**Analysis of Graph Search Algorithms**

**Breadth-First Search, A\* Search Algorithms and Greedy\_BSF in Maze Solving**

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## **1. Abstract**

This project investigates the performance of 3 search algorithms, the uninformed search algorithms i.e. **Breadth-First Search (BFS)** and informed searched algorithms i.e. **A\* Algorithm, and Greedy Best-First Search (Greedy BFS)** in solving a **maze of 50 x 120 size.** This maze is created by python script. with **loopPercent = 48%.**

On same maze, the algorithms were tested under 3 scenarios, with **goal positions at (1, 1), (49, 2), and (1, 119).** I am evaluating the effectiveness of these search algorithms based on path length, exploration order, and computational efficiency. The findings provide insight into the advantages and disadvantages of each algorithm under different goal positions. Results of this project shows that BFS consistently finds the shortest path but at the cost of high exploration value, while Greedy\_BFS gives faster exploration but less optimal paths. A\* balances both, providing optimal solutions with efficient exploration. The study of these algorithms Let’s get started.

## **2. Introduction**

Pathfinding and search algorithms are fundamental to Artificial Intelligence (AI), with applications in robotics, gaming, Geographical Information System (GIS), optimization problems and many more. This project focuses on implementing and comparing these below search algorithms:

1. **Breadth-First Search (BFS):** An uninformed search algorithm exploring all neighbours at the current depth level before moving deeper. [1]
2. ***A\* Algorithm:*** An informed search combining cost from start to node (g(n)) and a heuristic estimate to the goal (h(n)).[2]
3. **Greedy Best-First Search (Greedy BFS):** An informed search prioritizing exploration based solely on heuristic estimates (h(n)).[3]

By implementing and analysing these algorithms in the given maze to solve it by finding the optimal path from starting position to the goal, and by analysis of these algorithm’s performance across three different goal positions, this report briefs their methodology, implementation and results.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **cell** | **E** | **W** | **N** | **S** |
| **(1, 1)** | 1 | 0 | 0 | 1 |
| **(2, 1)** | 1 | 0 | 1 | 0 |
| **(3, 1)** | 1 | 0 | 0 | 1 |
| **(4, 1)** | 0 | 0 | 1 | 1 |
| **(5, 1)** | 1 | 0 | 1 | 0 |
| **(6, 1)** | 1 | 0 | 0 | 1 |
| **(7, 1)** | 1 | 0 | 1 | 1 |
| **(8, 1)** | 1 | 0 | 1 | 0 |
| **(9, 1)** | 0 | 0 | 0 | 1 |
| **(10, 1)** | 0 | 0 | 1 | 1 |

## **3. Methodology**

### **3.1 Problem Setup**

* The maze dimensions, structure and obstacles were predefined and loaded from a CSV file.
  + Dimensions: 50 x 120.
  + Structure: Cell (x, y)

Direction: E, W, N, S

* + Design: Cell (1, 1) represent cell number or cell position and (0 and 1) represent the presence of wall or not in given direction i.e. E, W, N and S.

**A computer screen shot of a program

Description automatically generated**

**Code 1: Create maze using pyamaze package**

A black and white maze

Description automatically generated

**Fig 1: Created maze look like this**

* The start position for each algorithm is the **bottom-right corner (50, 120)** of the maze.
* Three scenarios were defined with varying goal positions: **(1, 1), (49, 2), and (1, 119).**

### **3.2 Implementation**

Each algorithm was implemented in Python using the pyamaze library for maze creation, visualization, and pathfinding. The library provides a flexible framework for defining maze dimensions, walls, and goal positions, making it suitable for comparative studies of search algorithms. The details of each implementation are outlined below: The uploaded files include the following implementations:

#### **3.2.1 the\_BSF.py: BFS implementation​.**

A black background with green and blue text

Description automatically generated

Code 2: Import necessary modules

This code imports the necessary modules for creating and visualizing a maze, as well as implementing an agent that can navigate through it. Specifically, it imports the maze, agent, COLOR, and textLabel classes from the pyamaze library. The maze class is used to generate and manage the maze structure, while the agent class represents the entity that will traverse the maze. The main agents I will use in my project is, **Algorithm’s Agent:** This agent will visualize the movement of algorithm while searching the path from start point to goal position over maze. **Path Agent:** This agent will visualize the path from start to goal position, each algorithm has its own path, and these paths will show in different color, therefore The COLOR module is used to provides color options for customizing the maze's visual elements, and textLabel can be used to display text annotations within the maze. Additionally, the code imports deque from the collection’s module, which is a double-ended queue commonly used for efficiently managing data structures like queues and stacks, especially for pathfinding or traversal algorithms within the maze. This is very important to understand that use of deque as data structure here with search algorithms is to increase the flow of adding and removing of nodes from both ends, deque also help to manage this flow as well. [4]

A screen shot of a computer program

Description automatically generated

Code 3: The BFS part I

This is the beginning of the BFS algorithm code, ***start*** is the starting point for **BFS\_agent** ([explained here in detailed](#The_Agents)), the starting default point is at (50, 120) the bottom right corner of the maze. The frontier is deque which initiates from starting point, it is not just a simple choice of variable name. In BFS, the frontier refers to the set of nodes, here cells (x, y). In the case of a maze that are currently being explored. These are the nodes that have been discovered but not yet fully explored, meaning their neighbours are about to be visited. As BFS progresses, nodes are added to the frontier, and the algorithm explores them by removing nodes from the frontier one by one.

A computer screen shot of a program code

Description automatically generated

Code 4: The BFS part II

This code implements the core of the BFS algorithm for exploring a maze. Every cell will go to frontier then each cell is taken in current variable and if ***current !=goal*** then the neighbour cell is checked again and again by following the *for loop* with possible directions E,W, S, N. This moment is constrained by walls with Boolean values (0 and 1, where 0 means no wall and 1 means wall). [5] these walls contain the moment in that direction, if moment (direction) has wall (1) then it can’t move to that direction and check another direction if the moment is allowed (0) then go to the next cell and check if goal is there or not. Now to go to the next cell I have ***next\_cell***variable which use ***get\_next\_cell*** function. This next cell is added to frontier for future reference and if the goal is not there then these cells are put under visited variable that have list of all visited cells yet. If ***current = goal*** then the function break. Now to track this exploration I use ***exploration\_order***, this will use later when I want to see the path from start to goal.

A screen shot of a computer code

Description automatically generated

Code 5: Construct the path to goal.

Now, the algorithms reach the goal position, so I need to see what path optimal BFS does has taken to reach the goal from starting point, so each cell needs to be in on systematic order after each visit, therefore this code comes in light. The dictionary is needed to save the path, so that traversing to predecessor cell become possible after adding each new visited cell and after reaching the goal the path can be constructed with the help of visited cells.

A screen shot of a computer code

Description automatically generated

Code 6: Get next cell by reading direction ad walls

So, basically if an algorithm wants to move in any direction and if there is no wall, the return (row, Col+1) will add one column to that direction and our algorithm moves one step or cell. And if the algorithm choose direction that has wall, then no moment occurs, and next direction is chosen.

A screen shot of a computer program

Description automatically generated

Code 7: The main function to run the algorithm

50 x 120 maze is loaded ***.csv***, here the goal position is (1, 1). 3 agents are created and tracepath Is created for them. The 3 agents the ***Agent\_bfs:*** which show the actual movement of bfs algorithm***. Agent\_path:*** which activate when goal is reached and shows the path from starting till goal. ***Agent\_goal:*** which is shows the position of the goal. It stays at goal position and help to find the location of goal on the maze. The agents are designed like an entity to make decisions and take actions as according to the maze situation. These decisions are made according to the logic of algorithms.

#### **3.2.2 the\_Astar.py:**

A screen shot of a computer

Description automatically generated

Code 8: The heuristic function.

In A\* there is heuristic values which inform them about the direction of the goal from starting position, each cell has same heuristic value i.e. 1 and the below code is representing to implement the heuristic (Manhattan distance) from current cell to goal position.[4]

The heuristic function is most obvious function used in A\* algorithm, here the term,

**return abs ( cell [0] – goal [0] ) + abs ( cell [1] - goal [1] )**

is showing the calculation of Manhattan Distance. In mathematically it is done by calculating the distance between two points (A and B) by applying Manhattan distance formula. **A—B = {A(y) – A(x)} +{B(y) – B(x)}**

Where,x and y are coordinates for A and B point respectively. The calculation of heuristic function is same in A\* and Greedy\_BFS. [I will explain it a little later. [\*]](#The_real_reason_of_differene_in_formula)

A computer screen shot of text

Description automatically generated

Code 9: The A\* Algorithm

In this code for each neighbour, I need to calculate total cost f(n) which is equal to the sum of current cost g(n) and heuristic cost h(n).

**f(n) = g(n) + h(n)**

The use of heuristic value is to help in calculating the search efficiency when we move towards the goal. For eg: if the goal is at left direction w.r.t the current position then heuristic value give point to move at left side towards goal from current position. Same with right, up or down direction. The heuristic value will tell the A\* where it should move to get the goal ASAP. A\* does not have exact direction of a goal but have estimated it and this estimation help to move the algorithm towards goal path.

#### **3.2.3 the\_Greedy\_BFS.py:**

A computer screen shot of text

Description automatically generated

Code 10: The Greedy\_ BFS Algorithm

Same code as A\* just greedy used only heuristic value to find path towards goal.

Here,  **f(n) = h(n)**

This is a basic reason why the greedy\_BFS is not an optimal algorithm but faster. As compared to A\* the greedy\_BFS is only focus on moving forward. Greedy\_BFS only use heuristic values to calculate the total cost. It ignores the current cost and just focus on the value which let it to move faster towards goal.

Now, as I discuss about both the algorithms the **A\* and Grredy\_BFS,** let’s understand the reason why heuristic value is same calculated in both the algorithms, but formula od both algorithm is different.

[\*] The real reason of formula difference while calculating Manhattan distance is similar in both algorithms.

**A—B = (hn) = {A(y) – A(x)} +{B(y) – B(x)}.**

**A\* 🡪 f(n) = (h(n) + g(n).** as discuss previously in A\* the total cost is calculated by adding heuristic value along with current cost.

**Greedy\_BFS 🡪 f(n) = h(n)** in greedy\_BFS is only needed heuristic value therefore if impact of current cost is null in this case and greedy\_BFs will only focus on achieving the goal in fastest way without taking care of optimality of a path.

## **4. Results and Discussion**

### **4.1 Performance Metrics**

The algorithms were evaluated based on:

1. **Path Length:** The number of steps from the start to the goal.
2. **Exploration Length:** The number of nodes explored before reaching the goal.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Scenario** | **Algorithms** | **Goal Position (cell No)** | **Path Length** | **Exploration Length** |
| **1** | **BFS** | (1, 1) | 189 | 5991 |
| **Greedy\_BFS** | (1, 1) | 229 | 401 |
| **A\*** | (1, 1) | 189 | 4264 |
| **2** | **BFS** | (49, 2) | 174 | 5707 |
| **Greedy\_BFS** | (49, 2) | 204 | 331 |
| **A\*** | (49, 2) | 174 | 2358 |
| **3** | **BFS** | (1, 119) | 83 | 2253 |
| **Greedy\_BFS** | (1, 119) | 101 | 152 |
| **A\*** | (1, 119) | 83 | 657 |

Table 2: Comparing Algorithm’s path and search length

By using this table I’m comparing the performance of the 3 algorithms in 3 different scenarios. The goal is to find the best path from a starting point to goal position which chances.

Scenario 1(Goal Position: (1, 1):

When goal position is at (1,1), Both **BFS** and **A**\* find the shortest path to the goal at **(1, 1)**, which is **189 steps** long. However, **Greedy\_BFS** takes a longer path of **229 steps**. When it comes to exploration, **A**\* explores **4264 steps** to find the optimal path, while **BFS** explores **5991 steps**. On the other hand, **Greedy\_BFS** explores only **401 steps** to reach the goal, but it doesn't find the shortest path, making its exploration much smaller but less optimal.

**Scenario 2 (Goal Position: (49, 2)): BFS** and **A**\* both find the shortest path of **174 steps**, while **Greedy\_BFS** takes a longer path of **204 steps**. In terms of search length, **A**\* explores **2358 steps**, and **BFS** explores **5707 steps** to find the optimal path. In contrast, **Greedy\_BFS** only explores **331 steps** to reach the goal, making it the fastest in terms of exploration, though it doesn't find the shortest path like the other two algorithms.

**Scenario 3 (Goal Position: (1, 119)):**

In Scenario 3, the goal is at **(1, 119)**. **BFS** finds the shortest path of **83 steps**, while **Greedy\_BFS** takes a longer path of **101 steps**. For search length, **BFS** explores **2253 steps**, while **Greedy\_BFS** only explores **152 steps**. As in the previous scenarios, **Greedy\_BFS** explores fewer steps but takes a less optimal route, while **BFS** finds the shortest path with more exploration.

A graph of different colored bars

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Fig: Path Length Comparison with all 3 Scenarios

A graph of bar graph

Description automatically generated with medium confidence

Fig: Search Length Comparison with all 3 Scenarios

### **4.2 Explanation of the Results**

The comparison between the search algorithms BFS, Greedy BFS, and A\* across different scenarios reveals important insights into their performance.

* BFS performs consistently across all scenarios with the same path length but explores many more nodes, resulting in high search lengths. This is because BFS searches all possible paths level by level, making it exhaustive but less efficient in terms of exploration.
* Greedy BFS, on the other hand, focuses on reaching the goal based on a heuristic, which can make it faster in terms of search length, especially in scenarios like Scenario 1. However, this comes at a cost, it often takes longer paths to reach the goal compared to BFS or A\*. Greedy BFS does not guarantee the shortest path, as it is biased towards the most promising nodes based on the heuristic, rather than considering the entire search space.
* A\* strikes a balance between path length and search length. It combines the benefits of both BFS and Greedy BFS, using a heuristic to guide its search, but ensuring that it still finds the optimal path. While it sometimes explores more nodes than Greedy BFS, it generally results in shorter paths than Greedy BFS while being more efficient than BFS in terms of search length.

### **4.3 Algorithm Comparison**



Fig: Exploration path comparison of all algorithms with goal position (1, 1)

**|| Red path = BFS || || Yellow path = A\* || || Blue path = Greedy\_BFS ||**

#### **4.3.1 Breadth-First Search (BFS):**

* **Strength:** BFS is great for finding the shortest path, especially when all steps or edges have the same cost (like in unweighted graphs).
* **Weakness:** It can be slow and use a lot of memory because it checks all the nodes at each level before moving deeper.
* **Example:** If you're trying to find the shortest path between two people in a social network, BFS is perfect because it will explore all possible connections and guarantee the shortest one, without skipping any possibilities.

#### **4.3.2 A\* Algorithm:**

* **Strength:** A\* is great for finding the best, most efficient path because it combines the current distance with a guess of how far it is to the goal (using a heuristic).
* **Weakness**: It depends on having a good heuristic. If the guess isn’t accurate, it can take longer than necessary.
* **Example**: A\* is often used in GPS systems for navigation, where it can find the fastest route considering both distance and factors like traffic or road conditions. It’s the best choice when you need to be sure you're getting the most efficient route.

#### **4.3.3 Greedy Best-First Search (Greedy BFS):**

* **Strength:** Greedy BFS is faster than A\* because it focuses more on the goal and explores fewer nodes.
* **Weakness:** It might not always find the best (shortest) path because it can get stuck on a path that seems good at first but isn't the best in the end.
* **Example:** Imagine a robot trying to navigate a grid. If the goal is close and the robot has a good idea of where it is, Greedy BFS can get it there quickly. But if there are obstacles, it might choose a bad path because it only looks at the nearest options.

A black maze with a yellow line

Description automatically generated

Fig: Goal path comparison of all algorithms with goal position (1, 1)

**|| Red path = BFS || || Yellow path = A\* || || Blue path = Greedy\_BFS ||**

Here, we see the A\* and BFS have almost same path to reach goal just a little difference in between but that will not affect the lath length that’s the reason this difference is acceptable because both are giving the optimal path. Here we can conclude that there might be many optimal paths in a maze but the all optimal path should have same path length like, the BFS and A\* has different path as we can see the red color below the yellow color, this is because, BFS(red color) take little different path as compare to A\*(Yellow color), but as we can see from the result the path length is same in both algorithms in all 3 cases.

### **4.4 Discussion**

In this project, I had learn that A\* had given better result as compare to other algorithms, but it doesn’t meant that A\* is better in all scenarios. A\* is better when we want to focus on optimality and we need result faster than BFS, so A\* is good.

**Important Question: \_\_ If A\* is giving us best optimal path with less node search than BFS why we even need a Greedy\_BFS algorithm\_\_??**

This project reflects the implementation of above 3 algorithms which is important to give for me to understand the concept which make me able to give answer to this question:

Basically, every algorithm has its own advantages and disadvantages like I already highlighted above, so does have greedy\_BFS too. Greedy\_BFS is basically used when we want to focus on getting result rather than the cost of getting result.

Eg: Social Media recommendation system: In Facebook, snapchat or any other social media, the suggestion of friends are given by application on the bases of how close the person is to who, like friend’s of friend’s or friend etc… this system doesn’t care about connecting with you the best person, NO it only suggest you nearby connection, here we use Greedy\_BFS.

1. **Another eg of using Greedy\_BFS is in games like *GTA, farCry or* Assassin’s *Creed*,** [**[7]**](#ref8) in these games the NPC(Non-Player Charaters) are used to do some action. Their actions are only based on getting to the goal not to do anything, here we don’t need optimal solution, we just need faster solution which can be achieve by greedy\_BFS.

## **5. Achievements and Insights**

**I**n this project, I successfully compared three classic search algorithms BFS, Greedy BFS, and A\*, across three different goal positions, analysing their performance in terms of Path Length and Search Length. The key achievements and insights are:

1. BFS (Breadth-First Search), while consistent in its results, showed that it is a highly exhaustive search algorithm, exploring a significant number of nodes to find the goal. This led to higher search lengths compared to the other algorithms but ensured the shortest path to the goal.
2. Greedy BFS, which uses a heuristic to guide its search, was faster in terms of search length but often resulted in longer path lengths. This highlights that while Greedy BFS reduces the number of nodes explored, it doesn’t guarantee the shortest or optimal path.
3. A\* emerged as the most balanced algorithm. By combining the best of both BFS and Greedy BFS, it achieved shorter paths than Greedy BFS and explored fewer nodes than BFS, showing its effectiveness in finding optimal solutions efficiently.

## **6. Conclusion and Future Work**

1. In conclusion, this project demonstrated the strengths and weaknesses of BFS, Greedy BFS, and A\* algorithms in solving search problems. While BFS is exhaustive and guarantees the shortest path, it is computationally expensive in terms of search length. Greedy BFS offers speed but sacrifices optimality, and A\* provides a balanced approach, finding the optimal path with efficient node exploration.[**[8]**](#ref7)
2. Future work I’m planning to experiment with different heuristics in A\* like Manhattan, Euclidean etc and understand their performance. Another direction for future research could involve comparing these algorithms with other advanced search techniques, such as IDDFS (Iterative Deepening DFS) or Dijkstra’s Algorithm, to explore their performance in varied scenarios.
3. Another scenario for future understanding is to use some obstacles or non-uniform cost grids, which would add complexity and realism to the search problems**.**

## **7. References**

1. [Cormen, T. H., Leiserson, C. E., Rivest, R. L., & Stein, C. (2009).](https://mitpress.mit.edu/9780262533058/introduction-to-algorithms/) *[Introduction to Algorithms (3rd ed.)](https://mitpress.mit.edu/9780262533058/introduction-to-algorithms/)*[. MIT Press.](https://mitpress.mit.edu/9780262533058/introduction-to-algorithms/)

1. [Hart, P. E., Nilsson, N. J., & Raphael, B. (1968). "A Formal Basis for the Heuristic Determination of Minimum Cost Paths."](https://ieeexplore.ieee.org/abstract/document/4082128) *[IEEE Transactions on Systems Science and Cybernetics, 4](https://ieeexplore.ieee.org/abstract/document/4082128)*[(2), 100-107.](https://ieeexplore.ieee.org/abstract/document/4082128)

1. [Knuth, D. E. (1975).](https://seriouscomputerist.atariverse.com/media/pdf/book/Art%20of%20Computer%20Programming%20-%20Volume%203%20(Sorting%20&%20Searching).pdf) *[The Art of Computer Programming, Volume 3: Sorting and Searching](https://seriouscomputerist.atariverse.com/media/pdf/book/Art%20of%20Computer%20Programming%20-%20Volume%203%20(Sorting%20&%20Searching).pdf)*[. Addison-Wesley.](https://seriouscomputerist.atariverse.com/media/pdf/book/Art%20of%20Computer%20Programming%20-%20Volume%203%20(Sorting%20&%20Searching).pdf)

1. [Sedgewick, R., & Wayne, K. (2011).](https://books.google.co.uk/books?hl=en&lr=&id=MTpsAQAAQBAJ&oi=fnd&pg=PR6&dq=Sedgewick,+R.,+%26+Wayne,+K.+(2011).+Algorithms+(4th+ed.).+Addison-Wesley.&ots=QhmFBKGehV&sig=Ktr4mXAZzRBQq7Ly8PLprTcBVG0" \l "v=onepage&q&f=false) *[Algorithms (4th ed.)](https://books.google.co.uk/books?hl=en&lr=&id=MTpsAQAAQBAJ&oi=fnd&pg=PR6&dq=Sedgewick,+R.,+%26+Wayne,+K.+(2011).+Algorithms+(4th+ed.).+Addison-Wesley.&ots=QhmFBKGehV&sig=Ktr4mXAZzRBQq7Ly8PLprTcBVG0" \l "v=onepage&q&f=false)*[. Addison-Wesley.](https://books.google.co.uk/books?hl=en&lr=&id=MTpsAQAAQBAJ&oi=fnd&pg=PR6&dq=Sedgewick,+R.,+%26+Wayne,+K.+(2011).+Algorithms+(4th+ed.).+Addison-Wesley.&ots=QhmFBKGehV&sig=Ktr4mXAZzRBQq7Ly8PLprTcBVG0" \l "v=onepage&q&f=false)
2. [Pearl, J. (1984). *Heuristics: Intelligent Search Strategies for Computer Problem Solving*. Addison-Wesley.](https://mat.uab.cat/~alseda/MasterOpt/Judea_Pearl-Heuristics_Intelligent_Search_Strategies_for_Computer_Problem_Solving.pdf)
3. [Korf, R. E. (1985). "Iterative-Deepening A\*." *Artificial Intelligence, 27*(1), 97-109.](https://cse.sc.edu/~mgv/csce580f11/gradPres/korf_IDAStar_1985.pdf)

1. [S. R. Lawande, Graceline Jasmine, (2022), A Systematic Review and Analysis of Intelligence-Based Pathfinding Algorithms in the Field of Video Games, Lila Iznita Izhar](https://www.mdpi.com/2076-3417/12/11/5499)

1. [Russell, S., & Norvig, P. (2010).](https://thuvienso.hoasen.edu.vn/v/web/viewer.html?file=/bitstream/handle/123456789/8967/Contents.pdf?sequence=3&isAllowed=y) *[Artificial Intelligence: A Modern Approach (3rd ed.)](https://thuvienso.hoasen.edu.vn/v/web/viewer.html?file=/bitstream/handle/123456789/8967/Contents.pdf?sequence=3&isAllowed=y)*[. Pearson.](https://thuvienso.hoasen.edu.vn/v/web/viewer.html?file=/bitstream/handle/123456789/8967/Contents.pdf?sequence=3&isAllowed=y)

## **8. Appendix**

* **Code Files:** The complete implementation is included in the files attached to this report.
* **Execution Environment:** *(Put the details of your software, libraries, and hardware here.)*
* **Data Sources:** *(Put information about the CSV files or maze generation details here.)*