



UNIVERSITY OF
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Dark-Hex: An Imperfect Information Game

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Abstract

Dark-Hex is the imperfect information version of the game Hex. In this work, we have examined the game's interesting properties and provided the solution to some of the small board sizes. We were mainly interested in an approximate solution and a definitive player. We got Nash solution on small boards using pure strategy LP on different game modes. This allowed us to explore and analyze the properties of the different versions of the games we describe here. Next, we evaluated Sequence-LP on different board sizes, the results showed that for bigger board sizes we needed more approximate solutions. For the last part of our evaluation, we worked with the well-known algorithm for partial information environments; Counterfactual Regret Minimization. We did analyze vanilla CFR alongside evolved versions of it, RCFR, f-RCFR. We lastly present an increment to f-RCFR ;appendName; ... ;appendDifferences;. The end of the thesis is our player. We developed a state-of-the-art player (**not sure if we can call it state of the art as there is no player exist for the domain at the moment**). In this chapter, we have trained some classical Reinforcement Learning players, vanilla CFR, RCFR, f-RCFR, ;appendName; and some other popular algorithms (**Should include some combination etc. as well, I cannot name what exactly as I need to work on them before saying anything**). We got the benchmark by setting a league-like system and constantly competing with the players. Our player ;appendName; got the top place **like this...**

1 Introduction

Section structure is temporary

1.1 Definitions (Maybe on background instead)

Game — Game in Game Theory is defined as a set of states which has a result dependent on the actions of the players. Since we are mostly concerned on computational needs and limitations; we will accept a slightly different definition instead. A **game** is a series of actions taken by two or more players which result in a different state for every action. This definition is more complete for our purposes, since we consider information state rather than individual board states. For example;

$$\text{player2} = \left\{ \begin{array}{cc} \cdot & \cdot \\ \cdot & W \end{array} \right\} \neq \left\{ \begin{array}{cc} B & \cdot \\ \cdot & W \end{array} \right\}$$

Here player2(W)'s information state changes depending if the move tried hits a black stone prior to a legal move or not.

Strategy — An action plan for a player which includes an answer for every possible opponent move or game state.

2 Notes

2.1 Dark Hex Versions

Dark Hex is a very poorly researched topic as far as I see. First thing to do seems to be to bring out the interesting points of the game, why is it worth researching on, what properties lays underneath? The rules of the game is hardly described anywhere, therefore it seems like we have a quite wide definition window. We came up with multiple versions of the game, we are not sure what will be the version we investigate at the moment. I will list the current versions discussed, and look into them in detail when deciding the interesting properties of the game. We might look into more than one versions in this thesis. It's yet to be decided.

2.1.1 Classic Dark Hex (Kriegspiel Hex)

Dark Hex is the extension for Kriegspiel Chess on Hex game. It turns the perfect information game of Hex to its imperfect version. The rules of winning and losing still stands as Classic Hex. What changes is that the players are not exposed to opponents move information. So for a player the current state is his/her own stones on the board, the number of moves made by opponent, cells where there is no known stone, and opponent stones where the player tried to make a move and got rejected.

Rejection: If an opponent stone is on the position the player is trying to play on it will result in rejection. Rejection is not a terminal for the current player, meaning the player still needs to make a move, only this time he/she has information on one more of the opponents stones.

Example Game: TODO

2.1.2 Abrupt Dark Hex

Abrupt or short Dark Hex is also an interesting version of Dark Hex. The difference is that instead of rejection Abrupt DH has collisions. Other than that the two games follow same properties.

Collision: If an opponent already has a stone on the location the player tries to make a move, collision happens, the player who tried to make a move loses his/her turn.

2.1.3 Noisy Dark Hex

Noise is an extension for the other versions of DH. The game follows exact version of Abrupt DH or Classical DH with the exception of noise.

Noise: Knowledge of the attempted move is publicly available for both players instead of only the player who tried to make the move. i.e. Player 1 makes a move on a2, there is a Player 2 stone on a2 therefore collision or rejection happens (depending on the type of the game), Player 1 knows the exact location of where one of Player 2's stones are is, Player 2 hears 'a noise' meaning that he/she will have the information that Player 1 tried to make a move on one of his/her stones, but won't know which location that is.

2.1.4 Flash Dark Hex

Same as Noisy Dark Hex except that instead of a noise, flash takes place.

Flash: Instead of noise this time opponent gets a 'flash' for the collision or rejections. Flash's are shown on exact location where collision or rejections has happened.

3 Abrupt Dark Hex Practices

Here is the full pay-off matrix. I think 0-1 without any context looks very much confusing. As far as I can see if the first move of the player B is not blocking the first players second move strategy it's a win otherwise it's a loss. So; Couple other observations:

1. Diagonal is always first player win, since the strategies are the same second player will get rejected both moves and lose.
2. Pattern is the same for each strategy, first players second move is the only important move. If the move is

	01	02	03	10	12	13	20	21	23	30	31	32
01	1, 0	1, 0	1, 0	0, 0	0, 0	0, 1	1, 0	1, 0	1, 0	1, 0	1, 0	1, 0
02	0, 0	0, 0	0, 0	0, 0	0, 0	0, 1	0, 0	0, 0	0, 0	0, 1	0, 0	0, 0
03	0, 0	0, 0	0, 0	0, 0	0, 1	0, 0	0, 0	0, 1	0, 0	0, 0	0, 0	0, 0
10	0, 0	0, 0	0, 0	1, 0	1, 0	1, 0	1, 0	1, 0	1, 0	1, 0	1, 0	1, 0
12	1, 0	1, 0	1, 0	1, 0	1, 0	1, 0	0, 0	0, 0	0, 0	1, 0	1, 0	1, 0
13	0, 0	0, 1	0, 0	0, 0	0, 0	0, 0	0, 1	0, 0	0, 0	0, 0	0, 0	0, 0
20	0, 0	0, 0	0, 0	0, 0	0, 0	0, 1	0, 0	0, 0	0, 0	0, 0	0, 1	0, 0
21	1, 0	1, 0	1, 0	0, 1	0, 0	0, 0	1, 0	1, 0	1, 0	1, 0	1, 0	1, 0
23	1, 0	1, 0	1, 0	1, 0	1, 0	1, 0	1, 0	1, 0	1, 0	0, 0	0, 1	0, 0
30	0, 0	0, 0	0, 0	0, 0	0, 1	0, 0	0, 0	0, 1	0, 0	0, 0	0, 0	0, 0
31	0, 0	0, 1	0, 0	0, 0	0, 0	0, 0	0, 1	0, 0	0, 0	0, 0	0, 0	0, 0
32	1, 0	1, 0	1, 0	1, 0	1, 0	1, 0	0, 0	0, 1	0, 0	1, 0	1, 0	1, 0

4 Number of games for 2x2 board

How many possible games are there for Dark Hex games? What will be our search space? How can we make sure that we capture the bounds correctly? While discussing this all, we have come to realize that even for the smallest boards it is not visible really quick how big the search space or game strategies will be. The easiest way to grasp a concept is to go with an example and tackle a problem along the way. So here we will discover the number of possible strategies on a 2 by 2 board.

4.1 Without end game rules

What we are considering is not an optimal play, so that we can evaluate every possible pure strategy rather than dominant strategies. For the sake of seeing the bigger picture, we will first make an assumption; a game is not over unless the board is filled. On a 2 by 2 board this means there will be exactly 4 moves executed.

First move: b_1

The first move has no rejection possibility therefore the move will for sure go through. Since we do not care about the win at the moment (we only care about filling the board) we won't be checking the cells separately as advantageous or not. We also will ignore isomorphism. These conditions give us equally important 4 cells on the board. So Black's first move can be on any of these cells, and since all of them have the same value for us, we will examine only one, and results will multiply accordingly. We will call the first Black move b_1 . Let's call Black's information state B and White's information state W .

$$\begin{aligned} B &= \{b_1\} \\ W &= \{\} \end{aligned}$$

Second move: w_1

The second move divides into two; if white hits the b_1 or not. They both will have three possible moves (hits b_1 , and moves; or moves one of the other three cells). The information state differs depending on the rejection happening or not, therefore the two moves will have different continuations, let's call the strategy with rejection S_r and without rejection S_n .

$$\begin{aligned} B_{S_r} &= \{b_1\} \\ W_{S_r} &= \{b_1, w_1\} \\ W_{S_n} &= \{w_1\} \end{aligned} \quad \text{or}$$

Third move: b_2

The third move is the same as the second move, only this time for black. Black will make its move either finding w_1 or making a move directly. Gives us 2 move possibilities for each.

$$\begin{aligned} B_{S_r(1)} &= \{b_1, b_2\} & \text{or} \\ B_{S_r(2)} &= \{b_1, w_1, b_2\} \\ W_{S_r} &= \{b_1, w_1\} \end{aligned}$$

Last move: w_2

The last move is where it gets a little more complicated. Depending on what white's prior knowledge is, we have to have separate the results. There are 5 possible W 's for the strategy S_n and 2 for S_r .

$$\begin{aligned} W_{S_n} &= \{w_1, w_2\} & \text{or} \\ W_{S_n} &= \{w_1, b_1, w_2\} & \text{or} \\ W_{S_n} &= \{w_1, b_2, w_2\} & \text{or} \\ W_{S_n} &= \{w_1, b_1, b_2, w_2\} & \text{or} \\ W_{S_n} &= \{w_1, b_2, b_1, w_2\} \end{aligned}$$

$$\begin{aligned} W_{S_r} &= \{b_1, w_1, w_2\} & \text{or} \\ W_{S_r} &= \{b_1, w_1, b_2, w_2\} \end{aligned}$$

So we have;

$$\begin{aligned} &4 \times 3 \times (2 \times 2) \times 5 + \\ &4 \times 3 \times (2 \times 2) \times 2 = 336 \end{aligned}$$

Here we have two products; one for S_n and one for S_r , which are the same for the prior part since the only difference is on the second move where white either hits the black stone or not, and there are 3 different moves for both cases. We have resulted that 336 is the maximum number of games if we assume that the game doesn't end until the board is full. Now let's prune this tree by adding the end game rules.

4.2 With end game rules

It is a bit more manual to calculate the number of games when including the rules. We will examine the moves considering isomorphic properties, which will allow us to calculate the games as a whole when we can benefit. For the initial move for example we have 4 moves, but 2 isomorphic positions (0 is the same as 3, and 1 is the same as 2). So for the first move, we will only consider two positions -close corner(2) and far corner(0)-.

4.2.1 First move to far corner

We have two far corners, and they are isomorphic. That's why investigating one and multiplying the result by 2 is going to suffice. Let's assume we moved to 0 as the first move.

- **Second move to 1** We have two options after this move, either black finishes the game by moving to 2 or game goes to 4 moves if black goes for cell 3.
 - B win $\binom{1}{1} \binom{2}{1} \binom{2}{1}$
 - B loss $\binom{1}{1} \binom{1}{1} \binom{2}{1} \binom{7}{1}$
- **Second move to 2** Here it's easy to see that white will win no matter what black's last move is. This means this branch will expand all the way down (4 moves).
 - B loss $\binom{1}{1} \binom{1}{1} \binom{4}{1} \binom{7}{1}$
- **Second move to 3** We have again win-loss chance for both players. If black moves 2, it's a win (3 moves game) if not it will be a full branching (4 moves).
 - B win $\binom{1}{1} \binom{2}{1} \binom{2}{1}$
 - B loss $\binom{1}{1} \binom{1}{1} \binom{2}{1} \binom{7}{1}$

In the end for the far corner first move:

$$\binom{2}{1} \binom{2}{1} + \binom{2}{1} \binom{7}{1} + \binom{4}{1} \binom{7}{1} + \binom{2}{1} \binom{2}{1} + \binom{2}{1} \binom{7}{1} = 64$$

4.2.2 First move to close corner

The same goes here, we will examine only cell 2.

For the second move, white has two different options; either play to the virtual connection black has, or play next to the black move (and lose). So if the branch continues on VC the game might go on and white still has a probability to win, otherwise, the game ends on 3 moves for sure since both moves give black the connection.

- **Second move to VC** If next Black move is to VC black will win, otherwise black let's white to win in a 4 moves game.
 - B win $\binom{1}{1} \binom{4}{1} \binom{2}{1}$
 - B loss $\binom{1}{1} \binom{3}{1} \binom{2}{1} \binom{7}{1}$
- **Second move to 3** Black wins for sure since it owns the virtual connection and either remaining moves result in a win.
 - B win $\binom{1}{1} \binom{1}{1} \binom{4}{1}$

$$\binom{4}{1} \binom{2}{1} + \binom{3}{1} \binom{2}{1} \binom{7}{1} + \binom{4}{1} = 54$$

By the demonstration of every possible game we now see the result as $2 \cdot (64 + 54) = 236$.