201.1 - Algo. et struct. de données
Prof. L. Lettry
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Informatique et systèmes de communication ISC
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Image generated with ChatGPT

Report of the ISChess project

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1 - Introduction

The goal of this project was to apply the different notions seen during the course: 201.1 - Algo. et struct. de données.

To do so, we had to realize a chess bot based on the provided code provided by Prof. L. Lettry, that could play on it's own and hopefully perform better than a bot making random moves.[1]

In this report, we will go in depth about how we evaluated the 'quality' of different chess boards (resulting from a certain move) compared to each others, the different algorithms we used to make use of this move evaluations, an in depth comparison of this algorithms results and finally which further improvements we could make to strengthen our chess bot.

2 - The evaluation function

In this section, we will discuss how we assigned each chess piece a certain value, therefore allowing us to assign an evaluation score to a certain chess bord, as follow:

$$\text{Board score} = \sum(\text{values of one color's pieces}) - \sum(\text{values of the other color's pieces}) + \alpha$$

$$\text{With } \alpha = \text{a random number between} -0.05 \text{ and } 0.05$$

The chosen pieces values were heavily inspired by the one proposed by Tomasz Michniewski and are the following:

Piece	Value
Pawn	100
Knight	320
Bishop	330
Rook	500
Queen	900
King	20000

Table 1 - The different chess pieces values

It should be noted that this evaluation function is pretty bare-bones and and could be improved such as discussed in Section 5.

With an established board evaluation score, it is now possible to determine if a board is evaluated higher than another, resulting in the possibility to order moves resulting in boards from best to worst.

3 - The different algorithms

Now that we have defined an evaluation function, we can start to develop some algorithms to chose which move the chess bot should play.

In this section, we will present the different algorithms we used and explain their briefly how they work.

3.1 - Random move selection

The first algorithm we decided to implement was an algorithm which could select one of the different possible moves randomly.

However, as shown in Section 4 this bot isn't what we could qualify of a "good" player yet.

[1] The code of our project can be seen at https://github.com/MadeInShineA/ISChess

But it will be useful to use it as a metric to determine the ability of the other bots to defeat a “mindless” opponent.

3.2 - Minmax

The next algorithm we used is called Minmax.

We will demonstrate it’s procedure with the following steps going from left to right (see Figure 1):

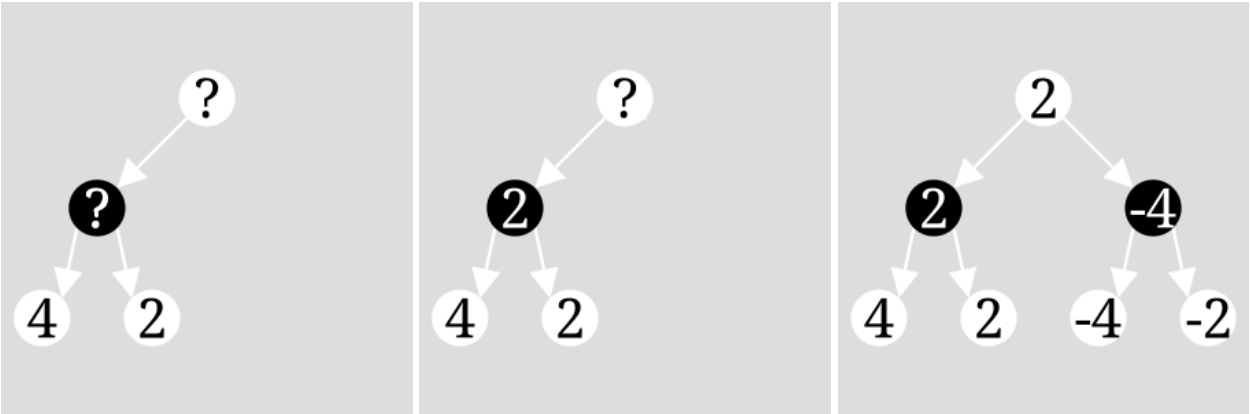


Figure 1 - The different steps of the Minmax algorithm

This explanation assumes the minmax algorithm operates at a depth of 2 and alternates between the white and black players, starting with white. Each step builds toward determining the optimal move for the white player.

Initial Exploration (First Step): The algorithm starts by systematically exploring all possible moves for the current game state, alternating turns between the white and black players. This traversal follows a depth-first approach. Once the specified depth is reached, the leaf nodes are evaluated to assign a value to each possible board configuration.

Value Propagation at Black Nodes (Second Step): As the algorithm begins to backtrack, it evaluates the black player’s nodes by selecting the minimum value from their immediate children. This reflects the black player’s goal of minimizing the white player’s score.

Value Propagation at White Nodes (Third Step): After processing the black nodes, the algorithm evaluates the white player’s nodes. It chooses the maximum value from the black nodes’ evaluations, as white aims to maximize its score

3.3 - Alpha-betta prunning

The last algorithm we applied is called Alpha-Beta Pruning.

Its process can be visualized in three stages, as shown below (refer to Figure 2):

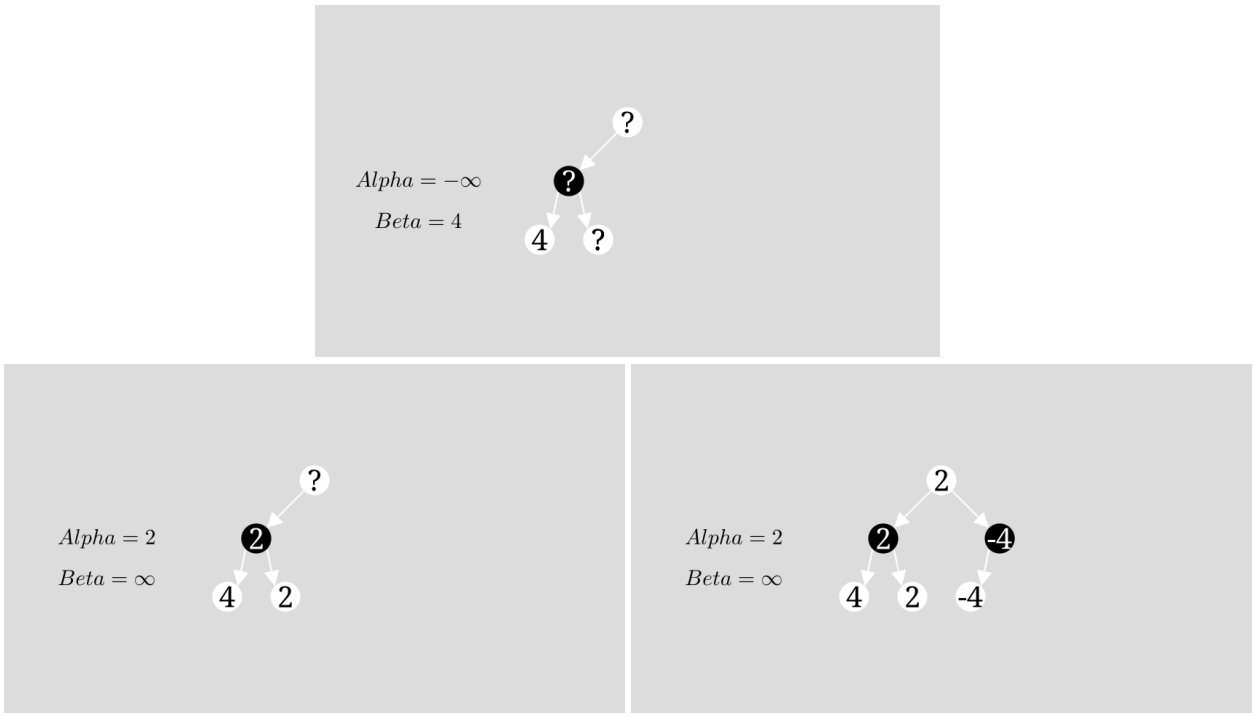


Figure 2 - The key steps of the Alpha-Beta Pruning algorithm

This example assumes each position leads to two possible outcomes and that the algorithm runs with a depth limit of 2, starting with the white player.

Unlike the basic Minimax algorithm, Alpha-Beta Pruning skips unnecessary evaluations by maintaining two values, alpha and beta, which represent the best scores achievable for the maximizer and minimizer, respectively. These bounds help eliminate paths that cannot influence the final decision.

Here is a clear breakdown of how the algorithm progresses.

Exploration Begins (First Stage): The algorithm evaluates potential moves by alternating between players, systematically visiting each node in a depth-first manner. As it calculates values, it updates the alpha and beta thresholds. When a node's value falls outside these bounds, further exploration of that branch is immediately halted.

Pruning at Black Nodes (Second Stage): When it's the black player's turn, the algorithm selects the smallest value from its children and adjusts the beta threshold. If a child's value is lower than the current alpha value, the remaining child nodes are skipped because they cannot affect the outcome.

Pruning at White Nodes (Third Stage): On the white player's turn, the algorithm identifies the largest value among the children and updates the alpha threshold. If a child's value exceeds the current beta threshold, the algorithm skips evaluating the rest of the nodes at this level.

By intelligently skipping branches that are guaranteed to be irrelevant, Alpha-Beta Pruning drastically reduces the number of nodes processed compared to Minimax, while ensuring the same optimal result.

4 - Algorithm comparisons

Now that we established the algorithms developed during this project, it is time to compare them with each other.

To do this, we created a chess bot for each algorithm, named:
- **Random**: Makes random moves.
- **Minimax**: Uses the Minimax algorithm.
- **Pruning**: Implements alpha-beta pruning.

For consistency and meaningful comparisons, the Minimax and Pruning algorithms were configured to run with a fixed search depth of 3 in all games, a time limit per moved was chosen randomly for each game between 0.5, 1.0, 1.5 and 2 seconds and the games were all lasting a maximum number of moves, chosen randomly between 10, 20, 30 … and 150.

4.1 - Collecting data

To gather some data, a small Rust program was written to allow efficiently running games simulations of bots playing against each-others with the power of multi threading.

The different statistics collected can be grouped into 2 categories:
- Turn stats
- End game stats

The turn stats each depends of the bot which played the turn, where the end game stats shows the overall stats at the end of the game.

Here are the different turn stats collected data for each chess bot

Chess bot	Gathered data
Random	number of possibilities
Min max	number of board evaluations
Pruning	number of board evaluations, number of branches cut

Table 2 - Turn stats collected for each chess bot

On top of that, each turn stat also features:
- The board position before the move[2]
- The board position after the move[2]
- The time taken by the bot to output the move
- If the bot reached it's time limit
- The turn number

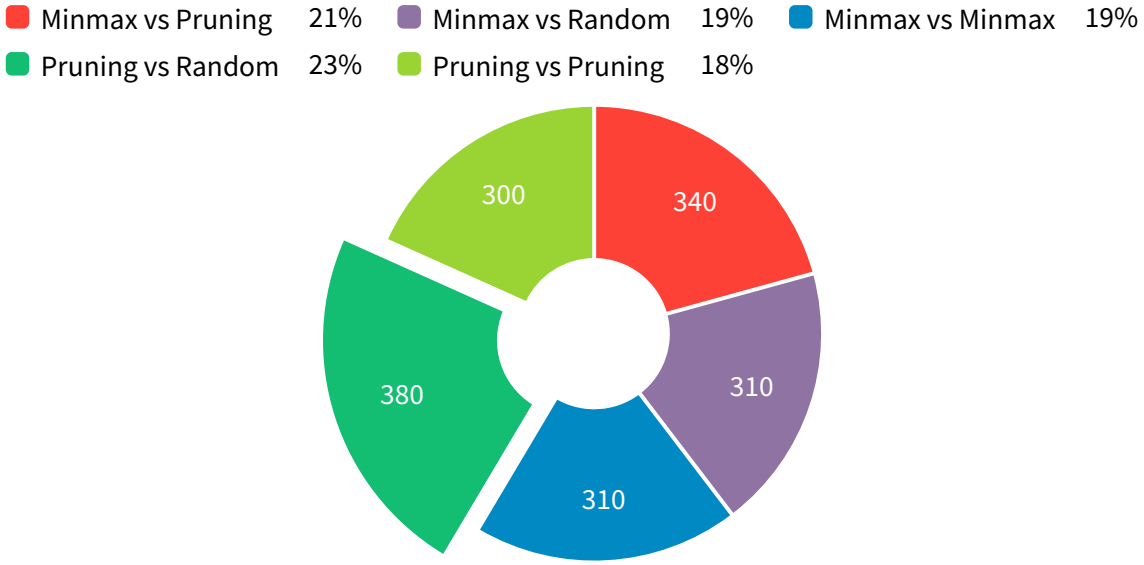
The different values inside each game stat are:
- The game winner
- The total number of turns
- The number of white pieces on the board
- The number of black pieces on the board
- The endgame state (whether it's a checkmate, a stalemate, or neither).

An example of a game statistics file can be seen in Listing 1 (in the appendix)

With all this data, 2 files were created
- One for the bot statistics (see Listing 2 in the appendix)
- One for the game statistics (see Listing 3 in the appendix)

[2] Encoded in Forsyth-Edwards Notation

Here is the matchups distribution out of the 1640 games collected:



4.2 - Data analysis

To compare the bots with one another, we will use three key metrics:

- The number of boards evaluated per move
- The frequency of timeouts relative to the allowed time
- The win rate of the bots against each others

Made with the data inside Table 5 (see appendix), The table below summarizes the number of boards evaluated per move and the timeout frequency for each bot. Each column is divided into four sections, corresponding to a time limits of 0.5, 1, 1.5, and 2 seconds per move.

Chess bot	Number of evaluations per move	Timeout frequency
Random	0, 0, 0, 0	0%, 0%, 0%, 0%
Min max	7465, 11638, 15532, 19102	92%, 75%, 41%, 40%
Pruning	5171, 6182, 6778, 6353	67%, 13%, 5%, 19%

Table 3 - Summary of the number of evaluations per move and timeout frequency for the different bots

As expected, the Random bot evaluates no boards and, therefore, does not experience any timeouts.

However, a more interesting comparison emerges when we look at the Min max and Pruning bots. The Min max bot consistently evaluates at least 44% more boards than the Pruning bot with a time limit of 0.5 seconds. This difference continues to grow, reaching 88%, 129%, and 200% as the time limit keeps increasing.
Regarding the timeout frequency, the Min max bot tends to decrease its timeout linearly upon reaching a threshold of 40% for a time limit of 2 seconds.The Pruning bot on the other end seems to decrease its timeout frequency in an exponential passe.Specifically, at a 1-second time limit, the Pruning bot experiences timeouts 13% of the time, but this decreases to 5% at 1.5 seconds and then rises to 19% at the 2-second limit. This is likely due to the fact that the Pruning bot played all of it's 2 seconds games against the Min max bot, therefore having to analyze more complex positions.

When examining the win rates of the different bots, the Table 4 provides a detailed breakdown of wins, draws, and losses for each bot. Each cell in the table should be interpreted from the perspective of the bot playing as White.

	Black Pruning	Black Min max	Black Random
White Pruning	0, 81, 36, 0 0, 46, 8, 0 0, 98, 31, 0	66, 6, 15, 31 25, 6, 7, 17 4, 0, 3, 5	70, 35, 50, 0 0, 0, 0, 0 0, 0, 0, 0
White Min max	1, 2 ,6, 4 15, 14, 11, 5 25, 39, 24, 9	14, 46, 14, 17 77, 43, 20, 9 8, 42, 6, 14,	5, 23, 168, 6 8, 16, 3, 3 7, 11, 9, 1
White Random	2, 0, 0, 0 3, 29, 0, 0 145, 46, 0, 0	6, 1, 0, 0 1, 3, 0, 0 3, 6, 0, 30	-

Table 4 - The result spread between the different bots

As we can see, the Pruning bot emerges as the clear leader, with a significant advantage over the Min max bot, winning 215 times, drawing 100 times, and losing 25 times.
Interestingly, the Random bot managed to secure 32 draws against the Pruning bot out of 348 games, despite losing 346 games and winning only 2. All of these 32 draws occurred when a turn limit of 10 was imposed. This suggests that in a limited number of moves, the Random bot could occasionally hold its ground against the Pruning bot, but over the course of a full game, the Pruning bot's superior strategy prevails.

5 - Possible improvements

While the initial version of the Pruning bot showed promising results, there are a few areas where performance could be improved further:

Memoization: One key improvement could be the implementation of memoization in the evaluation function. By storing previously computed evaluation results for certain board positions, the bot could avoid redundant calculations, especially when dealing with positions that repeat during the search process. This would speed up the decision-making process and reduce the overall computational time.

Evaluation Function Enhancements: The current evaluation function, while functional, could be further refined by considering more advanced factors such as piece positioning, control of the center, and king safety. These factors are crucial for more accurate board evaluations and can significantly improve the bot's playstyle.

Move Ordering: Improving the order in which the possible moves are explored can significantly reduce the number of evaluations. By prioritizing moves that are likely to lead to a better outcome (such as capturing an opponent's piece or controlling key squares), the bot could focus its resources on the most promising options, leading to a more efficient search.

6 - Conclusion

In conclusion, this project successfully applied various algorithms, such as Minimax and Alpha-Beta Pruning, to enhance the performance of a chess bot. We compared these algorithms using metrics like boards evaluated per move, timeout frequency, and win rates. The results showed that Alpha-Beta Pruning outperformed Minimax in terms of efficiency, evaluating fewer positions while maintaining competitive performance. Although the Random bot performed poorly, it served as a valuable baseline for evaluating the other algorithms. Future improvements could further refine the evaluation function and optimize the search depth for better performance.

Appendix

Chess bot	Number of boards evaluated	Number of time-outs	Total number of moves	Number of games played
Random	0, 0, 0, 0	0, 0, 0, 0	6205, 2040, 2919, 610	250, 170, 230, 40
Min max	83965518, 92643423, 99781721, 69418150	10316, 5985, 2628, 1465	11247, 7960, 6424, 3634	265, 258, 286, 151
Pruning	52083947, 94716756, 64353768, 8564825	6705, 2048, 523, 262	10071, 15319, 9494, 1348	356, 402, 191, 171

Table 5 - Number of evaluations, timeouts, moves and games played per time limit per bot


```
[
  {
      "type": "game_infos",
      "white_bot": "random_stats",
      "black_bot": "pruning_stats",
      "number_of_turns": 10,
      "time_per_turn": 1.0
  },
  {
      "bot": "random_stats",
      "board_before_move": "rnbqkbnr/pppppppp/8/8/8/8/PPPPPPPP/RNBKQBNR",
      "board_after_move": "rnbqkbnr/pppppppp/8/8/8/N7/PPPPPPPP/R1BKQBNR",
      "number_of_possible_moves": 12,
      "elapsed_time": 0.0007927417755126953,
      "is_timeout": false,
      "type": "turn_stat",
      "turn_number": 1
  },
  {
      "bot": "pruning_stats",
      "board_before_move": "rnbqkbnr/pppppppp/8/8/8/N7/PPPPPPPP/R1BKQBNR",
      "board_after_move": "rnbqkbnr/pppp1ppp/4p3/8/8/N7/PPPPPPPP/R1BKQBNR",
      "number_of_evaluation": 804,
      "number_of_branches_cut": 50,
      "depth": 3,
      "elapsed_time": 0.06253528594970703,
      "is_timeout": false,
      "type": "turn_stat",
      "turn_number": 2
  },
  {
      "bot": "random_stats",
      "board_before_move": "rnbqkbnr/pppp1ppp/4p3/8/8/N7/PPPPPPPP/R1BKQBNR",
      "board_after_move": "rnbqkbnr/pppp1ppp/4p3/8/8/N6N/PPPPPPPP/R1BKQB1R",
      "number_of_possible_moves": 13,
      "elapsed_time": 0.0005342960357666016,
      "is_timeout": false,
      "type": "turn_stat",
      "turn_number": 3
  },
  {
      "bot": "pruning_stats",
      "board_before_move": "rnbqkbnr/pppp1ppp/4p3/8/8/N6N/PPPPPPPP/R1BKQB1R",
      "board_after_move": "rnb1kbnr/pppp1ppp/4p3/8/7q/N6N/PPPPPPPP/R1BKQB1R",
```

```
        "number_of_evaluation": 1370,
        "number_of_branches_cut": 73,
        "depth": 3,
        "elapsed_time": 0.24674129486083984,
        "is_timeout": false,
        "type": "turn_stat",
        "turn_number": 4
    },
    {
        "bot": "random_stats",
        "board_before_move": "rnb1kbnr/pppp1ppp/4p3/8/7q/N6N/PPPPPPPP/R1BKQB1R",
        "board_after_move": "rnb1kbnr/pppp1ppp/4p3/8/7q/N1P4N/PP1PPPPP/R1BKQB1R",
        "number_of_possible_moves": 14,
        "elapsed_time": 0.0010650157928466797,
        "is_timeout": false,
        "type": "turn_stat",
        "turn_number": 5
    },
    {
        "bot": "pruning_stats",
        "board_before_move": "rnb1kbnr/pppp1ppp/4p3/8/7q/N1P4N/PP1PPPPP/R1BKQB1R",
        "board_after_move": "rnb1kbnr/pppp1ppp/4p3/8/q7/N1P4N/PP1PPPPP/R1BKQB1R",
        "number_of_evaluation": 4655,
        "number_of_branches_cut": 119,
        "depth": 3,
        "elapsed_time": 0.4394357204437256,
        "is_timeout": false,
        "type": "turn_stat",
        "turn_number": 6
    },
    {
        "bot": "random_stats",
        "board_before_move": "rnb1kbnr/pppp1ppp/4p3/8/q7/N1P4N/PP1PPPPP/R1BKQB1R",
        "board_after_move": "rnb1kbnr/pppp1ppp/4p3/8/q7/N1P3PN/PP1PPP1P/R1BKQB1R",
        "number_of_possible_moves": 16,
        "elapsed_time": 0.0006136894226074219,
        "is_timeout": false,
        "type": "turn_stat",
        "turn_number": 7
    },
    {
        "bot": "pruning_stats",
        "board_before_move": "rnb1kbnr/pppp1ppp/4p3/8/q7/N1P3PN/PP1PPP1P/R1BKQB1R",
        "board_after_move": "rnb1kbnr/pppp1ppp/4p3/8/8/N1P3PN/PP1PPP1P/R1BqQB1R",
        "number_of_evaluation": 2858,
        "number_of_branches_cut": 72,
        "depth": 3,
        "elapsed_time": 0.20112323760986328,
        "is_timeout": false,
        "type": "turn_stat",
        "turn_number": 8
    },
    {
        "type": "end_game_stat",
        "winner": "pruning_stats",
        "white_pieces": 15,
        "black_pieces": 16,
        "number_of_turns": 8,
        "checkmate": true,
        "stalemate": false
```

```
  }
]
```

Listing 1 - Example of a game statistics file


```
{
"minmax": {
    "number_of_evaluations": {
        "0.5": 83965518,
        "1.0": 92643423,
        "1.5": 99781721,
        "2.0": 69418150,
        "total": 345808812
    },
    "number_of_evaluations_per_move": {
        "0.5": 7465.592424646572,
        "1.0": 11638.620979899497,
        "1.5": 15532.646481942715,
        "2.0": 19102.4078150798,
        "total": 11816.463762173244
    },
    "number_of_games": {
        "0.5": 265,
        "1.0": 258,
        "1.5": 286,
        "2.0": 151,
        "total": 960
    },
    "timeout_frequency": {
        "0.5": 0.9172223704098871,
        "1.0": 0.7518844221105527,
        "1.5": 0.4090909090909091,
        "2.0": 0.403137039075399,
        "total": 0.696873398257304
    },
    "timeouts": {
        "0.5": 10316,
        "1.0": 5985,
        "1.5": 2628,
        "2.0": 1465,
        "total": 20394
    },
    "turns_played": {
        "0.5": 11247,
        "1.0": 7960,
        "1.5": 6424,
        "2.0": 3634,
        "total": 29265
    }
},
"pruning": {
    "number_of_evaluations": {
        "0.5": 52083947,
        "1.0": 94716756,
        "1.5": 64353768,
        "2.0": 8564825,
        "total": 219719296
    },
    "number_of_evaluations_per_move": {
        "0.5": 5171.675801807169,
        "1.0": 6182.959462105881,
        "1.5": 6778.361912787023,
        "2.0": 6353.727744807122,
```

```
                "total": 6064.233164053875
            },
            "number_of_games": {
                "0.5": 356,
                "1.0": 402,
                "1.5": 191,
                "2.0": 71,
                "total": 1020
            },
            "timeout_frequency": {
                "0.5": 0.6657730116175157,
                "1.0": 0.1336901886546119,
                "1.5": 0.05508742363598062,
                "2.0": 0.1943620178041543,
                "total": 0.26324795760653563
            },
            "timeouts": {
                "0.5": 6705,
                "1.0": 2048,
                "1.5": 523,
                "2.0": 262,
                "total": 9538
            },
            "turns_played": {
                "0.5": 10071,
                "1.0": 15319,
                "1.5": 9494,
                "2.0": 1348,
                "total": 36232
            }
        },
        "random": {
            "number_of_evaluations": {
                "0.5": 0,
                "1.0": 0,
                "1.5": 0,
                "2.0": 0,
                "total": 0
            },
            "number_of_evaluations_per_move": {
                "0.5": 0.0,
                "1.0": 0.0,
                "1.5": 0.0,
                "2.0": 0.0,
                "total": 0.0
            },
            "number_of_games": {
                "0.5": 250,
                "1.0": 170,
                "1.5": 230,
                "2.0": 40,
                "total": 690
            },
            "timeout_frequency": {
                "0.5": 0.0,
                "1.0": 0.0,
                "1.5": 0.0,
                "2.0": 0.0,
                "total": 0.0
            },
            "timeouts": {
```

```
                    "0.5": 0,
                    "1.0": 0,
                    "1.5": 0,
                    "2.0": 0,
                    "total": 0
                },
                "turns_played": {
                    "0.5": 6205,
                    "1.0": 2040,
                    "1.5": 2919,
                    "2.0": 610,
                    "total": 11774
                }
            }
        }
```


Listing 2 - Content of the bot statistics file


```
{
    "total_number_of_games": 1640,
    "white_minmax_stats vs black_minmax_stats": {
        "black_minmax_stats": {
            "number_of_evaluations": {
                "0.5": 21164927,
                "1.0": 34126761,
                "1.5": 18463064,
                "2.0": 21010271,
                "total": 94765023
            },
            "time_spent_computing": {
                "0.5": 1216.4294662475586,
                "1.0": 2109.8125927448273,
                "1.5": 856.9621732234955,
                "2.0": 911.7069272994995,
                "total": 5094.911159515381
            },
            "timeouts": {
                "0.5": 2298,
                "1.0": 1634,
                "1.5": 221,
                "2.0": 137,
                "total": 4290
            },
            "turns_played": {
                "0.5": 2527,
                "1.0": 2425,
                "1.5": 1110,
                "2.0": 840,
                "total": 6902
            }
        },
        "black_minmax_stats_wins": {
            "0.5": {
                "checkmate": 1,
                "pieces": 7,
                "total": 8
            },
            "1.0": {
                "checkmate": 4,
                "pieces": 38,
                "total": 42
            },
```

```
            "1.5": {
                "checkmate": 3,
                "pieces": 3,
                "total": 6
            },
            "2.0": {
                "checkmate": 6,
                "pieces": 8,
                "total": 14
            },
            "total": 70
        },
        "draws": {
            "0.5": {
                "pieces": 32,
                "stalemate": 45,
                "total": 77
            },
            "1.0": {
                "pieces": 41,
                "stalemate": 2,
                "total": 43
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                "total": 20
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                "pieces": 9,
                "stalemate": 0,
                "total": 9
            },
            "total": 149
        },
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            "0.5": 99,
            "1.0": 131,
            "1.5": 40,
            "2.0": 40,
            "total": 310
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        "number_of_turns": {
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            "1.0": 4859,
            "1.5": 2229,
            "2.0": 1685,
            "total": 13850
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        "white_minmax_stats": {
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                "1.0": 33903388,
                "1.5": 19761327,
                "2.0": 21034525,
                "total": 95888732
            },
            "time_spent_computing": {
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                "1.0": 2091.600911140442,
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```

```
                    "2.0": 915.0333411693573,
                    "total": 5120.763126850128
                },
                "timeouts": {
                    "0.5": 2291,
                    "1.0": 1645,
                    "1.5": 228,
                    "2.0": 182,
                    "total": 4346
                },
                "turns_played": {
                    "0.5": 2550,
                    "1.0": 2434,
                    "1.5": 1119,
                    "2.0": 845,
                    "total": 6948
                }
            },
            "white_minmax_stats_wins": {
                "0.5": {
                    "checkmate": 4,
                    "pieces": 10,
                    "total": 14
                },
                "1.0": {
                    "checkmate": 9,
                    "pieces": 37,
                    "total": 46
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                "1.5": {
                    "checkmate": 8,
                    "pieces": 6,
                    "total": 14
                },
                "2.0": {
                    "checkmate": 5,
                    "pieces": 12,
                    "total": 17
                },
                "total": 91
            }
        },
        "white_minmax_stats vs black_pruning_stats": {
            "black_pruning_stats": {
                "branches_cut": {
                    "0.5": 227442,
                    "1.0": 251428,
                    "1.5": 235649,
                    "2.0": 79458,
                    "total": 793977
                },
                "number_of_evaluations": {
                    "0.5": 6669408,
                    "1.0": 7158496,
                    "1.5": 6442415,
                    "2.0": 2186361,
                    "total": 22456680
                },
                "time_spent_computing": {
                    "0.5": 615.9396069049835,
                    "1.0": 1225.7142338752747,
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                "1.5": 790.6945979595184,
                "2.0": 256.27303767204285,
                "total": 2888.6214764118195
            },
            "timeouts": {
                "0.5": 1031,
                "1.0": 986,
                "1.5": 161,
                "2.0": 42,
                "total": 2220
            },
            "turns_played": {
                "0.5": 1389,
                "1.0": 1442,
                "1.5": 1134,
                "2.0": 355,
                "total": 4320
            }
        },
        "black_pruning_stats_wins": {
            "0.5": {
                "checkmate": 9,
                "pieces": 16,
                "total": 25
            },
            "1.0": {
                "checkmate": 3,
                "pieces": 36,
                "total": 39
            },
            "1.5": {
                "checkmate": 12,
                "pieces": 12,
                "total": 24
            },
            "2.0": {
                "checkmate": 4,
                "pieces": 5,
                "total": 9
            },
            "total": 97
        },
        "draws": {
            "0.5": {
                "pieces": 14,
                "stalemate": 1,
                "total": 15
            },
            "1.0": {
                "pieces": 14,
                "stalemate": 0,
                "total": 14
            },
            "1.5": {
                "pieces": 11,
                "stalemate": 0,
                "total": 11
            },
            "2.0": {
                "pieces": 5,
                "stalemate": 0,
```

```
            "total": 5
        },
        "total": 45
    },
    "number_of_games": {
        "0.5": 41,
        "1.0": 55,
        "1.5": 41,
        "2.0": 18,
        "total": 155
    },
    "number_of_turns": {
        "0.5": 2780,
        "1.0": 2884,
        "1.5": 2270,
        "2.0": 710,
        "total": 8644
    },
    "white_minmax_stats": {
        "number_of_evaluations": {
            "0.5": 9866525,
            "1.0": 10881385,
            "1.5": 15760287,
            "2.0": 5494276,
            "total": 42002473
        },
        "time_spent_computing": {
            "0.5": 676.2884154319763,
            "1.0": 1361.3495507240295,
            "1.5": 1313.2281322479248,
            "2.0": 432.3860719203949,
            "total": 3783.2521703243256
        },
        "timeouts": {
            "0.5": 1294,
            "1.0": 1271,
            "1.5": 547,
            "2.0": 128,
            "total": 3240
        },
        "turns_played": {
            "0.5": 1391,
            "1.0": 1442,
            "1.5": 1136,
            "2.0": 355,
            "total": 4324
        }
    },
    "white_minmax_stats_wins": {
        "0.5": {
            "checkmate": 1,
            "pieces": 0,
            "total": 1
        },
        "1.0": {
            "checkmate": 0,
            "pieces": 2,
            "total": 2
        },
        "1.5": {
            "checkmate": 2,
```

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                "pieces": 4,
                "total": 6
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            "2.0": {
                "checkmate": 0,
                "pieces": 4,
                "total": 4
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            "total": 13
        }
    },
    "white_minmax_stats vs black_random_stats": {
        "black_random_stats": {
            "time_spent_computing": {
                "0.5": 1.4126219749450684,
                "1.0": 2.5639524459838867,
                "1.5": 2.611511707305908,
                "2.0": 0.1983647346496582,
                "total": 6.7864508628845215
            },
            "timeouts": {
                "0.5": 0,
                "1.0": 0,
                "1.5": 0,
                "2.0": 0,
                "total": 0
            },
            "turns_played": {
                "0.5": 638,
                "1.0": 1223,
                "1.5": 2393,
                "2.0": 97,
                "total": 4351
            }
        },
        "black_random_stats_wins": {
            "0.5": {
                "checkmate": 2,
                "pieces": 5,
                "total": 7
            },
            "1.0": {
                "checkmate": 2,
                "pieces": 9,
                "total": 11
            },
            "1.5": {
                "checkmate": 1,
                "pieces": 8,
                "total": 9
            },
            "2.0": {
                "checkmate": 0,
                "pieces": 1,
                "total": 1
            },
            "total": 28
        },
        "draws": {
            "0.5": {
                "pieces": 8,
```

```
            "stalemate": 0,
            "total": 8
        },
        "1.0": {
            "pieces": 16,
            "stalemate": 0,
            "total": 16
        },
        "1.5": {
            "pieces": 3,
            "stalemate": 0,
            "total": 3
        },
        "2.0": {
            "pieces": 3,
            "stalemate": 0,
            "total": 3
        },
        "total": 30
    },
    "number_of_games": {
        "0.5": 20,
        "1.0": 50,
        "1.5": 180,
        "2.0": 10,
        "total": 260
    },
    "number_of_turns": {
        "0.5": 1277,
        "1.0": 2454,
        "1.5": 4943,
        "2.0": 195,
        "total": 8869
    },
    "white_minmax_stats": {
        "number_of_evaluations": {
            "0.5": 3031548,
            "1.0": 10702175,
            "1.5": 40651761,
            "2.0": 1153887,
            "total": 55539371
        },
        "time_spent_computing": {
            "0.5": 315.65266847610474,
            "1.0": 1168.133902311325,
            "1.5": 2890.7267396450043,
            "2.0": 157.6209375858307,
            "total": 4532.134248018265
        },
        "timeouts": {
            "0.5": 619,
            "1.0": 1084,
            "1.5": 1234,
            "2.0": 62,
            "total": 2999
        },
        "turns_played": {
            "0.5": 639,
            "1.0": 1231,
            "1.5": 2550,
            "2.0": 98,
```

```
                    "total": 4518
                }
            },
            "white_minmax_stats_wins": {
                "0.5": {
                    "checkmate": 1,
                    "pieces": 4,
                    "total": 5
                },
                "1.0": {
                    "checkmate": 8,
                    "pieces": 15,
                    "total": 23
                },
                "1.5": {
                    "checkmate": 157,
                    "pieces": 11,
                    "total": 168
                },
                "2.0": {
                    "checkmate": 1,
                    "pieces": 5,
                    "total": 6
                },
                "total": 202
            }
        },
        "white_pruning_stats vs black_minmax_stats": {
            "black_minmax_stats": {
                "number_of_evaluations": {
                    "0.5": 25932003,
                    "1.0": 2387823,
                    "1.5": 5145282,
                    "2.0": 13228974,
                    "total": 46694082
                },
                "time_spent_computing": {
                    "0.5": 1739.15141248703,
                    "1.0": 299.11893463134766,
                    "1.5": 695.4714615345001,
                    "2.0": 1699.932373046875,
                    "total": 4433.674181699753
                },
                "timeouts": {
                    "0.5": 3276,
                    "1.0": 268,
                    "1.5": 398,
                    "2.0": 628,
                    "total": 4570
                },
                "turns_played": {
                    "0.5": 3591,
                    "1.0": 328,
                    "1.5": 509,
                    "2.0": 983,
                    "total": 5411
                }
            },
            "black_minmax_stats_wins": {
                "0.5": {
                    "checkmate": 1,
```

```
            "pieces": 3,
            "total": 4
        },
        "1.0": {
            "checkmate": 0,
            "pieces": 0,
            "total": 0
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        "1.5": {
            "checkmate": 0,
            "pieces": 3,
            "total": 3
        },
        "2.0": {
            "checkmate": 2,
            "pieces": 3,
            "total": 5
        },
        "total": 12
    },
    "draws": {
        "0.5": {
            "pieces": 23,
            "stalemate": 2,
            "total": 25
        },
        "1.0": {
            "pieces": 5,
            "stalemate": 1,
            "total": 6
        },
        "1.5": {
            "pieces": 6,
            "stalemate": 1,
            "total": 7
        },
        "2.0": {
            "pieces": 17,
            "stalemate": 0,
            "total": 17
        },
        "total": 55
    },
    "number_of_games": {
        "0.5": 95,
        "1.0": 12,
        "1.5": 25,
        "2.0": 53,
        "total": 185
    },
    "number_of_turns": {
        "0.5": 7196,
        "1.0": 658,
        "1.5": 1020,
        "2.0": 1976,
        "total": 10850
    },
    "white_pruning_stats": {
        "branches_cut": {
            "0.5": 578925,
            "1.0": 53332,
```

```
                "1.5": 98415,
                "2.0": 216835,
                "total": 947507
            },
            "number_of_evaluations": {
                "0.5": 17179583,
                "1.0": 1489614,
                "1.5": 2897252,
                "2.0": 6378464,
                "total": 27944913
            },
            "time_spent_computing": {
                "0.5": 1537.397088766098,
                "1.0": 260.1847207546234,
                "1.5": 555.9801635742188,
                "2.0": 1133.261745929718,
                "total": 3486.823719024658
            },
            "timeouts": {
                "0.5": 2451,
                "1.0": 200,
                "1.5": 249,
                "2.0": 220,
                "total": 3120
            },
            "turns_played": {
                "0.5": 3605,
                "1.0": 330,
                "1.5": 511,
                "2.0": 993,
                "total": 5439
            }
        },
        "white_pruning_stats_wins": {
            "0.5": {
                "checkmate": 13,
                "pieces": 53,
                "total": 66
            },
            "1.0": {
                "checkmate": 2,
                "pieces": 4,
                "total": 6
            },
            "1.5": {
                "checkmate": 2,
                "pieces": 13,
                "total": 15
            },
            "2.0": {
                "checkmate": 10,
                "pieces": 21,
                "total": 31
            },
            "total": 118
        }
    },
    "white_pruning_stats vs black_pruning_stats": {
        "black_pruning_stats": {
            "branches_cut": {
                "1.0": 1568922,
```

```
            "1.5": 933112,
            "total": 2502034
        },
        "number_of_evaluations": {
            "1.0": 41305263,
            "1.5": 25739787,
            "total": 67045050
        },
        "time_spent_computing": {
            "1.0": 2738.2957978248596,
            "1.5": 1352.5165507793427,
            "total": 4090.8123486042023
        },
        "timeouts": {
            "1.0": 393,
            "1.5": 53,
            "total": 446
        },
        "turns_played": {
            "1.0": 6384,
            "1.5": 3625,
            "total": 10009
        }
    },
    "black_pruning_stats_wins": {
        "1.0": {
            "checkmate": 31,
            "pieces": 67,
            "total": 98
        },
        "1.5": {
            "checkmate": 24,
            "pieces": 7,
            "total": 31
        },
        "total": 129
    },
    "draws": {
        "1.0": {
            "pieces": 44,
            "stalemate": 2,
            "total": 46
        },
        "1.5": {
            "pieces": 1,
            "stalemate": 7,
            "total": 8
        },
        "total": 54
    },
    "number_of_games": {
        "1.0": 225,
        "1.5": 75,
        "total": 300
    },
    "number_of_turns": {
        "1.0": 12795,
        "1.5": 7282,
        "total": 20077
    },
    "white_pruning_stats": {
```

```
                "branches_cut": {
                    "1.0": 1562011,
                    "1.5": 975074,
                    "total": 2537085
                },
                "number_of_evaluations": {
                    "1.0": 41291156,
                    "1.5": 25916879,
                    "total": 67208035
                },
                "time_spent_computing": {
                    "1.0": 2740.776922941208,
                    "1.5": 1360.6223676204681,
                    "total": 4101.399290561676
                },
                "timeouts": {
                    "1.0": 417,
                    "1.5": 35,
                    "total": 452
                },
                "turns_played": {
                    "1.0": 6411,
                    "1.5": 3657,
                    "total": 10068
                }
            },
            "white_pruning_stats_wins": {
                "1.0": {
                    "checkmate": 26,
                    "pieces": 55,
                    "total": 81
                },
                "1.5": {
                    "checkmate": 27,
                    "pieces": 9,
                    "total": 36
                },
                "total": 117
            }
        },
        "white_pruning_stats vs black_random_stats": {
            "black_random_stats": {
                "time_spent_computing": {
                    "0.5": 1.5550682544708252,
                    "1.0": 0.2845313549041748,
                    "1.5": 0.4211404323577881,
                    "total": 2.260740041732788
                },
                "timeouts": {
                    "0.5": 0,
                    "1.0": 0,
                    "1.5": 0,
                    "total": 0
                },
                "turns_played": {
                    "0.5": 1738,
                    "1.0": 352,
                    "1.5": 526,
                    "total": 2616
                }
            },
```

```
    "black_random_stats_wins": {
        "0.5": {
            "checkmate": 0,
            "pieces": 0,
            "total": 0
        },
        "1.0": {
            "checkmate": 0,
            "pieces": 0,
            "total": 0
        },
        "1.5": {
            "checkmate": 0,
            "pieces": 0,
            "total": 0
        },
        "total": 0
    },
    "draws": {
        "0.5": {
            "pieces": 0,
            "stalemate": 0,
            "total": 0
        },
        "1.0": {
            "pieces": 0,
            "stalemate": 0,
            "total": 0
        },
        "1.5": {
            "pieces": 0,
            "stalemate": 0,
            "total": 0
        },
        "total": 0
    },
    "number_of_games": {
        "0.5": 70,
        "1.0": 35,
        "1.5": 50,
        "total": 155
    },
    "number_of_turns": {
        "0.5": 3538,
        "1.0": 739,
        "1.5": 1093,
        "total": 5370
    },
    "white_pruning_stats": {
        "branches_cut": {
            "0.5": 282659,
            "1.0": 67710,
            "1.5": 100566,
            "total": 450935
        },
        "number_of_evaluations": {
            "0.5": 10155287,
            "1.0": 2198288,
            "1.5": 3357435,
            "total": 15711010
        },
```

```
            "time_spent_computing": {
                "0.5": 743.2771902084351,
                "1.0": 184.44838547706604,
                "1.5": 275.54965329170227,
                "total": 1203.2752289772034
            },
            "timeouts": {
                "0.5": 1121,
                "1.0": 45,
                "1.5": 25,
                "total": 1191
            },
            "turns_played": {
                "0.5": 1800,
                "1.0": 387,
                "1.5": 567,
                "total": 2754
            }
        },
        "white_pruning_stats_wins": {
            "0.5": {
                "checkmate": 62,
                "pieces": 8,
                "total": 70
            },
            "1.0": {
                "checkmate": 35,
                "pieces": 0,
                "total": 35
            },
            "1.5": {
                "checkmate": 41,
                "pieces": 9,
                "total": 50
            },
            "total": 155
        }
    },
    "white_random_stats vs black_minmax_stats": {
        "black_minmax_stats": {
            "number_of_evaluations": {
                "0.5": 2781023,
                "1.0": 641891,
                "2.0": 7496217,
                "total": 10919131
            },
            "time_spent_computing": {
                "0.5": 273.00743079185486,
                "1.0": 92.78599762916565,
                "2.0": 866.8144435882568,
                "total": 1232.6078720092773
            },
            "timeouts": {
                "0.5": 538,
                "1.0": 83,
                "2.0": 328,
                "total": 949
            },
            "turns_played": {
                "0.5": 549,
                "1.0": 100,
```

```
            "2.0": 513,
            "total": 1162
        }
    },
    "black_minmax_stats_wins": {
        "0.5": {
            "checkmate": 3,
            "pieces": 0,
            "total": 3
        },
        "1.0": {
            "checkmate": 0,
            "pieces": 6,
            "total": 6
        },
        "2.0": {
            "checkmate": 30,
            "pieces": 0,
            "total": 30
        },
        "total": 39
    },
    "draws": {
        "0.5": {
            "pieces": 0,
            "stalemate": 1,
            "total": 1
        },
        "1.0": {
            "pieces": 3,
            "stalemate": 0,
            "total": 3
        },
        "2.0": {
            "pieces": 0,
            "stalemate": 0,
            "total": 0
        },
        "total": 4
    },
    "number_of_games": {
        "0.5": 10,
        "1.0": 10,
        "2.0": 30,
        "total": 50
    },
    "number_of_turns": {
        "0.5": 1100,
        "1.0": 200,
        "2.0": 1026,
        "total": 2326
    },
    "white_random_stats": {
        "time_spent_computing": {
            "0.5": 1.3085403442382812,
            "1.0": 0.20029473304748535,
            "2.0": 0.9692645072937012,
            "total": 2.4780995845794678
        },
        "timeouts": {
            "0.5": 0,
```

```
                    "1.0": 0,
                    "2.0": 0,
                    "total": 0
                },
                "turns_played": {
                    "0.5": 551,
                    "1.0": 100,
                    "2.0": 513,
                    "total": 1164
                }
            },
            "white_random_stats_wins": {
                "0.5": {
                    "checkmate": 2,
                    "pieces": 4,
                    "total": 6
                },
                "1.0": {
                    "checkmate": 0,
                    "pieces": 1,
                    "total": 1
                },
                "2.0": {
                    "checkmate": 0,
                    "pieces": 0,
                    "total": 0
                },
                "total": 7
            }
        },
        "white_random_stats vs black_pruning_stats": {
            "black_pruning_stats": {
                "branches_cut": {
                    "0.5": 520465,
                    "1.0": 44231,
                    "total": 564696
                },
                "number_of_evaluations": {
                    "0.5": 18079669,
                    "1.0": 1273939,
                    "total": 19353608
                },
                "time_spent_computing": {
                    "0.5": 1383.2838823795319,
                    "1.0": 115.32559871673584,
                    "total": 1498.6094810962677
                },
                "timeouts": {
                    "0.5": 2102,
                    "1.0": 7,
                    "total": 2109
                },
                "turns_played": {
                    "0.5": 3277,
                    "1.0": 365,
                    "total": 3642
                }
            },
            "black_pruning_stats_wins": {
                "0.5": {
                    "checkmate": 107,
```

```
            "pieces": 38,
            "total": 145
        },
        "1.0": {
            "checkmate": 9,
            "pieces": 37,
            "total": 46
        },
        "total": 191
    },
    "draws": {
        "0.5": {
            "pieces": 3,
            "stalemate": 0,
            "total": 3
        },
        "1.0": {
            "pieces": 29,
            "stalemate": 0,
            "total": 29
        },
        "total": 32
    },
    "number_of_games": {
        "0.5": 150,
        "1.0": 75,
        "total": 225
    },
    "number_of_turns": {
        "0.5": 6555,
        "1.0": 730,
        "total": 7285
    },
    "white_random_stats": {
        "time_spent_computing": {
            "0.5": 2.9399707317352295,
            "1.0": 0.29627394676208496,
            "total": 3.2362446784973145
        },
        "timeouts": {
            "0.5": 0,
            "1.0": 0,
            "total": 0
        },
        "turns_played": {
            "0.5": 3278,
            "1.0": 365,
            "total": 3643
        }
    },
    "white_random_stats_wins": {
        "0.5": {
            "checkmate": 1,
            "pieces": 1,
            "total": 2
        },
        "1.0": {
            "checkmate": 0,
            "pieces": 0,
            "total": 0
        },
```

```
                "total": 2
            }
        }
    }
```

Listing 3 - Content of the game statistics file