Artificial Intelligence & Applications

Coursework Submission

Foreward

Question 1.1

By definition, a maze solver involves finding a path from a starting node to a goal node somewhere else in a maze. The solver explores the maze by moving from one node to another, evaluating it's next move and, based on the algorithm in use, moving to the next node in the sequence. We can re-phrase this logic in order to understand it as a search algorithm, where the solver generates a sequence of moves that lead to the goal node while avoiding dead-ends and loops. From this point of view, the possible paths through the maze can be seen as a search space, and the solver is tasked with finding a solution path that reaches the goal node and optionally satisfies additional constraints or criteria, such as minimising the number of steps taken or avoiding obstacles.

Question 1.2

1. The depth-first search algorithm attempts to traverse a given graph by going down a branch as far as possible before backtracking. In the computer, we can represent this as two primary data structures: a stack and a hashtable/hashmap. The algorithm will always examine the node at the head of the stack to detect it's neighbours. This process repeats until the head of the stack has no more unvisited neighbours, at which point it is popped and we check the previous node for unvisited neighbours, effectively backtracking to the previously visited node. If we detect that the current node is our target node, we can stop our algorithm, and the path we've taken to get there is, in reverse order, all the nodes in the stack.

2. The solution to the file `maze-Easy.txt` is as follows:

```
{0, 1}, {1, 1}, {1, 2}, {1, 3}, {1, 4}, {1, 5}, {1, 6}, {1, 7}, {1, 8},
{1, 9}, {1, 10}, {1, 11}, {1, 12}, {1, 13}, {1, 14}, {1, 15}, {2, 15}, {3,
15}, {4, 15}, {5, 15}, {6, 15}, {6, 16}, {6, 17}, {7, 17}, {8, 17}, {8,
18}, {9, 18}
```

It can be visualised like so:
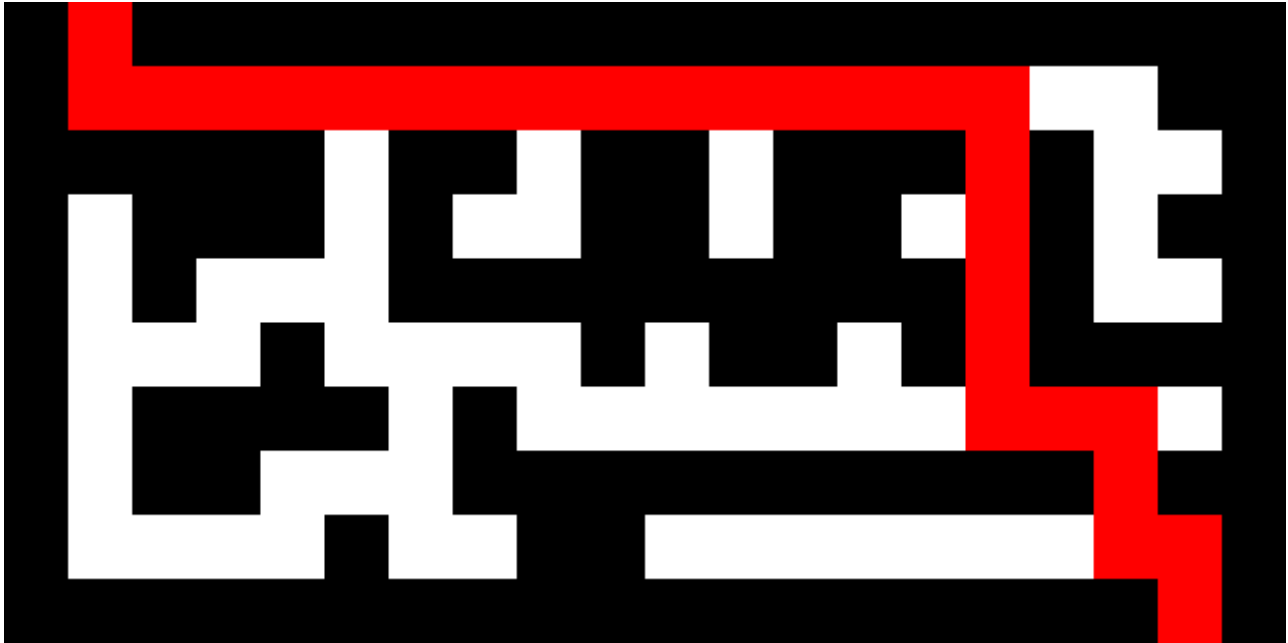
3. Having updated the program, we can obtain some more details about it's performance. The output of the program computing the solution to `maze-Easy.txt` is:

```
///////////////////////////////
/   Explored 78 nodes
/   The final path contains 27 nodes
/   The program took 0.000158s to compute the final path
///////////////////////////////
```

Here, we can see that although DFS is in no way a slow algorithm, it explores a lot of nodes for the amount of nodes in the final path. Since it has no understanding of direction or goal, it simply explores the maze branch-by-branch until it stumbles across the ending. It is fast, due to the small amount of data structures being used, and the fact that they're very efficient data structures (hashmap, stack), so little computational time is required to update, access and modify them. However, it's theoretical 'efficiency' with regard to the nodes explored is not very high, and in particular it lacks any intent behind it's searches, exploring aimlessly until it stumbles upon the target node.

4. We can generalise the algorithm to compute the solutions of the following 3 mazes:

```
maze-Medium.txt
///////////////////////////////
/   Explored 6526 nodes
/   The final path contains 641 nodes
/   The program took 0.012859s to compute the final path
///////////////////////////////
```

```
maze-Large.txt
////////////////////////////////
/  Explored 13580 nodes
/  The final path contains 1120 nodes
/  The program took 0.017514s to compute the final path
////////////////////////////////

maze-VLarge.txt
////////////////////////////////
/  Explored 123291 nodes
/  The final path contains 4085 nodes
/  The program took 0.145307s to compute the final path
////////////////////////////////
```

The maze solution paths are as follows:

maze-Medium.txt:

```
{0, 1}, {1, 1}, {1, 2}, {1, 3}, {1, 4}, {1, 5}, {1, 6}, {1, 7}, {1, 8},
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1874}, {988, 1875}, {989, 1875}, {989, 1876}, {989, 1877}, {989, 1878},
{990, 1878}, {990, 1879}, {990, 1880}, {991, 1880}, {992, 1880}, {992,
1881}, {993, 1881}, {994, 1881}, {995, 1881}, {996, 1881}, {997, 1881},
{997, 1880}, {998, 1880}, {999, 1880}
```

In the program output, we can see a correlation between the amount of nodes explored and the execution time, which can be visualised on a graph:
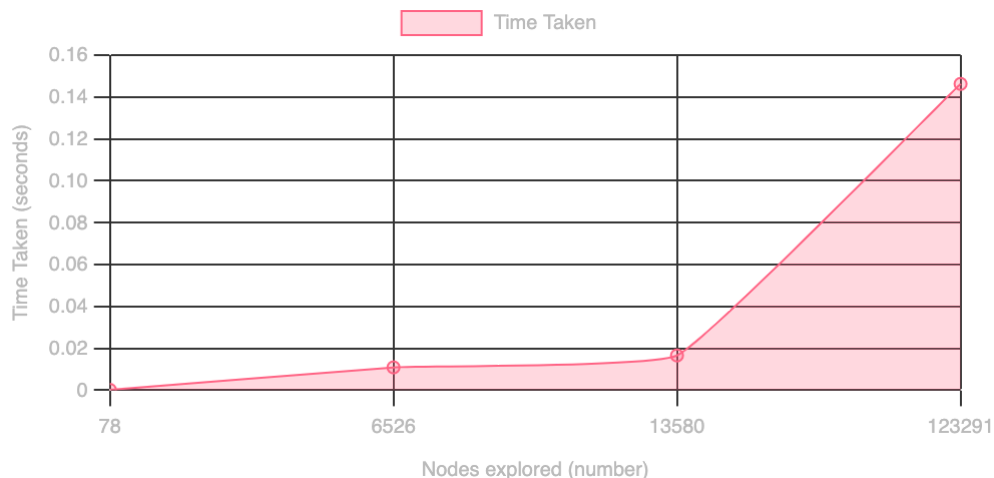
As in the previous example, we can see a glimpse at the inefficiency of DFS, particularly it's inability to detect complex paths. In fact, DFS is largely limited by the pattern it searches for neighbouring nodes in, since this determines the general direction in which it will search first. The choice between the 4 cardinal directions (in the case of a maze such as the one given) can be the difference between DFS finding the target almost instantly or taking an excessive amount of time and iteration to discover it's target. In fact, the only reason the amount of nodes searched in the `maze-Large.txt` file is so low is due to a specific optimisation in the code which check to see if a maze is wider than it is tall or not. If it is, we check for Left/Right nodes first, and only then check Down/Up, wheres if it's not, we check Down/Up first, and then Left/Right.

If we look at the performance of the `maze-Large.txt` file *without* this optimisation (setting the `FORCESINGLESEARCHPATTERN` global variable to true), we see the following result:

```
/////////////////////////////////
/   Explored 71838 nodes
/   The final path contains 1050 nodes
/   The program took 0.087401s to compute the final path
/   The computed solution was stored in ./maze-Large-solution.txt
/   A visualization of the computed solution was stored in ./maze-Large.ppm
/////////////////////////////////
```

Interestingly, we obtain a theoretically better solution, with a final path containing just `1050` nodes compared to the `1150` of the 'optimised' DFS. However, the amount of nodes explored is drastically different, jumping from `13580` to a whopping `71838`, a 5.2x jump in nodes searched, along with an equal jump from `0.019069s` of search time to `0.087401s`, a leap of 4.58x.

It's clear from these findings that with Depth-First search, we're very limited by the maze that we search. We might get lucky and find a maze for which depth-first search performs very well, as a possible solution exists along it's early search path. However, we can also run into a situation where the maze does not suit our DFS algorithm, and we can waste a lot of time backtracking and searching to no avail.

Question 1.3

1. There are many other maze-solving/pathfinding algorithms, such as Breadth-First-Search (BFS) or Dijkstra's algorithm. Both of these prioritise exploring outwards from the starting node, which works well when there are multiple target nodes which to find a path to. However, in our case, we're looking for a more directed algorithm, as we have just one goal node in each maze. In this case, neither of the mentioned algorithms guarantee us the best result. Enter the A* algorithm, essentially an upgraded version of Dijkstra's algorithm, it incorporates a heuristic function which ranks nodes based on how close they are to the finish. In this situation, we will use the manhattan heuristic, as our maze is computed along a grid, and nodes can only move in the 4 cardinal directions. A* guarantees us the best possible path, meaning we can be confident that we'll always have the shortest and most efficient solution, even if it means more nodes searched.

2. The path and statistics for the A* algorithm are as follows:

```
maze-Easy.txt
////////////////////////////////
/  Explored 53 nodes
/  The final path contains 27 nodes
/  The program took 0.000086s to compute the final path
/  The computed solution was stored in ./maze-Easy-solution-astar.txt
/  A visualization of the computed solution was stored in ./maze-Easy-
astar.ppm
////////////////////////////////

maze-Medium.txt
////////////////////////////////
/  Explored 2020 nodes
/  The final path contains 321 nodes
/  The program took 0.002956s to compute the final path
/  The computed solution was stored in ./maze-Medium-solution-astar.txt
/  A visualization of the computed solution was stored in ./maze-Medium-
astar.ppm
////////////////////////////////

maze-Large.txt
////////////////////////////////
/  Explored 41923 nodes
/  The final path contains 974 nodes
```

```
/   The program took 0.048294s to compute the final path
/   The computed solution was stored in ./maze-Large-solution-astar.txt
/   A visualization of the computed solution was stored in ./maze-Large-
astar.ppm
/////////////////////////////////

maze-VLarge.txt
/////////////////////////////////
/   Explored 274033 nodes
/   The final path contains 3691 nodes
/   The program took 0.361687s to compute the final path
/   The computed solution was stored in ./maze-VLarge-solution-astar.txt
/   A visualization of the computed solution was stored in ./maze-VLarge-
astar.ppm
/////////////////////////////////
```

The paths for the solutions are as follows:

maze-Easy.txt:

```
{0, 1}, {1, 1}, {1, 2}, {1, 3}, {1, 4}, {1, 5}, {2, 5}, {3, 5}, {4, 5},
{5, 5}, {5, 6}, {5, 7}, {5, 8}, {6, 8}, {6, 9}, {6, 10}, {6, 11}, {6, 12},
{6, 13}, {6, 14}, {6, 15}, {6, 16}, {6, 17}, {7, 17}, {8, 17}, {8, 18},
{9, 18}
```

maze-Medium.txt:

```
{0, 1}, {1, 1}, {1, 2}, {1, 3}, {1, 4}, {1, 5}, {1, 6}, {1, 7}, {1, 8},
{1, 9}, {2, 9}, {3, 9}, {3, 10}, {3, 11}, {4, 11}, {5, 11}, {5, 12}, {5,
13}, {5, 14}, {6, 14}, {7, 14}, {8, 14}, {9, 14}, {10, 14}, {11, 14}, {12,
14}, {13, 14}, {14, 14}, {14, 15}, {14, 16}, {14, 17}, {15, 17}, {16, 17},
{17, 17}, {18, 17}, {19, 17}, {20, 17}, {21, 17}, {21, 18}, {21, 19}, {21,
20}, {21, 21}, {21, 22}, {22, 22}, {23, 22}, {24, 22}, {25, 22}, {25, 23},
{25, 24}, {25, 25}, {26, 25}, {26, 26}, {27, 26}, {28, 26}, {29, 26}, {30,
26}, {31, 26}, {32, 26}, {32, 27}, {32, 28}, {33, 28}, {33, 29}, {33, 30},
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{52, 68}, {52, 69}, {53, 69}, {53, 70}, {54, 70}, {55, 70}, {56, 70}, {57,
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70}, {58, 70}, {58, 71}, {58, 72}, {58, 73}, {58, 74}, {58, 75}, {58, 76}, {58, 77}, {59, 77}, {60, 77}, {61, 77}, {61, 78}, {61, 79}, {61, 80}, {61, 81}, {61, 82}, {62, 82}, {63, 82}, {63, 83}, {64, 83}, {65, 83}, {65, 84}, {65, 85}, {65, 86}, {65, 87}, {65, 88}, {65, 89}, {66, 89}, {67, 89}, {67, 90}, {68, 90}, {68, 91}, {69, 91}, {69, 92}, {70, 92}, {71, 92}, {71, 93}, {72, 93}, {73, 93}, {73, 92}, {74, 92}, {75, 92}, {75, 93}, {76, 93}, {76, 94}, {76, 95}, {76, 96}, {76, 97}, {77, 97}, {77, 98}, {78, 98}, {78, 99}, {79, 99}, {80, 99}, {80, 100}, {80, 101}, {80, 102}, {81, 102}, {81, 103}, {81, 104}, {81, 105}, {81, 106}, {81, 107}, {82, 107}, {82, 108}, {82, 109}, {82, 110}, {83, 110}, {84, 110}, {84, 111}, {85, 111}, {86, 111}, {86, 112}, {86, 113}, {85, 113}, {85, 114}, {85, 115}, {85, 116}, {85, 117}, {85, 118}, {85, 119}, {85, 120}, {85, 121}, {86, 121}, {87, 121}, {87, 122}, {87, 123}, {87, 124}, {88, 124}, {89, 124}, {90, 124}, {90, 125}, {91, 125}, {91, 126}, {91, 127}, {91, 128}, {91, 129}, {91, 130}, {91, 131}, {92, 131}, {92, 132}, {92, 133}, {92, 134}, {92, 135}, {93, 135}, {93, 136}, {93, 137}, {92, 137}, {91, 137}, {91, 138}, {91, 139}, {90, 139}, {90, 140}, {90, 141}, {90, 142}, {90, 143}, {91, 143}, {91, 144}, {91, 145}, {92, 145}, {93, 145}, {94, 145}, {94, 146}, {94, 147}, {95, 147}, {95, 148}, {95, 149}, {95, 150}, {94, 150}, {94, 151}, {94, 152}, {93, 152}, {93, 153}, {93, 154}, {93, 155}, {93, 156}, {92, 156}, {92, 157}, {92, 158}, {92, 159}, {92, 160}, {92, 161}, {92, 162}, {92, 163}, {92, 164}, {92, 165}, {92, 166}, {92, 167}, {92, 168}, {92, 169}, {92, 170}, {92, 171}, {92, 172}, {92, 173}, {92, 174}, {92, 175}, {92, 176}, {92, 177}, {92, 178}, {92, 179}, {92, 180}, {92, 181}, {92, 182}, {93, 182}, {94, 182}, {95, 182}, {96, 182}, {96, 183}, {96, 184}, {96, 185}, {96, 186}, {95, 186}, {95, 187}, {95, 188}, {95, 189}, {95, 190}, {96, 190}, {96, 191}, {96, 192}, {95, 192}, {95, 193}, {95, 194}, {95, 195}, {95, 196}, {95, 197}, {95, 198}, {96, 198}, {97, 198}, {98, 198}, {99, 198}

maze-Large.txt:

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As with DFS, let us graph our results, comparing the nodes searched vs the time taken:
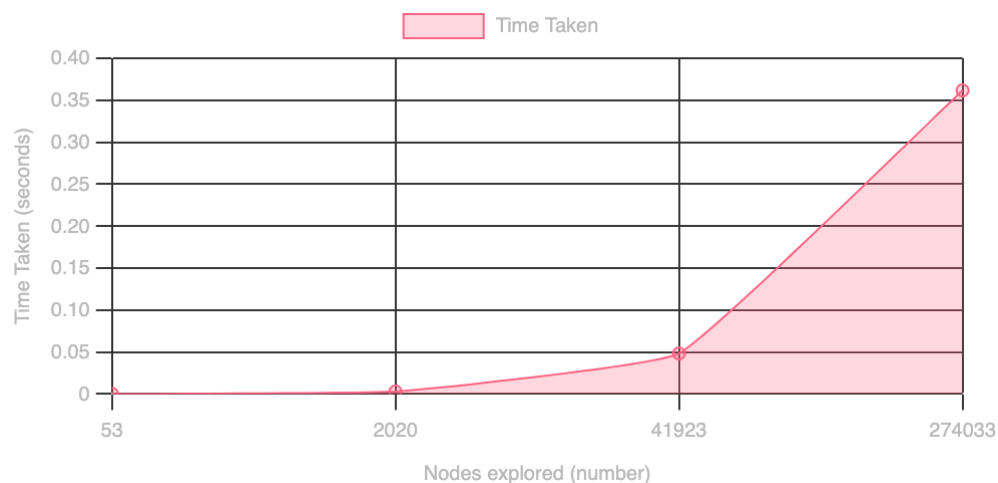
Again, we can see a clear correlation between the amount of nodes searched and our execution time. It's clear from these answers that A* in general finds significantly more efficient solutions to the given mazes. For example, in the case of the medium maze, the solution length is cut almost in half, from `641` nodes to just `321`. If the numbers themselves weren't a large enough difference, let us look at the generated visualisations for these two mazes:
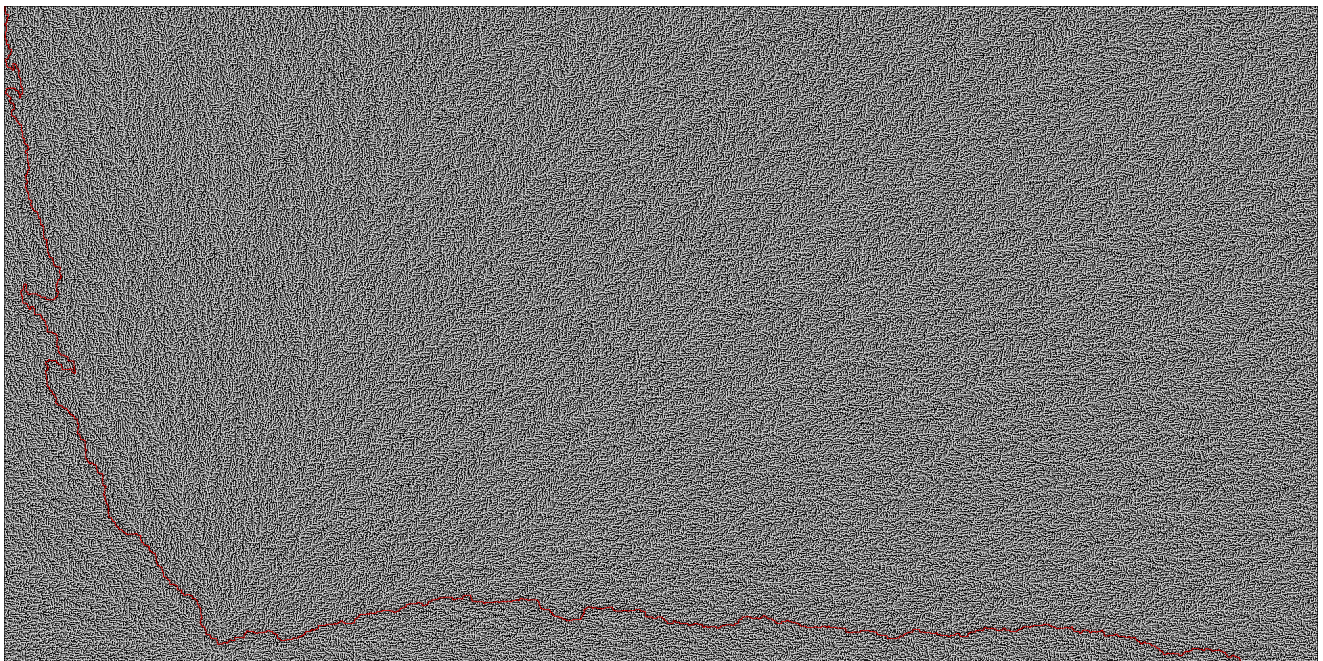
DFS solution:

A* solution:
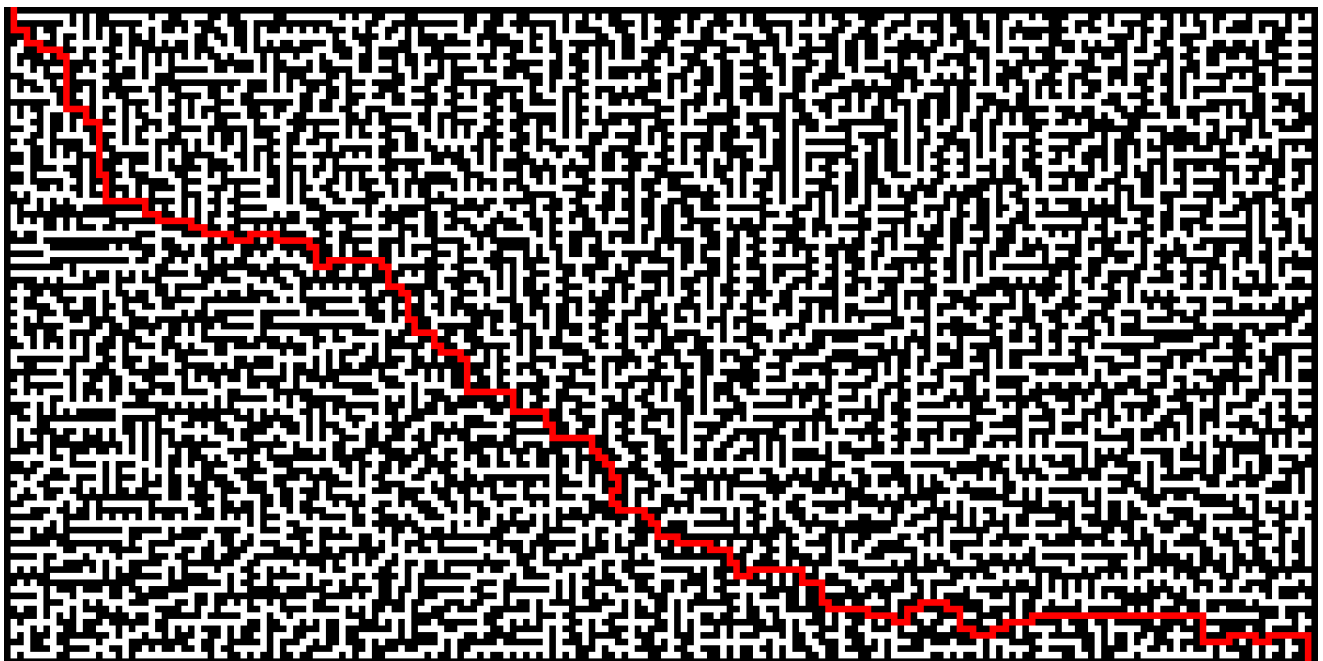
the effect of the heuristic on A*'s pathfinding is very clear here, demonstrating it's sense of direction and intent when choosing new nodes which to move to. As a result, it finds this significantly better solution while searching just 30% of the nodes that DFS does, and as a result solves the maze in just 27% the time it took DFS.

3. Interestingly, this performance and time improvement doesn't necessarily carry over to every maze. If we look at `maze-VLarge.txt`, we can see that the A* algorithm explored more than twice the amount of nodes (`274033` vs `123291`), and as a result took 2.4x as much time to compute the solution (`0.361687s` vs `0.149463s`).

There main culprit for this behaviour is likely the possibility that **there are many solutions to the maze of similar length.** Whereas DFS is not burdened by knowledge of the endpoint, A* searches specifically in the direction of the endpoint by checking the nodes with the lowest f-score first. If we have many solutions to the given maze, and thus many paths with similar f-score's, the A* algorithm will attempt to explore all of them in order to find the best solution, thus needlessly exploring a number of false positives, which add to it's visited node count and slow it down.

Nonetheless, this overestimation seems to be worth it, given that, as expected, A* returns an optimal result, with it's path spanning just `3691` nodes, rather than DFS' `4085`. It's interesting to note here that another reason that the delta in searched nodes between A* and DFS in the `VLarge` scenario is that the DFS algorithm gets quite lucky here, in that one of the early paths is a valid and complete solution. Let's compare the two:

DFS:

A*:
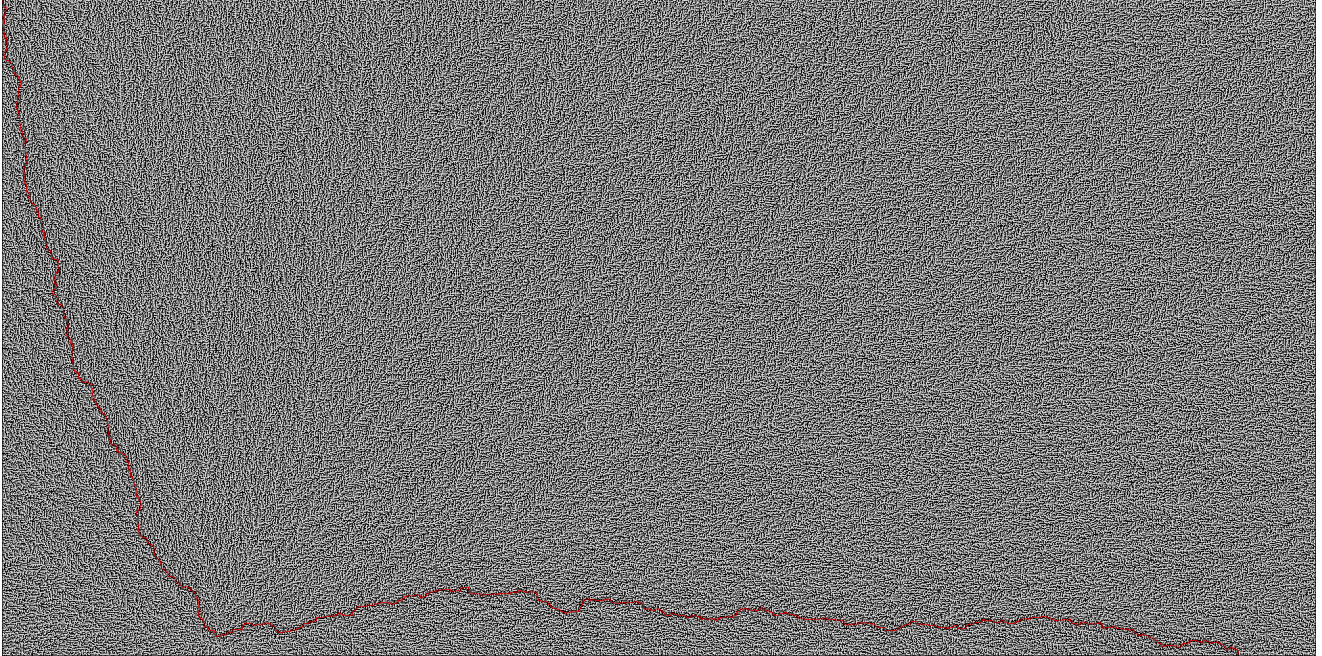
We can see here that the solutions of both DSF and A* are quite similar, and as a result can make a reasonable guess that in this particular situation, DFS got lucky and performed exceptionally well, allowing it to beat A* in both it's performance and node exploration, with only a minimal reduction in solution efficiency.

4. With our information laid out in front of us, we can reach a conclusion:

DFS is very dependant on the maze it is exploring. In an ideal maze where the optimal solution path fits the DFS' search pattern closely, DFS is able to comfortably outperform A*. However, as it is blind to it's target and the cost of progression, it's unable to perform a search with any sort of intelligence, and so it can get caught up on very simple junctions where moving outside of it's designated search pattern could lead it to a significantly more optimal solution.

In this, A* reigns supreme. Though in certain cases (such as our `VLarge` example) it gets outperformed by DFS, it's strengths are in consistency. In 50% of cases (75% without the DFS optimisation) given, it outperforms DFS while also providing a more optimal result, and is always able to provide a more optimal result, undoubtedly thanks to it's use of a heuristic function in order to 'steer' the algorithm in the direction of the target.