CSE 318 Assignment-03: Adversarial Search in Chain Reaction

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Abstract

This report presents the implementation and analysis of a minimax agent with alpha-beta pruning for the Chain Reaction game, a two-player strategic game involving red and blue orbs on a 9x6 grid. The project encompasses the development of a user interface (Task 1), the minimax algorithm (Task 2), six domain-inspired heuristic evaluation functions (Task 3), and an experimental analysis of their performance (Task 4). Experiments were conducted with varying search depths and heuristics, pitting the AI (Blue) against a random agent (Red). Results indicate that most heuristics favor the AI, with notable exceptions, providing insights into their effectiveness and trade-offs.

1 Introduction

Chain Reaction is a deterministic, turn-based game where two players, Red and Blue, place orbs on a 9x6 board, aiming to eliminate their opponent's orbs through explosions triggered by reaching a cell's critical mass. This assignment required building a game UI, implementing a minimax agent with alpha-beta pruning, designing heuristic evaluation functions, and analyzing their performance. This report details the experimental setup, results, and analysis for Tasks 1 through 4, based on games where the AI (Blue) competes against a random agent (Red).

2 Heuristic Evaluation Functions

To guide the minimax agent's decision-making, six domain-inspired heuristic evaluation functions were designed, each focusing on different strategic aspects of the Chain Reaction game. These heuristics aim to estimate the desirability of a board state from the AI's perspective (playing as Blue). Below, each heuristic is described along with its rationale.

- **Heuristic 0: Explosion Cascade**
  This heuristic evaluates the potential for a player's move to trigger a series of explosions that benefit the player. In Chain Reaction, when a cell reaches its critical mass, it explodes, distributing orbs to adjacent cells, which can lead to further explosions if those cells also reach their critical mass. This chain reaction can rapidly change the board state, potentially converting opponent orbs and gaining control over multiple cells. The rationale behind this heuristic is that moves leading

to beneficial cascades can quickly turn the tide of the game, especially in the mid to late stages when the board is more populated. By estimating the likelihood and impact of such cascades, the AI prioritizes moves that are likely to result in significant gains.

- **Heuristic 1: Strategic Positioning**
  This heuristic focuses on controlling strategically important positions on the board, such as corners, edges, and center cells. Corner cells have a lower critical mass (2), making them easier to defend once controlled, as they are less likely to be exploded by adjacent cells. Edge cells, with a critical mass of 3, serve as defensible buffers or staging points for expansion. Center cells, with a critical mass of 4, are more volatile but can influence a larger area due to their connectivity. The rationale is that controlling these key positions provides defensive stability (for corners and edges) or offensive potential (for center cells), enabling the AI to build a strong foundation for both defense and attack.

- **Heuristic 2: Defensive Stability**
  This heuristic prioritizes moves that enhance the stability of the player's positions, minimizing the risk of explosions that could benefit the opponent. It focuses on avoiding placement in cells near critical mass if adjacent cells are opponent-controlled, reinforcing threatened cells, and maintaining buffers of empty or low-orb cells around critical areas. The rationale is that a defensively stable board state reduces the opponent's opportunities to trigger harmful cascades, allowing the player to build up their presence safely before launching an offensive.

- **Heuristic 3: Chain Amplification**
  This heuristic aims to maximize the potential for chain reactions that amplify the player's control. Unlike Explosion Cascade, which focuses on immediate cascades, Chain Amplification emphasizes setting up sequences where multiple cells are poised to explode in a controlled manner, creating a domino effect that overwhelms the opponent. The rationale is that by carefully building up multiple cells near their critical mass, the player can trigger large-scale conversions of opponent orbs when the chain reaction is initiated, offering a powerful offensive strategy.

- **Heuristic 4: Territorial Dominance**
  This heuristic evaluates the extent of the player's control over the board, emphasizing the occupation of a larger territory. In Chain Reaction, controlling more cells not only brings the player closer to winning but also limits the opponent's options for placement. The rationale is that dominating more territory restricts the opponent's moves and creates more opportunities for explosions that benefit the player, providing both immediate and long-term advantages.

- **Heuristic 5: Critical Mass Control**
  This heuristic focuses on controlling cells that are close to their critical mass, as these cells are pivotal in triggering explosions. By maintaining cells that are one or two orbs away from exploding, the player can time their explosions strategically, either to defend against opponent moves or to launch an attack. The rationale is that having cells near critical mass gives the player flexibility and initiative, allowing them to respond effectively to the opponent's actions and capitalize on key moments in the game.

3 Experimental Setup

The Chain Reaction game was implemented with a console-based UI displaying the board state and game progression. The AI, playing as Blue, uses a minimax algorithm with alpha-beta pruning, while Red's moves are chosen randomly to simulate a human player. Experiments tested the AI's performance across three search depths (1, 4, and 6) and six heuristics:

- **Heuristic 0: Explosion Cascade** - Prioritizes positions likely to trigger beneficial chain reactions.
- **Heuristic 1: Strategic Positioning** - Values control of key board positions (corners, edges, center).
- **Heuristic 2: Defensive Stability** - Emphasizes safe, defensible positions.
- **Heuristic 3: Chain Amplification** - Focuses on maximizing chain reaction potential.
- **Heuristic 4: Territorial Dominance** - Rewards board control and expansion.
- **Heuristic 5: Critical Mass Control** - Evaluates control over cells nearing critical mass.

For each depth-heuristic combination, at least one game was run, with outcomes recorded in "outcome.txt". Depth 1 with Heuristic 0 had three runs, while others had one, possibly due to additional executions or variability from the random agent. The time limit per move was set to 3000 ms, though specific timing data was not analyzed here.

4 Results

The experimental results are summarized below, with Blue (AI) wins indicating heuristic effectiveness against the random Red agent. Table 1 lists outcomes for each depth-heuristic pair.

Summary by Heuristic: - **Heuristic 0**: 4 Blue wins out of 5 games (80%). - **Heuristic 1**: 3/3 (100%). - **Heuristic 2**: 3/3 (100%). - **Heuristic 3**: 1/3 (33.3%). - **Heuristic 4**: 3/3 (100%). - **Heuristic 5**: 3/3 (100%).

5 Analysis

5.1 Best Performing Heuristic

Heuristics 1, 2, 4, and 5 achieved a 100% win rate for the AI (Blue) across all tested depths, suggesting they are highly effective against a random opponent. Heuristic 0 won 80% of its games, with variability at depth 1, while Heuristic 3 performed worst, with only a 33.3% win rate, losing at depths 1 and 6.

Heuristics 1 (Strategic Positioning), 2 (Defensive Stability), 4 (Territorial Dominance), and 5 (Critical Mass Control) consistently outperformed others, likely due to their balanced focus on control, stability, and critical mass timing, which exploit the random

Table 1: Game Outcomes by Depth and Heuristic

Depth	Heuristic	Winner	AI Win?
1	0 (Explosion Cascade)	RED, BLUE, BLUE	2/3
1	1 (Strategic Positioning)	BLUE	1/1
1	2 (Defensive Stability)	BLUE	1/1
1	3 (Chain Amplification)	RED	0/1
1	4 (Territorial Dominance)	BLUE	1/1
1	5 (Critical Mass Control)	BLUE	1/1
4	0	BLUE	1/1
4	1	BLUE	1/1
4	2	BLUE	1/1
4	3	BLUE	1/1
4	4	BLUE	1/1
4	5	BLUE	1/1
6	0	BLUE	1/1
6	1	BLUE	1/1
6	2	BLUE	1/1
6	3	RED	0/1
6	4	BLUE	1/1
6	5	BLUE	1/1

agent's lack of strategy. Heuristic 0's success (80%) indicates that prioritizing explosion cascades is viable but less reliable at shallow depths. Heuristic 3's poor performance suggests that an aggressive focus on chain amplification may overextend the AI, making it vulnerable.

5.2 Trade-offs Observed

- **Depth Impact**: At depth 4, all heuristics resulted in Blue wins, indicating that deeper search compensates for heuristic weaknesses (e.g., Heuristic 3). At depth 6, Heuristic 3 failed again, suggesting its strategy scales poorly with increased computation. - **Aggressiveness vs. Stability**: Heuristic 3 (Chain Amplification) prioritizes aggressive chain reactions, which may lead to losses against even a random opponent if explosions benefit Red. In contrast, Heuristics 2 and 5 emphasize stability and control, yielding consistent wins. - **Consistency**: Heuristic 0's mixed results at depth 1 (2 wins, 1 loss) highlight variability, possibly due to the random agent's unpredictable moves affecting cascade outcomes at shallow depths.

6 Conclusion

The minimax agent with alpha-beta pruning, supported by a robust UI and diverse heuristics, effectively models Chain Reaction. Heuristics 1, 2, 4, and 5 emerged as the most reliable, achieving perfect win rates, while Heuristic 3 underperformed, likely due to its aggressive nature. Deeper search depths generally improved performance, though limitations in sample size (e.g., single runs for most combinations) suggest further experiments could refine these insights. Future work could explore AI vs. AI matches to test heuristic robustness against strategic opponents.