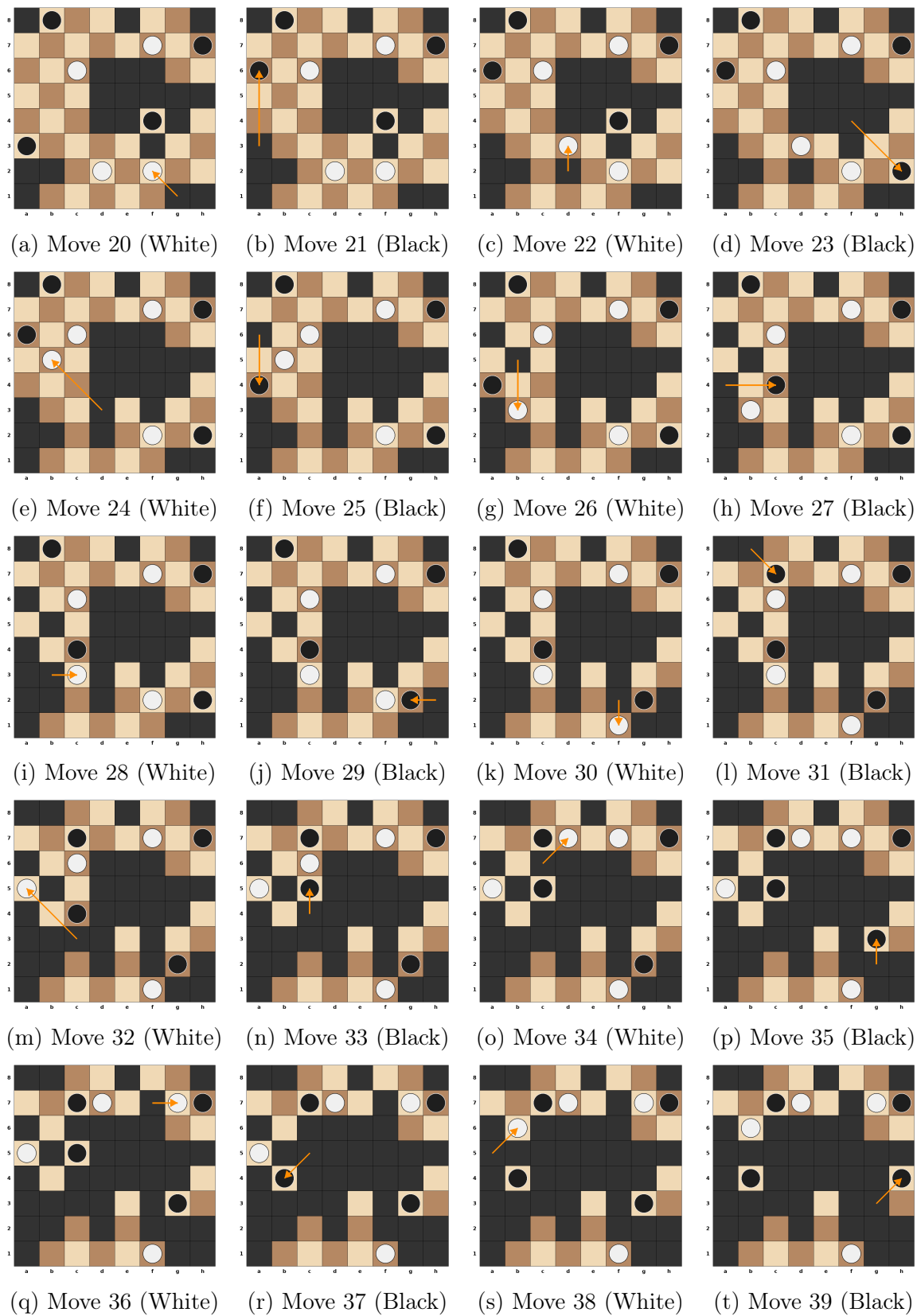


Figure 1.8: Game example between two AIs - moves 20 to 39

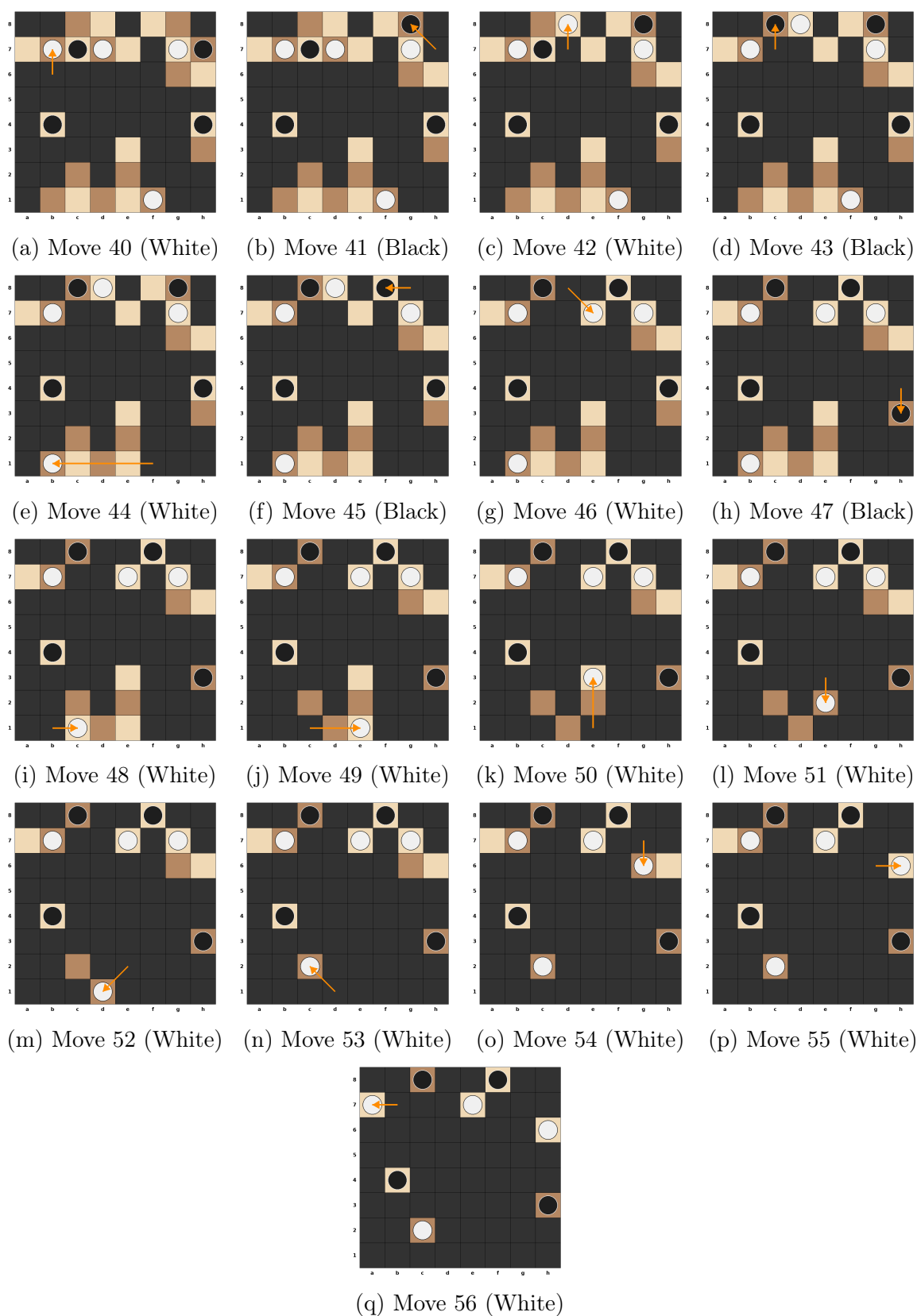


Figure 1.9: Game example between two AIs - moves 40 to 56. White wins 32 to 24

Chapter 2

Game Engine

Nous allons implémenter la gestion du jeu en C++ en essayant de créer une implémentation efficace pour pouvoir réaliser un maximum de parties à la seconde, ce qui sera important pour obtenir des IA de bons niveaux. Nous testerons notre implémentation en générant un maximum de parties aléatoires en un temps donné à la fin de ce chapitre.

2.1 Structure de données

Nous allons représenter la position des noirs, des blancs et des cases détruites par des entiers non signés sur 64 bits : `uint64_t`. Nous appellerons bitboard ces entiers. Nous prenons des `uint64_t` car le plateau de Yolah contient 64 cases, nous avons donc un bit par case. La table 2.1 donne la position de chaque cases du plateau dans le bitboard. Cette information est représentée dans le code par l'énumération du listing 1 ¹.

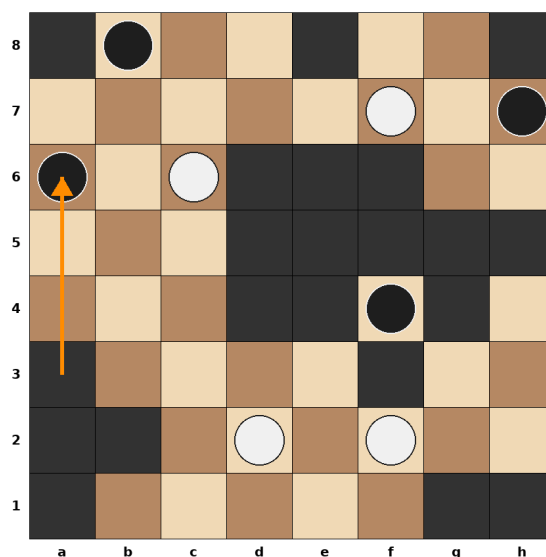
Table 2.1: Positions de chaque cases du plateau dans le bitboard

8	bit ₅₆	bit ₅₇	bit ₅₈	bit ₅₉	bit ₆₀	bit ₆₁	bit ₆₂	bit ₆₃
7	bit ₄₈	bit ₄₉	bit ₅₀	bit ₅₁	bit ₅₂	bit ₅₃	bit ₅₄	bit ₅₅
6	bit ₄₀	bit ₄₁	bit ₄₂	bit ₄₃	bit ₄₄	bit ₄₅	bit ₄₆	bit ₄₇
5	bit ₃₂	bit ₃₃	bit ₃₄	bit ₃₅	bit ₃₆	bit ₃₇	bit ₃₈	bit ₃₉
4	bit ₂₄	bit ₂₅	bit ₂₆	bit ₂₇	bit ₂₈	bit ₂₉	bit ₃₀	bit ₃₁
3	bit ₁₆	bit ₁₇	bit ₁₈	bit ₁₉	bit ₂₀	bit ₂₁	bit ₂₂	bit ₂₃
2	bit ₈	bit ₉	bit ₁₀	bit ₁₁	bit ₁₂	bit ₁₃	bit ₁₄	bit ₁₅
1	bit ₀	bit ₁	bit ₂	bit ₃	bit ₄	bit ₅	bit ₆	bit ₇
	a	b	c	d	e	f	g	h

```

1  enum Square : int8_t {
2      SQ_A1, SQ_B1, SQ_C1, SQ_D1, SQ_E1, SQ_F1, SQ_G1, SQ_H1,
3      SQ_A2, SQ_B2, SQ_C2, SQ_D2, SQ_E2, SQ_F2, SQ_G2, SQ_H2,
```

¹Par défaut, l'énumération commence à la valeur 0, donc `SQ_A1` vaut 0, `SQ_A1` vaut 1, ...



- Les positions des pièces noires sur le plateau (table 2.2) sont représentées par le bitboard : `0b000000101000000000000010000000001000000000000000000000000000`.
- Les positions des pièces blanches sur le plateau (table 2.3) sont représentées par le bitboard : `0b0000000000100000000010000000000000000000000001010000000000`.
- Les positions des trous (table 2.4) sont représentées par le bitboard :
`0b1001000100000000001110001111100001011000001000010000001111000001`.

Table 2.2: Positions des pièces noires

8	.	•	.	.	.	.	.	.
7	.	.	.	.	.	.	.	•
6	•	.	.	.	.	.	.	.
5	.	.	.	.	.	.	.	.
4	.	.	.	.	.	•	.	.
3	.	.	.	.	.	.	.	.
2	.	.	.	.	.	.	.	.
1	.	.	.	.	.	.	.	.
	a	b	c	d	e	f	g	h

Table 2.3: Positions des pièces blanches

8	.	.	.	.	.	.	.	.
7	.	.	.	.	.	○	.	.
6	.	.	○	.	.	.	.	.
5	.	.	.	.	.	.	.	.
4	.	.	.	.	.	.	.	.
3	.	.	.	.	.	.	.	.
2	.	.	.	○	.	○	.	.
1	.	.	.	.	.	.	.	.
	a	b	c	d	e	f	g	h

Table 2.4: Positions des cases détruites (les trous)

8	×	.	.	.	×	.	.	×
7	.	.	.	.	.	.	.	.
6	.	.	.	×	×	×	.	.
5	.	.	.	×	×	×	×	×
4	.	.	.	×	×	.	×	.
3	×	.	.	.	.	×	.	.
2	×	×	.	.	.	.	.	.
1	×	.	.	.	.	.	×	×
	a	b	c	d	e	f	g	h

Les bitboards vont nous permettre une manipulation efficace du plateau, en utilisant des opérations bits à bits, et nécessiterons peu de place mémoire pour représenter celui-ci.

Nous représentons le plateau de jeu par la classe `Yolah` dont un extrait est donné dans le listing 2.

```
1 constexpr uint64_t BLACK_INITIAL_POSITION =
2 0b10000000'00000000'00000000'00001000'00010000'00000000'00000000'00000001;
3 constexpr uint64_t WHITE_INITIAL_POSITION =
4 0b00000001'00000000'00000000'00010000'00001000'00000000'00000000'10000000;
5 class Yolah {
6     uint64_t black = BLACK_INITIAL_POSITION;
7     uint64_t white = WHITE_INITIAL_POSITION;
8     uint64_t holes = 0;
9     uint8_t black_score = 0;
10    uint8_t white_score = 0;
11    uint8_t ply = 0;
12 public:
13     // ...
14 };
```

Listing 2: Les attributs de la classe `Yolah` représentant le plateau de jeu

Les attributs de la classe `Yolah` sont :

- Ligne 6, `black` : le bitboard pour les pièces noires.
- Ligne 7, `white` : le bitboard pour les pièces blanches.
- Ligne 8, `holes` : le bitboard pour les trous (les cases détruites).
- Ligne 9, `black_score` : le score, ou le nombre de déplacements, du joueur noir.
- Ligne 10, `white_score` : le score, ou le nombre de déplacements, du joueur blanc.
- Ligne 11, `ply` : le nombre de coups joués par les deux joueurs depuis le début de la partie.

Un objet de type `Yolah` prendra en mémoire `sizeof(Yolah) == 32` octets. Notons qu'avec le padding², il n'aurait pas été judicieux d'écrire, par exemple,

```
1 class Yolah {
2     uint64_t black = BLACK_INITIAL_POSITION;
```

²https://en.wikipedia.org/wiki/Data_structure_alignment

```

3     uint8_t black_score = 0;
4     uint64_t white = WHITE_INITIAL_POSITION;
5     uint8_t white_score = 0;
6     uint64_t holes = 0;
7     uint8_t ply = 0;
8 public:
9     // ...
10 };

```

car avec cette implémentation, nous aurions eu `sizeof(Yolah) == 48` octets.

La représentation en bitboard permet d'obtenir efficacement des informations sur le jeu. Par exemple pour voir les cases occupées par les pièces noires et les pièces blanches, il suffit d'effectuer : `black | white`. Pour les positions des tables 2.2 et 2.3, on obtiendrait en une seule opération très efficace ³ les positions des pièces noires et blanches de la table 2.5. En notation binaire, on obtient :

```

1 black | white
2 == 00000010100000000000000100000000010000000000000000000000000000 |
3    00000000001000000000010000000000000000000000000000001010000000000
4 == 0000001010100000000001010000000001000000000000001010000000000

```

Table 2.5: Positions des pièces noires et blanches que l'on obtient en faisant : `black | white`

8	.	●	.	.	.	.	.	.
7	.	.	.	.	.	○	.	●
6	●	.	○	.	.	.	.	.
5	.	.	.	.	.	.	.	.
4	.	.	.	.	.	●	.	.
3	.	.	.	.	.	.	.	.
2	.	.	.	○	.	○	.	.
1	.	.	.	.	.	.	.	.
	a	b	c	d	e	f	g	h

Nous allons continuer d'utiliser des opérations bits-à-bits dans la suite de ce chapitre, pour tester notamment la fin d'une partie et la génération des coups possibles.

³Vous pouvez trouver des informations sur la latence et le débit des instructions pour plusieurs processeurs via le lien suivant : https://agner.org/optimize/instruction_tables.pdf

2.2 Test de fin de partie

Pour tester la fin de partie nous allons avoir besoin de quelques énumérations et constantes (listings 3 et 5) et de la fonction `shift` (listing 4). La constante `NORTH` de l'énumération `Direction` (listing 3) est égale à 8. Pourquoi avoir choisi cette valeur ? Reprenons ci-dessous, voir la table 2.6, la table vu au chapitre précédent représentant la position de chaque bit d'un bitboard dans le plateau. On peut voir que si l'on ajoute 8 au numéro de bit contenu dans une des cases, on obtient le numéro de bit de la case au nord de cette dernière (sauf si l'on sort du plateau de jeu). Il en va de même pour les autres valeurs des constantes de l'énumération `Direction` (listing 3).

Table 2.6: Positions de chaque cases du plateau dans le bitboard. Remarquons que pour une case qui ne se trouve pas dans la rangée 8, bit_{i+8} est le bit correspondant à la case au nord de la case du bit_{*i*}

8	bit ₅₆	bit ₅₇	bit ₅₈	bit ₅₉	bit ₆₀	bit ₆₁	bit ₆₂	bit ₆₃
7	bit ₄₈	bit ₄₉	bit ₅₀	bit ₅₁	bit ₅₂	bit ₅₃	bit ₅₄	bit ₅₅
6	bit ₄₀	bit ₄₁	bit ₄₂	bit ₄₃	bit ₄₄	bit ₄₅	bit ₄₆	bit ₄₇
5	bit ₃₂	bit ₃₃	bit ₃₄	bit ₃₅	bit ₃₆	bit ₃₇	bit ₃₈	bit ₃₉
4	bit ₂₄	bit ₂₅	bit ₂₆	bit ₂₇	bit ₂₈	bit ₂₉	bit ₃₀	bit ₃₁
3	bit ₁₆	bit ₁₇	bit ₁₈	bit ₁₉	bit ₂₀	bit ₂₁	bit ₂₂	bit ₂₃
2	bit ₈	bit ₉	bit ₁₀	bit ₁₁	bit ₁₂	bit ₁₃	bit ₁₄	bit ₁₅
1	bit ₀	bit ₁	bit ₂	bit ₃	bit ₄	bit ₅	bit ₆	bit ₇
	a	b	c	d	e	f	g	h

```
1 enum Direction : int8_t {
2     NORTH = 8,
3     EAST  = 1,
4     SOUTH = -NORTH,
5     WEST  = -EAST,
6     NORTH_EAST = NORTH + EAST,
7     SOUTH_EAST = SOUTH + EAST,
8     SOUTH_WEST = SOUTH + WEST,
9     NORTH_WEST = NORTH + WEST
10 };
```

Listing 3: Directions

```
1 template<Direction D>
2 constexpr uint64_t shift(uint64_t b) {
3     if constexpr (D == NORTH)
4         return b << NORTH;
```

```

1 shift<NORTH>(board) | shift<SOUTH>(board) | shift<EAST>(board) |
2 shift<WEST>(board) | shift<NORTH_EAST>(board) | shift<NORTH_WEST>(board) |
3 shift<SOUTH_EAST>(board) | shift<SOUTH_WEST>(board)

```

Pour le plateau de la table 2.9 on obtient les positions représentées par des étoiles dans la table 2.10.

Table 2.9: Plateau de jeu

8	○	.	.	.	.	.	.	●
7	.	●	.	.	.	.	.	.
6	.	.	.	.	.	.	.	.
5	.	.	.	×	○	.	.	.
4	.	.	.	×	×	●	.	.
3	.	.	.	.	.	.	.	.
2	.	.	.	○	.	.	.	.
1	●	.	.	.	.	.	.	○
	a	b	c	d	e	f	g	h

Table 2.10: Positions autour des pièces

8	*	*	*	.	.	.	*	.
7	*	*	*	.	.	.	*	*
6	*	*	*	*	.	*	.	.
5	.	.	.	*	*	*	*	.
4	.	.	.	*	*	*	*	.
3	.	.	*	*	*	*	*	.
2	*	*	*	.	*	.	*	*
1	.	*	*	*	*	.	*	.
	a	b	c	d	e	f	g	h

Dans le code de la fonction `shift` (listing 4) on peut voir l'utilisation des constantes `FileHBB` et `FileABB` (BB pour bitboard). Ces constantes vont nous permettre de masquer certains bits qui se retrouveraient après décalage dans une position incorrecte. Par exemple, si nous décalons dans la direction `EAST` le bitboard représenté dans la table 2.9, le pion blanc en `h1` se retrouverait en `a2`. Pour éviter cela, avant le décalage, on élimine les éléments de la colonne `h` pour qu'ils ne se retrouvent pas dans la colonne `a` (ligne 8 du listing 4). Les constantes `FileABB` et `FileHBB` ainsi que les énumérations pour les rangées et colonnes sont définies dans le listing 5.

```

1 enum File : uint8_t {
2     FILE_A, FILE_B, FILE_C, FILE_D, FILE_E, FILE_F, FILE_G, FILE_H,
3     FILE_NB
4 };
5 enum Rank : uint8_t {
6     RANK_1, RANK_2, RANK_3, RANK_4, RANK_5, RANK_6, RANK_7, RANK_8,
7     RANK_NB
8 };
9 constexpr uint64_t FileABB = 0x0101010101010101;
10 // 0x0101010101010101
11 //== 0b00000001000000010000000100000001000000010000000100000001
12 //      a8      a7      a6      a5      a4      a3      a2      a1
13
14 constexpr uint64_t FileHBB = FileABB << 7;
15 // 0x1010101010101010

```

```

16  //== 0b10000000100000001000000010000000100000001000000010000000
17  //      h8      h7      h6      h5      h4      h3      h2      h1

```

Listing 5: Colonnes et rangées

La fonction qui teste la fin de partie s'appelle `game_over` et elle est décrite dans le listing 6. Son implémentation est assez simple,

- À la ligne 2, on récupère dans `possible` le bitboard où il y a des 1 dans les positions libres.
- Les lignes 4 à 7 permettent de créer le bitboard `around_black` qui contient des 1 aux positions autour de chacun des pièces noires.
- Les lignes 9 à 12 font de même pour les pièces blanches.
- À la ligne 14, on récupère dans le bitboard `around_players` les positions (à 1 dans le bitboard) des cases autour des deux joueurs.
- Enfin, à la ligne 16, on teste s'il n'existe aucune position libre à côté d'un des joueurs. En effet, le et bit-à-bit ne gardera un 1 dans un bit du résultat, que si et seulement s'il y a un 1 à cette position dans le bitboard `possible` et dans le bitboard `around_players`. Donc que la case correspondante est libre et accessible par le joueur. Si le résultat de `around_players & possible` vaut 0, cela veut dire qu'aucune position n'est à la fois à côté d'un des joueurs et libre.

```

1  bool Yolah::game_over() const {
2      uint64_t possible = ~holes & ~black & ~white;
3
4      uint64_t around_black = shift<NORTH>(black) | shift<SOUTH>(black) |
5          shift<EAST>(black) | shift<WEST>(black) |
6          shift<NORTH_EAST>(black) | shift<NORTH_WEST>(black) |
7          shift<SOUTH_EAST>(black) | shift<SOUTH_WEST>(black);
8
9      uint64_t around_white = shift<NORTH>(white) | shift<SOUTH>(white) |
10         shift<EAST>(white) | shift<WEST>(white) |
11         shift<NORTH_EAST>(white) | shift<NORTH_WEST>(white) |
12         shift<SOUTH_EAST>(white) | shift<SOUTH_WEST>(white);
13
14     uint64_t around_players = around_black | around_white;
15
16     return (around_players & possible) == 0;
17 }

```

Listing 6: Test de fin de partie

Maintenant que nous savons tester la fin d’une partie, nous allons étudier comment générer efficacement les coups possibles dans une position donnée.

2.3 Génération des mouvements possibles pour les pièces

2.4 Code du plateau de jeu

```
1  #ifndef TYPES_H
2  #define TYPES_H
3  #include <stdint>
4  #include <bit>
5  enum Square : int8_t {
6      SQ_A1, SQ_B1, SQ_C1, SQ_D1, SQ_E1, SQ_F1, SQ_G1, SQ_H1,
7      SQ_A2, SQ_B2, SQ_C2, SQ_D2, SQ_E2, SQ_F2, SQ_G2, SQ_H2,
8      SQ_A3, SQ_B3, SQ_C3, SQ_D3, SQ_E3, SQ_F3, SQ_G3, SQ_H3,
9      SQ_A4, SQ_B4, SQ_C4, SQ_D4, SQ_E4, SQ_F4, SQ_G4, SQ_H4,
10     SQ_A5, SQ_B5, SQ_C5, SQ_D5, SQ_E5, SQ_F5, SQ_G5, SQ_H5,
11     SQ_A6, SQ_B6, SQ_C6, SQ_D6, SQ_E6, SQ_F6, SQ_G6, SQ_H6,
12     SQ_A7, SQ_B7, SQ_C7, SQ_D7, SQ_E7, SQ_F7, SQ_G7, SQ_H7,
13     SQ_A8, SQ_B8, SQ_C8, SQ_D8, SQ_E8, SQ_F8, SQ_G8, SQ_H8,
14     SQ_NONE,
15     SQUARE_ZERO = 0,
16     SQUARE_NB   = 64
17 };
18 enum Direction : int8_t {
19     NORTH = 8,
20     EAST  = 1,
21     SOUTH = -NORTH,
22     WEST  = -EAST,
23     NORTH_EAST = NORTH + EAST,
24     SOUTH_EAST = SOUTH + EAST,
25     SOUTH_WEST = SOUTH + WEST,
26     NORTH_WEST = NORTH + WEST
27 };
28 enum File : uint8_t {
29     FILE_A, FILE_B, FILE_C, FILE_D, FILE_E, FILE_F, FILE_G, FILE_H,
30     FILE_NB
31 };
32 enum Rank : uint8_t {
```

```

33     RANK_1, RANK_2, RANK_3, RANK_4, RANK_5, RANK_6, RANK_7, RANK_8,
34     RANK_NB
35 };
36 constexpr uint64_t FileABB = 0x0101010101010101;
37 constexpr uint64_t FileBBB = FileABB << 1;
38 constexpr uint64_t FileCBB = FileABB << 2;
39 constexpr uint64_t FileDBB = FileABB << 3;
40 constexpr uint64_t FileEBB = FileABB << 4;
41 constexpr uint64_t FileFBB = FileABB << 5;
42 constexpr uint64_t FileGBB = FileABB << 6;
43 constexpr uint64_t FileHBB = FileABB << 7;
44 constexpr uint64_t Rank1BB = 0xFF;
45 constexpr uint64_t Rank2BB = Rank1BB << (8 * 1);
46 constexpr uint64_t Rank3BB = Rank1BB << (8 * 2);
47 constexpr uint64_t Rank4BB = Rank1BB << (8 * 3);
48 constexpr uint64_t Rank5BB = Rank1BB << (8 * 4);
49 constexpr uint64_t Rank6BB = Rank1BB << (8 * 5);
50 constexpr uint64_t Rank7BB = Rank1BB << (8 * 6);
51 constexpr uint64_t Rank8BB = Rank1BB << (8 * 7);
52 constexpr uint64_t BLACK_INITIAL_POSITION =
53 0b10000000'00000000'00000000'00001000'00010000'00000000'00000000'00000001;
54 constexpr uint64_t WHITE_INITIAL_POSITION =
55 0b00000001'00000000'00000000'00010000'00001000'00000000'00000000'10000000;
56 constexpr uint64_t FULL = 0xFFFFFFFFFFFFFFFF;
57 constexpr Square make_square(File f, Rank r) {
58     return Square((r << 3) + f);
59 }
60 inline Square lsb(uint64_t b) {
61     return Square(std::countr_zero(b));
62 }
63 inline Square pop_lsb(uint64_t& b) {
64     const Square s = lsb(b);
65     b &= b - 1;
66     return s;
67 }
68 constexpr bool more_than_one(uint64_t b) {
69     return b & (b - 1);
70 }
71 template<Direction D>
72 constexpr uint64_t shift(uint64_t b) {
73     if constexpr (D == NORTH)         return b << 8;
74     else if constexpr (D == SOUTH)    return b >> 8;

```

```
75     else if constexpr (D == EAST)         return (b & ~FileHBB) << 1;
76     else if constexpr (D == WEST)         return (b & ~FileABB) >> 1;
77     else if constexpr (D == NORTH_EAST)    return (b & ~FileHBB) << 9;
78     else if constexpr (D == NORTH_WEST)    return (b & ~FileABB) << 7;
79     else if constexpr (D == SOUTH_EAST)    return (b & ~FileHBB) >> 7;
80     else if constexpr (D == SOUTH_WEST)    return (b & ~FileABB) >> 9;
81     else return 0;
82 }
83 constexpr uint64_t shift_all_directions(uint64_t b) {
84     uint64_t b1 = b & ~FileHBB;
85     uint64_t b2 = b & ~FileABB;
86     return b << 8 | b >> 8 | b1 << 1 | b1 << 9
87           | b1 >> 7 | b2 >> 1 | b2 << 7 | b2 >> 9;
88 }
89 #endif
```

Listing 7: Squares, files, ranks and directions

```
1  #ifndef MOVE_H
2  #define MOVE_H
3  #include "types.h"
4  #include <iostream>
5  class Move {
6      uint16_t data;
7  public:
8      Move() = default;
9      constexpr explicit
10     Move(uint16_t d) : data(d) {}
11     constexpr explicit
12     Move(Square from, Square to) : data((to << 6) + from) {}
13     constexpr Square to_sq() const {
14         return Square((data >> 6) & 0x3F);
15     }
16     constexpr Square from_sq() const {
17         return Square(data & 0x3F);
18     }
19     static constexpr Move none() {
20         return Move(0);
21     }
22     constexpr bool operator==(const Move& m) const {
```



```
23     return data == m.data;
24 }
25 constexpr bool operator!=(const Move& m) const {
26     return !(*this == m);
27 }
28 constexpr explicit operator bool() const {
29     return data != 0;
30 }
31 constexpr uint16_t raw() const {
32     return data;
33 }
34 };
35 std::ostream& operator<<(std::ostream& os, const Move& m);
36 std::istream& operator>>(std::istream& is, Move& m);
37 #endif
```

Listing 8: implémentation d'un coup

```
1  #ifndef GAME_H
2  #define GAME_H
3  #include <iostream>
4  #include <vector>
5  #include <utility>
6  #include "types.h"
7  #include "move.h"
8  #include "json.hpp"
9  #include "misc.h"
10 using json = nlohmann::json;
11 class Yolah {
12     uint64_t black = BLACK_INITIAL_POSITION;
13     uint64_t white = WHITE_INITIAL_POSITION;
14     uint64_t empty = 0;
15     uint8_t black_score = 0;
16     uint8_t white_score = 0;
17     uint8_t ply = 0;
18 public:
19     static constexpr uint8_t MAX_NB_MOVES = 75;
20     static constexpr uint8_t MAX_NB_PLIES = 120;
21     class MoveList {
22         Move moveList[MAX_NB_MOVES], *last;
```

```
23     public:
24         explicit MoveList() : last(moveList) {}
25         const Move* begin() const { return moveList; }
26         const Move* end() const { return last; }
27         Move* begin() { return moveList; }
28         Move* end() { return last; }
29         size_t size() const { return last - moveList; }
30         const Move& operator[](size_t i) const { return moveList[i]; }
31         Move& operator[](size_t i) { return moveList[i]; }
32         Move* data() { return moveList; }
33         friend class Yolah;
34     };
35     static constexpr uint8_t BLACK = 0;
36     static constexpr uint8_t WHITE = 1;
37     static constexpr uint8_t HOLE = 2;
38     static constexpr uint8_t FREE = 3;
39     constexpr std::pair<uint8_t, uint8_t> score() const;
40     constexpr int8_t score(uint8_t player) const;
41     constexpr uint8_t current_player() const;
42     static constexpr uint8_t other_player(uint8_t player);
43     uint8_t get(Square) const;
44     uint8_t get(File f, Rank r) const;
45     bool game_over() const;
46     void play(Move m);
47     void undo(Move m);
48     void moves(uint8_t player, MoveList& moves) const;
49     void moves(MoveList& moves) const;
50     bool valid(Move m) const;
51     constexpr uint64_t free_squares() const;
52     constexpr uint64_t occupied_squares() const;
53     constexpr uint64_t bitboard(uint8_t player) const;
54     constexpr uint16_t nb_plies() const;
55     constexpr uint64_t empty_bitboard() const;
56     std::string to_json() const;
57     static Yolah from_json(std::istream& is);
58     static Yolah from_json(const std::string&);
59     friend std::ostream& operator<<(std::ostream& os, const Yolah&
    ↪ yolah);
60 };
61 std::ostream& operator<<(std::ostream& os, const Yolah& yolah);
62 bool Yolah::game_over() const {
63     uint64_t possible = ~empty & ~black & ~white;
```

```
64
65     uint64_t around_black = shift<NORTH>(black) | shift<SOUTH>(black) |
↪     shift<EAST>(black) |
66         shift<WEST>(black) | shift<NORTH_EAST>(black) |
↪     shift<NORTH_WEST>(black) |
67         shift<SOUTH_EAST>(black) | shift<SOUTH_WEST>(black);
68
69     uint64_t around_white = shift<NORTH>(white) | shift<SOUTH>(white) |
↪     shift<EAST>(white) |
70         shift<WEST>(white) | shift<NORTH_EAST>(white) |
↪     shift<NORTH_WEST>(white) |
71         shift<SOUTH_EAST>(white) | shift<SOUTH_WEST>(white);
72
73     uint64_t around_players = around_black | around_white;
74
75     return (around_players & possible) == 0;
76 }
77 #endif
```

Listing 9: implémentation du plateau

2.5 Test avec des parties aléatoires

2.6 La suite

Chapter 3

AI Players

Chapter 4

Monte Carlo Player

Chapter 5

MCTS Player

Chapter 6

Minmax Player

Chapter 7

Minmax with Neural Network Player

Chapter 8

AI Tournament

Chapter 9

Conclusion

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