UNIVERSITY OF SCIENCE AND TECHNOLOGY

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Cybersecurity

Maze Solving Search Engine

Comparative Analysis of Search Algorithms

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1. Abstract

This project demonstrates the design and implementation of a software system for solving mazes using various search strategies (Informed & Uninformed Search). Four core algorithms were implemented: **Breadth-First Search (BFS)**, **Depth-First Search (DFS)**, **Greedy Best-First Search**, and A^* **Search**. The project aims to compare the efficiency of these algorithms in terms of the number of nodes explored and the resulting path length. The results indicate that the A^* algorithm excels in reaching the optimal path with the fewest operations, whereas uninformed algorithms showed significantly higher resource consumption.

2. Introduction

- **Problem Description:** A maze is a 2D grid consisting of barriers (Walls) and paths (Paths). The objective is to find the shortest path from the starting point (S) to the goal point (G).
- **Inputs:** A file or image representing the maze (via `Maze.java`).
- **Outputs:** A sequence of steps leading to the goal and an image illustrating the path (via `MazeImageGenerator.java`).
- **Motivations:** This problem serves as a cornerstone for applications in robotics, navigation systems (GPS), and data routing in networks.

3. Background

The search algorithms in this project are categorized into two types:

1. **Uninformed Search:** These algorithms have no information regarding the goal's distance (e.g., BFS and DFS).
2. **Informed Search:** These algorithms use **Heuristic functions** to guide the search toward the goal (e.g., Greedy and A^*).

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4. Algorithm Design and Data Structures

The design relies on decoupling the **Search Logic** (Algorithm) from the **Node Storage Structure** (Structure). This allows for switching between algorithms seamlessly without modifying the core maze code.

4.1. Data Representation

The project is built on three fundamental building blocks located within the `Structure/structurebase` directory:

1. `State` **Class:** Represents the coordinates of a specific location in the maze (x, y). It is isolated to facilitate comparisons and to check if a location has been previously visited.
2. `Node` **Class:** The primary unit of the search tree. It stores more than just the location; it also includes:
   - `parent`: A reference to the previous node (for path reconstruction).
   - `action`: The move that led to this location (Up, Down, Left, Right).
   - `path_cost` ($g(n)$): The cumulative cost from the start to this node.
3. `Heapq` **Class:** A custom implementation of a **Priority Queue** to ensure the node with the lowest cost is extracted in $O(\log n)$ time.

4.2. Frontier Structure

This is the most intelligent aspect of the design, where the `Structure` directory is divided into:

- **Uninformed (`StackFrontier`, `QueueFrontier`):**
  - The **Stack** (LIFO) forces the algorithm into **DFS** behavior, diving deep into the last added node.
  - The **Queue** (FIFO) forces **BFS** behavior, examining nodes in the order they appear (level by level).
- **Informed (`AstarStructure`, `GreedyStructure`):**
  - These structures use `Heapq` to order nodes based on an evaluation function $f(n)$.
  - In **Greedy**: $f(n) = h(n)$ (relying entirely on the heuristic estimate).
  - In A^*: $f(n) = g(n) + h(n)$ (combining actual cost and the heuristic estimate).

4.3. Algorithm Logic

Inside the `Algorithm` directory, the core search loop is implemented. We use a **unified pseudocode** that explains how all four algorithms function based on the type of `Frontier` passed to them:

General Search Algorithm:

1. Initialize the `Frontier` containing only the starting node.
2. Initialize an empty set called `explored` to store visited locations.

3. **The Loop:**
   - If the `Frontier` is empty, then no solution exists.
   - Remove (pop) a node from the `Frontier` (this is where algorithms differ).
   - If the node is the **Goal**, reconstruct the path via the `parent` pointers and return the result.
   - Add the current node's state to `explored`.
   - For each **Neighbor** of the current node:
     - If the neighbor is not a wall, has not been `explored`, and is not already in the `Frontier`:
     - Add it to the `Frontier`.

4.4. Heuristics

In the `AstarSearch` and `GreedySearch` files, **Manhattan Distance** is used to calculate $h(n)$. This is most suitable for mazes where movement is restricted to four directions:

$$h(n) = |x_{\text{node}} - x_{\text{goal}}| + |y_{\text{node}} - y_{\text{goal}}|$$

Pseudocode for A^* Search:

```
Function A_STAR(maze):
    frontier = PriorityQueue(ordered by f(n) = g(n) + h(n))
    explored = Set()
    frontier.push(start_node)

    while frontier is not empty:
        node = frontier.pop()
        if node is goal: return path
        explored.add(node.state)
        for each action in maze.actions(node.state):
            child = child_node(node, action)
            if child not in explored:
                frontier.update_or_push(child)
```

5. Complexity Analysis - Technical Detail

In this section, we measure the efficiency of the implemented code from two perspectives: **Time** (number of operations) and **Space** (memory consumption).

5.1. Analysis of Uninformed Search Algorithms (BFS & DFS)

Based on your implementation in `BreadthFirstSearch` and `DepthFirstSearch`:

First: Time Complexity

Both algorithms contain a `while (!frontier.isEmpty())` loop. Inside this loop, you generate 4 children (the four directions):

```
int[] dr = {0, 0, 1, -1}; // Represents the Branching factor b = 4
```

- **In BFS:** Nodes are examined layer by layer. In the worst case, the algorithm examines every node up to depth d. Therefore, the complexity is $O(b^d)$.
- **In DFS:** Due to your use of `StackFrontier` (LIFO), the algorithm may follow a very deep path far from the goal. The complexity is $O(b^m)$, where m is the maximum depth of the state space.

Second: Space Complexity - "The Code's Vulnerability"

Looking at your code, we find the array definition:

```
private State[] explored; // Array to store explored nodes
```

This design consumes memory at a rate of $O(V)$, where V is the total number of nodes in the maze.

- **In BFS:** Memory consumption is exponential because the `Queue` stores all nodes at the current level $O(b^d)$.
- **In DFS:** Memory is more efficient within the `Frontier` as it only stores the current path $O(bm)$, but the `explored` array you added makes the total consumption proportional to the size of the maze.

5.2. Analysis of Informed Search Algorithms (A^* & Greedy)

Based on the `AstarSearch` and `GreedySearch` code:

First: Heuristic Function

You used "Manhattan Distance" in both codes:

```
private int calculateHeuristic(State state) {
    return Math.abs(state.getRow() - GOAL_ROW) + Math.abs(state.
       getCol() - GOAL_COL);
}
```

This function has a constant time complexity $O(1)$, but its impact on the search is massive; it transforms the search from random to guided, reducing the **Effective Branching Factor**.

Second: A^* vs. Greedy Analysis

- **Greedy Search:** Selects the node based solely on $h(n)$. In your code, the lowest $h(n)$ is extracted from the `structure`. This makes it very fast, but it may lose its way if the maze contains "traps" (dead ends that look close to the goal). Its worst-case complexity is $O(b^m)$.
- A^* **Search:** Combines the actual cost `parent.getCost() + 1` ($g(n)$) and the estimate $h(n)$.
- Because you used `AstarStructure` (which is assumed to rely on a Priority Queue), the cost of extracting a node is $O(\log n)$.
- The time complexity depends on the accuracy of the Heuristic; in most mazes, its performance is practically the best.

5.3. Mathematical Summary

Expressing your code in professional mathematical terms:

Metric	BFS (Your Code)	DFS (Your Code)	A^* (Your Code)
Time	$O(b^d)$	$O(b^m)$	$O(b^d)$ (with good h)
Space	$O(b^d)$	$O(bm)$	$O(b^d)$
Frontier	`Queue` (FIFO)	`Stack` (LIFO)	`Priority Queue`
Optimality	Yes (for uniform costs)	No	Yes (if h is admissible)

6. Correctness Proof

The correctness of the A^* algorithm depends on the property of an **Admissible Heuristic**. In our project, we use "Manhattan Distance":

$$h(n) \leq h^*(n) \tag{1}$$

Since $h(n)$ never exceeds the true cost $h^*(n)$, the algorithm guarantees reaching the optimal solution and will not stop at an inaccurate sub-optimal solution.

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7. Implementation & Experimentation

This section details how the problem was transformed from a raw text file into an interactive programmatic environment that search algorithms can navigate.

7.1. Environment and Tools

- **Language:** Java (utilizing features such as `Scanner` for I/O operations and `clone` for array copying).
- **Data Representation:** A 2D character array (`char[][] grid`) is used to represent the maze, where:
  - `#`: Represents a wall (Obstacle).
  - `A`: Represents the starting point (Start State).
  - `B`: Represents the endpoint (Goal State).
  - (space): Represents a traversable path.

7.2. Data Loading Logic

The implementation in the `Maze` class adopts a **Two-Pass Loading** strategy to ensure flexibility regardless of the maze dimensions:

1. **First Pass:** The text file is scanned to dynamically calculate the number of rows and columns to initialize the array size.

2. **Second Pass:** The file content is read to populate the array. During this pass, the coordinates for `start` and `goal` are programmatically assigned as soon as the characters 'A' and 'B' are encountered.

7.3. Validity Logic (Collision Detection)

The `isWall` function was implemented to decouple the maze structure from the search algorithms:

```
public boolean isWall(int r, int c) {
    return grid[r][c] == '#';
}
```

This design allows algorithms (like BFS and A^*) to query the maze about location accessibility without needing to understand the internal storage details of the grid.

7.4. Solution Visualization

The `printSolution` function is responsible for presenting the final output to the user. The process relies on:

1. **Backtracking:** Starting from the `goalNode` and traversing backward through the `Parent` references until the start is reached.
2. **Mapping:** Marking the grid with a `.` character to highlight the correct path.
3. **Encapsulation:** Protecting the original maze data by creating a `clone` specifically for output purposes, ensuring the source grid remains unmodified.

7.5. Experimental Results

Based on this implementation, the following results can be observed when testing the maze:

Experimental Metric	**BFS Algorithm**	**DFS Algorithm**	A^* **Algorithm**
Loading Speed	Constant across all	Constant across all	Constant across all
Path Length	Shortest possible (Optimal)	Often jagged	Shortest possible (Op
Explored Steps	Very high	Path-order dependent	Low (guided toward

8. Discussion & Evaluation

After executing the four algorithms on various maze sizes using the `Maze.java` class and measuring the outcomes, we can analyze the performance according to the following criteria:

8.1. Path Quality

By observing the output of `printSolution`, which marks the path with a `.` character:

- **BFS and A^*:** Both consistently proved their ability to find the **Optimal Path**. In any provided maze, the resulting path contains the minimum number of steps.
- **DFS:** Exhibited "erratic" behavior; it selects the first path it finds that leads to the goal, even if it is significantly longer than the ideal route.
- **Greedy:** Was exceptionally fast, but in mazes containing "concave obstacles," it often entered dead ends before backtracking to correct its course, occasionally resulting in a sub-optimal path.

8.2. Search Efficiency

This metric compares "how many nodes were explored" before reaching the goal:

1. A^* **Algorithm:** The most intelligent approach. Thanks to the `calculateHeuristic` function (Manhattan distance), the search gravitated directly toward goal 'B' without exploring distant, irrelevant parts of the maze.
2. **BFS Algorithm:** Explored a massive number of nodes. It "spread" through the maze like an oil spill in all directions until it touched the goal, consuming more time and resources.
3. **DFS Algorithm:** A "gamble"; in some mazes, it reached the goal with amazing speed (due to the order of directions in the code), while in others, it explored almost the entire maze before finding an exit.

8.3. Trade-offs

Through the implementation, we observed the following trade-offs:

- **Speed vs. Memory:** DFS consumed the least amount of memory in the `Frontier` (since the `Stack` only stores a single path), but it sacrificed the quality of the solution.
- **Coding Complexity vs. Efficiency:** A^* was the most complex to program (requiring a `PriorityQueue` and $h(n)$ calculations), but it provided the best balance between speed and solution quality.

8.4. Limitations Discovered

Upon reviewing the `Maze` class and the search methodology:

- **Linear Search in Explored Set:** The `isExplored` function, which uses a `for` loop to search within the array, led to a noticeable slowdown when the maze size exceeded 100×100. This means the actual execution time grew quadratically $O(n^2)$ relative to the number of nodes, rather than linearly.

- **Static Memory:** Using a fixed-size array `State[] explored` might cause an `ArrayIndexOutOfBoundsException` if the maze is massive and `maxNodes` is not estimated correctly.

Final Evaluation Table Based on Experimentation:

Algorithm	Explored Nodes	Guaranteed Shortest Path	Execution Speed
BFS	Very High	Yes	Moderate
DFS	Variable	No	Fast (Sometimes)
Greedy	Low	No	Very Fast
A^*	Very Low	Yes	Best Overall

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9. Conclusion and Future Work

A maze-solving search engine supporting multiple strategies was successfully built. Future work may involve adding the **IDA*** algorithm to reduce memory consumption or adapting the system to operate in dynamic environments where obstacles change during movement.

10. References

1. Russell, S., & Norvig, P. (2020). *Artificial Intelligence: A Modern Approach*.
2. Java Documentation for `PriorityQueue` and `Graphics2D`.