Exploring search algorithms in the context of maze solving

1.1 - Framing the maze as a search problem

A problem can be classified as a search problem if it consists of the following:

- A search space
- Start state
- Goal state/condition

A maze can be characterised as a search space as it can be represented as an undirected graph of nodes connected by the valid paths formed.

The problem of solving a maze involves all three characteristics, i.e. we must traverse the maze, start at some point, and exit at another.

Following this, a maze solver would be something that solves our problem by **searching the graph** to find a path between the start and goal state.

Thus, we can frame a maze solving problem as a search problem.

1.2 - Solving the maze using a depth-first search

1. **Briefly outline the depth first search algorithm**

   The depth first search algorithm is an uninformed search technique that starts at the root of a graph, (in our case at the entrance of the maze) and explores each branch (or path) as far as possible before backtracking (i.e hitting a wall and finding another path).
   A DFS is incomplete, not optimal, of high time complexity, and of low space complexity.

2. **Implement depth-first to solve the maze. The solution of the maze should print the locations in the map that the algorithm will take to reach from the start to the goal. This question can be solved using the file 'maze-Easy.txt".**

   The path found by the DFS for the maze in file 'maze-Easy.txt' is as follows (in (y,x) format) :

```
> [(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)]
```

3. **Update your algorithm to calculate some statistics about its performance. The number of nodes explored to find the path, the time of the execution, and the number of steps in the resulting path.**

   Statistics of DFS on maze in file 'maze-Easy.txt':

   ```
   > Explored 43 nodes and found path with length: 27
   > Time taken to execute: 4.410743713378906e-05 seconds
   ```

4. **Update your algorithm to be generalised to read any maze in the same format. Then calculate the paths and statistics for all 'maze-Medium.txt"/ 'maze-Large.txt" / 'maze-VLarge.txt".**

   The statisics for a general implementation of the DFS on the given mazes are as follows:

   For the Medium maze:

   ```
   > Explored 666 nodes and found path with length: 321
   > Time taken to execute: 0.00048422813415527344 seconds
   ```

   For final path: see Appendix

   For the Large maze:

   ```
   > Explored 61935 nodes and found path with length: 1028
   > Time taken to execute: 0.03405189514160156 seconds
   ```

   For final path: see Appendix

   For the Very Large maze:

   ```
   > Explored 381919 nodes and found path with length: 3737
   > Time taken to execute: 0.2459566593170166 seconds
   ```

For final path: see Appendix

1.3 - An improved algorithm for this problem

1. **Briefly outline another algorithm to solve the maze. That decision should be justified by what you expect to improve in the performance over depth-first search.**

   Another algorithm to solve the maze is the A-Star search algorithm. It is an informed algorithm which uses a heuristic function to gain more information about the search space than just what is provided.

   It uses the evaluation function $f(n) = g(n) + h(n)$ where:
   - $g(n)$ is the actual cost of getting to node n from the start node.
   - $h(n)$ is the estimated cost of going from the current node to the end node.
   - $f(n)$ is the estimated cost of the cheapest path to the goal that goes through node n.

   The DFS algorithm is fast, however, it does not find the shortest path and for most applications, finding the shortest path is more useful. In the context of a maze, the shortest path would be the optimal solution, even if it takes longer to discover.

   Thus, a verifiable and valid improvement in performance could be to find the shortest path between the start and end nodes by exploring nodes in a more efficient manner. To achieve this, an informed algorithm such as the A-Star algorithm can be used.

2. **Implement the suggested algorithm to solve the maze. It should also calculate the same statistics about its performance as the previous depth-first algorithm. The solution of the maze should print the locations in the map that the algorithm will take to reach from the start to the goal.**

   The relevant code for this implementation can be found in the submission folder. The statistics are discussed in detail in the solution for question 3 below, and the path taken from start to goal for every maze can be found in the appendix.

   An In-depth analyses and comparison of both implementations is provided as the answer for Question 4.

3. **Run your algorithm to calculate the paths and statistics for all given mazes which are 'maze-Easy.txt"/ 'maze-Medium.txt"/ 'maze-Large.txt" / 'maze-VLarge.txt".**

The statisics for a general implementation of the A* search algorithm on the given mazes are as follows:

For the Small maze:

```
> Explored 63 nodes and found path with length: 27
> Time taken to execute: 0.0002701282501220703 seconds
> A* path: [(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)]
```

For the Medium maze:

```
> Explored 2130 nodes and found path with length: 321
> Time taken to execute: 0.014735221862792969 seconds
```

For final path: see Appendix

For the Large maze:

```
> Explored 42225 nodes and found path with length: 974
> Time taken to execute: 0.24378275871276855 seconds
```

For final path: see Appendix

For the Very Large maze:

```
> Explored 274615 nodes and found path with length: 3691
> Time taken to execute: 3.0128519535064697 seconds
```

For final path: see Appendix

4. **Discuss based on your results and analyse how the suggested algorithm performed better than the depth-first-search algorithm.**

The statistics provided above reveal the following:

- The A-Star search algorithm always discovers a shorter path than the DFS, if one exists.

- It is less performant in terms of time complexity when compared to the DFS, which can be contributed to the fact that it aims to explore more nodes, the heuristic calculation and priority queue actions (additions, deletions, lookup etc.)
- However, it can be noted, that for the Large and Very Large mazes, the A-Star algorithm explored significantly less nodes than the DFS while also finding shorter paths, thereby confirming indicating that the DFS is particularly wasteful in the amount of nodes it explores.

The stats illustrate that although certainly slower than the DFS, the A-Star algorithm discovers the shortest path between two points and is more efficient with node exploration when exploring larger search spaces. In reference to what was defined earlier as a verifiable and valid optimization, we can conclude that the A-Star achieves the goal of being a more useful algorithm for practical applications such as video games or gps path finding services as it consistently discovers the shortest path at the expense of being slower.

Further experimentation: Optimization

The findings above are intriguing, and prompt further exploration. The chosen way to explore this problem through a different lens was through optimization.

The implementations of these algorithms is far from ideal or optimized, thus, seeing how these algorithms would stack up against each other in their optimized forms may reveal new insight about how search problems can be approached, and answer the question of why exactly different approaches to solving the same problem are different.

DFS optimization: Checking for valid neighbours

Seeing as the DFS' performance is maze specific, swapping around the directions in which valid nodes are checked can lead to improvements in performance.

The order of checking directions in the original implementation above was as follows:
→ West → North → South → East

The reasoning for this was as follows:

- The maze entrance is at top left of every maze
- The exit is generally towards the bottom right of the maze
- So, when checking paths, it would make sense to exhaust all invalid directions first, and then correct itself by checking valid directions after, reducing the risk of going through a large number of nodes that may be invalid

It was assumed during development that swapping around the first two and last two directions would, in theory, achieve the same goal.
However, for the purposes of this extension, the following order was experimented with:
→ North → West → East → South

The following statistics were obtained:

```
> Searching maze-Small.txt using DFS-faster
> Explored 54 nodes and found path with length: 27
> Time taken to execute: 6.198883056640625e-05 seconds


> Searching maze-Medium.txt using DFS-faster
> Explored 2590 nodes and found path with length: 339
> Time taken to execute: 0.001909017562866211 seconds


> Searching maze-Large.txt using DFS-faster
> Explored 10651 nodes and found path with length: 1092
> Time taken to execute: 0.00797891616821289 seconds


> Searching maze-Vlarge.txt using DFS-faster
> Explored 114441 nodes and found path with length: 3737
> Time taken to execute: 0.07386088371276855 seconds


 > Time taken to execute all: 0.1147007942199707 seconds
```

You can find this implementation in the dfs_faster.py file

Comparing this to the original DFS implementation which completes all the mazes in approximately `0.29720425605773926 seconds`, we see that the new DFS is almost **~2.6 times faster!**

Following observations are key:

- For the small maze, it explores a larger number of nodes, and is slower than before.
- For the medium maze, it explores a larger number of nodes, finds a longer path, and is significantly slower than before.
- For the large maze, It explores almost ~6 times less nodes than the original implementation, finds a longer path, and is significantly more time performant.
- For the very large maze, it again, explores almost ~4 times less nodes, finds the exact same sized path, and executes significantly faster.

It must be noted that the behaviour of the dfs is extremely maze specific, and so are these improvements that may not be relevant in other mazes.

A-STAR optimization : Alternative data structures?

As the statistics show, the A-Star implementation takes ~3.3-3.4 seconds to run through all the mazes, the aim is to see how the comparision between A-Star and DFS would change if the time to run the A-Star was further optimized.

To discover flaws in the implementation, the source code was profiled using Cprofile. This revealed that some of the most time consuming aspects of the implementation were the thread safety measures that come with the python PriorityQueue import.

Seeing as my project has no need for thread safety, I explored an alternative python library for the priority queue implementation - heapq. Heapq does the same thing as the PriorityQueue module, except it has no thread safety measures and is based on a binary heap implementation, making it ever so slightly quicker.

Implementing this gave me a total runtime anywhere in the range of ~2.7-2.92 seconds, making this version 13-21% faster. Virtually every other statistic remained the same:

For the Small maze:

```
Searching maze-Small.txt using A-STAR-faster
Explored 63 nodes and found path with length: 27
Time taken to execute: 0.0001780986785888672 seconds
```

For the Medium maze:

```
Searching maze-Medium.txt using A-STAR-faster
Explored 2130 nodes and found path with length: 321
Time taken to execute: 0.01215982437133789 seconds
```

For the Large maze:

```
Searching maze-Large.txt using A-STAR-faster
Explored 42225 nodes and found path with length: 974
Time taken to execute: 0.18695878982543945 seconds
```

For the Very large maze:

```
        Searching maze-Vlarge.txt using A-STAR-faster
        Explored 274615 nodes and found path with length: 3691
        Time taken to execute: 2.574759006500244 seconds

 Time taken to execute all: 2.799075126647949 seconds
```

You can find this implementation in the a_star_faster.py file

Following this, the most resource intensive part of the implementation was the way the maze was traversed. Based on some research and direction from the blog listed in the references, a secondary optimization that could not be implemented due to time constraints involved representing the maze as an adjacency matrix to reduce the resoures wasted on traversal.

Conclusion :

The findings from this extension illustrate that there are a variety of ways to optimize implementations, but optimization doesn't change anything about the nature of the algorithms.
I discovered ways to optimise the DFS and the A-STAR, and the results stayed the same :
The A-star takes longer and finds the shortest path, and the DFS finds a path, any path but in a quicker time. However, exploring ways to improve these alogrithms helped provide a clearer understanding of what a search problem is and how it can be abstracted and approached through various different methodologies.

Appendix

Section 1 - DFS paths

Medium maze:

```
  >>       DFS path for Medium: [(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), (34, 30), (34, 31), (34, 32), (34, 33), (34, 34),
  (35, 34), (35, 35), (35, 36), (35, 37), (34, 37), (34, 38), (34, 39), (34,
```

```
40), (34, 41), (35, 41), (35, 42), (35, 43), (35, 44), (35, 45), (35, 46),
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195), (95, 196), (95, 197), (95, 198), (96, 198), (97, 198), (98, 198), (99,
198)]
```

Large maze:

```
>>      DFS path for Large: [(0, 1), (1, 1), (1, 2), (1, 3), (1, 4), (1, 5),
(1, 6), (1, 7), (2, 7), (2, 8), (2, 9), (2, 10), (3, 10), (3, 11), (3, 12),
```

(3, 13), (2, 13), (1, 13), (1, 14), (1, 15), (1, 16), (2, 16), (3, 16), (3, 17), (3, 18), (3, 19), (4, 19), (4, 20), (4, 21), (4, 22), (5, 22), (6, 22), (6, 23), (7, 23), (7, 24), (7, 25), (7, 26), (8, 26), (9, 26), (9, 27), (9, 28), (9, 29), (9, 30), (9, 31), (10, 31), (11, 31), (11, 32), (11, 33), (10, 33), (10, 34), (10, 35), (10, 36), (11, 36), (12, 36), (12, 37), (12, 38), (12, 39), (12, 40), (12, 41), (12, 42), (13, 42), (13, 43), (13, 44), (13, 45), (13, 46), (13, 47), (13, 48), (14, 48), (14, 49), (15, 49), (15, 50), (15, 51), (16, 51), (17, 51), (17, 52), (18, 52), (19, 52), (20, 52), (21, 52), (22, 52), (23, 52), (23, 53), (24, 53), (24, 54), (25, 54), (26, 54), (26, 55), (26, 56), (26, 57), (27, 57), (27, 58), (27, 59), (28, 59), (29, 59), (30, 59), (30, 60), (30, 61), (30, 62), (31, 62), (31, 63), (31, 64), (32, 64), (33, 64), (34, 64), (35, 64), (36, 64), (36, 65), (37, 65), (37, 66), (38, 66), (39, 66), (39, 67), (40, 67), (40, 68), (40, 69), (40, 70), (40, 71), (41, 71), (42, 71), (43, 71), (43, 72), (43, 73), (43, 74), (42, 74), (42, 75), (42, 76), (42, 77), (42, 78), (42, 79), (42, 80), (42, 81), (41, 81), (41, 82), (41, 83), (41, 84), (41, 85), (41, 86), (42, 86), (43, 86), (44, 86), (45, 86), (46, 86), (47, 86), (48, 86), (48, 87), (49, 87), (50, 87), (51, 87), (51, 88), (52, 88), (52, 89), (52, 90), (51, 90), (51, 91), (51, 92), (50, 92), (50, 93), (50, 94), (50, 95), (50, 96), (50, 97), (50, 98), (50, 99), (51, 99), (51, 100), (52, 100), (53, 100), (54, 100), (55, 100), (56, 100), (57, 100), (58, 100), (58, 101), (58, 102), (59, 102), (59, 103), (59, 104), (59, 105), (59, 106), (60, 106), (61, 106), (62, 106), (62, 107), (62, 108), (62, 109), (62, 110), (62, 111), (63, 111), (64, 111), (65, 111), (65, 112), (66, 112), (66, 113), (67, 113), (68, 113), (69, 113), (70, 113), (71, 113), (72, 113), (73, 113), (73, 114), (73, 115), (73, 116), (73, 117), (73, 118), (74, 118), (74, 119), (74, 120), (74, 121), (75, 121), (76, 121), (77, 121), (77, 122), (77, 123), (76, 123), (76, 124), (76, 125), (76, 126), (77, 126), (78, 126), (78, 127), (79, 127), (80, 127), (80, 126), (80, 125), (80, 124), (80, 123), (80, 122), (81, 122), (82, 122), (83, 122), (83, 123), (84, 123), (85, 123), (86, 123), (86, 122), (86, 121), (87, 121), (88, 121), (89, 121), (90, 121), (91, 121), (92, 121), (93, 121), (94, 121), (94, 120), (94, 119), (94, 118), (95, 118), (96, 118), (97, 118), (98, 118), (99, 118), (100, 118), (100, 117), (101, 117), (102, 117), (102, 116), (102, 115), (102, 114), (103, 114), (104, 114), (104, 113), (105, 113), (106, 113), (106, 114), (107, 114), (108, 114), (109, 114), (109, 113), (110, 113), (111, 113), (112, 113), (113, 113), (114, 113), (115, 113), (116, 113), (116, 112), (116, 111), (116, 110), (116, 109), (117, 109), (118, 109), (118, 108), (118, 107), (118, 106), (118, 105), (118, 104), (119, 104), (120, 104), (120, 103), (120, 102), (121, 102), (122, 102), (122, 101), (123, 101), (124, 101), (125, 101), (126, 101), (126, 100), (127,

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Section 2 - A* Search paths

Medium maze:

> A* path for Medium: [(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), (34, 30), (34, 31), (34, 32), (34, 33), (34, 34), (35, 34), (35, 35), (35, 36), (35, 37), (34, 37), (34, 38), (34, 39), (34, 40), (34, 41), (35, 41), (35, 42), (35, 43), (35, 44), (35, 45), (35, 46), (36, 46), (36, 47), (37, 47), (38, 47), (39, 47), (39, 48), (39, 49), (38, 49), (38, 50), (38, 51), (38, 52), (38, 53), (38, 54), (38, 55), (38, 56), (38, 57), (39, 57), (39, 58), (40, 58), (41, 58), (42, 58), (42, 59), (42, 60), (43, 60), (43, 61), (44, 61), (45, 61), (46, 61), (47, 61), (47, 62), (48, 62), (49, 62), (49, 63), (49, 64), (49, 65), (50, 65), (51, 65), (51, 66),

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Large maze:

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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)]
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