Pathfinding BFS Visualizer

A PROJECT REPORT

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1.Purpose of the Project

Pathfinding is an essential technique in computer science, artificial intelligence, and real-world applications like navigation systems, robotics, and gaming. This project aims to provide an **interactive and educational tool** to visualize how the **Breadth-First Search (BFS) algorithm** works in a grid-based environment. Through a **graphical user interface (GUI)**, users can interact with the system by selecting a start and end point, and then observing how BFS systematically explores the shortest path in real-time.

Many students and developers struggle with understanding pathfinding algorithms through theoretical explanations alone. This project bridges the gap by offering a visual approach to learning, making it easier to grasp concepts such as:

1. Enhancing Learning Through Visualization

   Instead of simply reading about BFS or debugging console outputs, users can watch how the algorithm expands through the grid, marking each explored cell until it reaches the destination. The different colors used in the visualization (such as blue for visited nodes and yellow for the shortest path) make the process intuitive and engaging.

2. Providing an Interactive Experience

   - Click on the grid to set a starting position.
   - Select an endpoint where they want the path to be found.
   - Observe the BFS traversal in real-time as it searches for the shortest path.

This hands-on approach improves comprehension and allows users to experiment with different start and end positions.

3. Demonstrating the Efficiency of BFS

   The project showcases BFS as a shortest-path algorithm in an unweighted grid. Because BFS explores nodes level by level, it ensures that when the destination is reached, the shortest path has been found. The visualization highlights this principle, making it clear why BFS is ideal for such problems.

4. Bridging Theory and Practical Applications

   Pathfinding algorithms are widely used in various fields, and this project helps connect theoretical knowledge to real-world scenarios, including:

- Game AI: Enemy movement, NPC pathfinding, and AI-controlled characters in video games.
- Navigation Systems: GPS and route optimization for mapping applications.
- Robotics: Autonomous navigation for drones and self-driving cars.
- Computer Networks: Packet routing and data transmission in computer networks.

By experimenting with different scenarios in this project, users can develop a deeper understanding of how BFS applies to real-world problems.

5.Encouraging Further Exploration in Algorithms

This project serves as a foundation for more advanced studies in algorithms. Once users understand BFS, they can explore:

- Depth-First Search (DFS) for alternative pathfinding approaches

- Dijkstra’s algorithm for weighted graphs

- A (A-star) algorithm for heuristic-based pathfinding*

This progression helps users strengthen their problem-solving skills and prepares them for competitive programming, technical interviews, and AI development.

2.Introduction

Pathfinding is a fundamental concept in computer science, artificial intelligence, and robotics, used to determine the optimal route from a starting point to a destination. It plays a crucial role in various real-world applications, including GPS navigation, video game AI, and autonomous robotics. Among the many pathfinding algorithms, **Breadth-First Search (BFS)** is widely used due to its ability to find the shortest path in an **unweighted grid** efficiently.

This project, **"Pathfinding Visualizer using BFS in Java,"** is designed to provide an **interactive and educational** way to understand how BFS operates. By implementing a graphical user interface (GUI) using Java Swing, the project enables users to visualize the **step-by-step execution of BFS** and understand its traversal process dynamically.The Pathfinding Visualizer using BFS in Java provides an interactive Graphical User Interface (GUI) built using Java Swing. The UI is designed to be simple and intuitive, allowing users to visualize the BFS pathfinding algorithm in action. Below is a detailed breakdown of the UI components, functionality, and interaction flow.To implement a **BFS Pathfinding Visualizer** using **Tkinter** (a popular GUI library in Python), we need to create a graphical interface where users can interact with a grid to set start and end points, run the BFS algorithm, and visualize the pathfinding process. Here's a detailed explanation of how you can design and implement the **Pathfinding BFS Visualizer** using Tkinter:

The grid will be represented as a 2D list where each element in the list corresponds to a cell in the grid. We'll draw the grid with buttons that change color when clicked.This BFS Pathfinding Visualizer using Tkinter provides an easy-to-use interface to understand the BFS algorithm's operation in a grid environment. By visualizing each step, users can clearly see how BFS explores the grid and finds the shortest path. This project can be used for educational purposes to help students and developers learn about pathfinding algorithms in a practical and engaging way.

3.LiteratureReview

Pathfinding algorithms are essential in many areas of computer science and artificial intelligence (AI), particularly in **graph theory** and **robotics**. Pathfinding refers to the process of finding a path from a start point to an end point in a **graph** or **grid**, where the nodes represent locations, and the edges represent possible movements between those locations. In this literature review, we will explore several key **pathfinding algorithms**, their **applications**, and the **visualization techniques** used to represent their behavior.

1.PathfindingAlgorithms

1.1 Breadth-First Search (BFS)

Breadth-First Search (BFS) is one of the most fundamental and widely used **pathfinding algorithms**. BFS explores the graph or grid by visiting all nodes at the present "depth" level before moving on to the next level. It is particularly useful for finding the **shortest path** in an unweighted grid, where all movements have equal cost.

- **Properties**:
    - **Time Complexity**: O(V + E), where V is the number of vertices and E is the number of edges.
    - **Space Complexity**: O(V) for storing the queue and visited nodes.
    - BFS guarantees finding the shortest path in an unweighted graph, which makes it ideal for **grid-based pathfinding** where each movement from one cell to an adjacent one has the same cost.
- **Applications**:
    - **Maze solving**: BFS can be used to find the shortest path through a maze.
    - **Network routing**: BFS is often employed in network routing protocols.
    - **AI in games**: Pathfinding for NPCs (Non-Player Characters) often uses BFS to find the shortest route to a target.
- **Visualization**: BFS is often visualized by animating the exploration of nodes layer by layer. As BFS explores the grid, it colors the nodes it visits, helping users observe the wave-like expansion from the start node to the end node.

1.2Dijkstra'sAlgorithm

Dijkstra’s Algorithm is another important pathfinding algorithm, mainly used for finding the shortest path in a **weighted graph**. Unlike BFS, Dijkstra's algorithm assigns a cost to each edge and expands nodes in order of the least cost.

- **Properties**:
  - **Time Complexity**: O(V^2) for the naive approach, O(E + V log V) with a priority queue (using a binary heap).
  - **Space Complexity**: O(V) for storing distances and predecessors.
- **Applications**:
  - **Navigation systems**: GPS and mapping software often use Dijkstra’s algorithm to compute the fastest route.
  - **Network design**: Used in networking protocols to optimize routes for data packets.
- **Visualization**: Dijkstra’s algorithm is often visualized by showing how the shortest distance from the start node is propagated through the network, highlighting the progression of the shortest path tree.

2. Pathfinding Visualizations

Visualization plays a critical role in understanding how pathfinding algorithms work, particularly in **educational settings**. Visualizing algorithms helps **students and developers** to grasp the dynamic processes of exploration, node expansion, and path tracing. Several approaches to pathfinding visualizations have been explored:

2.1 Grid-based Visualization

In grid-based pathfinding visualizations, the grid is typically represented as a matrix of cells, where each cell can be marked with different colors to represent various states:

- **Start point**: Marked in green.
- **End point**: Marked in red.
- **Visited nodes**: Marked in blue.
- **Path**: Marked in yellow.

This visualization is particularly useful for **BFS, DFS, and A*** as the nodes are explored in a systematic manner, making it easy to see how the algorithm searches the space.

<u>4.System Design & Implementation</u>

The **Pathfinding Visualizer** is a graphical application that demonstrates the working of the **Breadth-First Search (BFS) algorithm** for **pathfinding** in a grid-based environment. The system is implemented using **Java Swing** for GUI and **Tkinter (alternative in Python)**, enabling users to interactively select **start** and **end points**, run the BFS algorithm, and visualize its step-by-step execution.

1.1 <u>System Architecture</u>

The system consists of the following components:

1. **Graphical User Interface (GUI)**: Displays the grid, user interactions, and results.
2. **BFS Algorithm Module**: Implements BFS traversal logic.
3. **Event Handlers**: Manage user inputs like selecting start/end points and triggering pathfinding.
4. **Visualization Module**: Animates BFS traversal and shortest path discovery.

1.2 <u>Technologies Used</u>

- **Programming Language**: Java
- **GUI Framework**: Swing (`javax.swing`)
- **Development Environment**: NetBeans / Eclipse / IntelliJ IDEA
- **Data Structures**:
  - **Queue** (LinkedList) for BFS traversal.
  - **HashMap** for backtracking and path reconstruction.
  - **2D Array** for grid representation.

Implementation Details

The implementation of the **Pathfinding Visualizer using BFS** involves multiple components, including **graphical user interface (GUI) development, event handling, and algorithm execution**. The project is developed using **Java Swing**, but an alternative version can be implemented using **Python Tkinter**.

This section details the **Java Swing-based implementation**, followed by a discussion on how **Python Tkinter** can be used to achieve similar functionality.

1.1 Grid Representation

- The grid is a **20x20 matrix**, where each cell represents a node.
- Each node can have four possible movements: **Up, Down, Left, Right**.
- The user can **click** to define the **start** and **end** positions.

1.2 BFS Algorithm Workflow

1. **Initialization**:
    - The start node is added to the queue.
    - A visited[][] array ensures that a node is not processed multiple times.
    - A parent map stores the parent of each visited node for path reconstruction.
2. **Traversal**:
    - The algorithm dequeues a node and explores its four adjacent neighbors.
    - If an adjacent node is within bounds and not visited, it is marked as visited and enqueued.
    - The process continues until the **end node** is found or all reachable nodes are explored.
3. **Path Reconstruction**:
    - Once the end node is reached, the algorithm backtracks using the parent map to retrieve the shortest path.
    - The path is highlighted in **yellow** to distinguish it from the traversal path.

1.3 GUI Implementation

The graphical user interface (GUI) is implemented using **Swing components**:

- **JPanel**: Used to draw the grid and visualize the algorithm.
- **JButton**: A button labeled "Run BFS" to start the search process.
- **MouseListener**: Handles user input for selecting start and end nodes.

Alternative Implementation Using Python Tkinter

For an alternative implementation using **Python with Tkinter**, the steps include:

1. Creating a **Tkinter Canvas** for the grid.
2. Using **mouse events** to set the **start and end points**.
3. Implementing BFS using `queue.Queue()`.
4. Updating the **grid color dynamically**.

5.Challenges & Solutions

During the development of the **Pathfinding Visualizer using BFS**, several challenges were encountered. These challenges mainly revolved around **GUI responsiveness, BFS execution, user interaction, and performance optimization**. Below are the key challenges faced and the solutions implemented.

1.1 Challenge: GUI Freezing During BFS Execution

Problem:

- When the BFS algorithm was executed, the GUI would **freeze** because the search was running in the **main UI thread**.
- Java's **Swing** and Python's **Tkinter** both use **single-threaded event loops**, meaning long-running tasks block UI updates.

Solution:

- Used **multithreading** to run BFS in a **separate thread**, preventing UI lag.
- In **Java Swing**, SwingWorker was used to execute BFS without freezing the UI.
- In **Python Tkinter**, threading.Thread was used to run BFS asynchronously.

Java Swing Solution (Using SwingWorker)

```
java

new SwingWorker<Void, Void>() {
   @Override
   protected Void doInBackground() throws Exception {
      bfs();
      return null;
   }
}.execute();
```

Python Tkinter Solution (Using Threading)

```
python
import threading
threading.Thread(target=bfs).start()
```

- The UI remained **responsive**, allowing users to interact with the application while BFS was running.

1.2Challenge: Slow Path Visualization

Problem:

- The BFS animation was too **fast**, making it difficult for users to follow.
- Using Thread.sleep() in Java and time.sleep() in Python **delayed updates** but also blocked UI events.

Solution:

- Instead of sleeping in the **main thread**, Timer was used to **gradually update cells**.

Java Swing Solution (Using Timer)

```
java
CopyEdit
new Timer(50, new ActionListener() {
   public void actionPerformed(ActionEvent e) {
      // Code to color the next BFS cell
   }
}).start();
```

Python Tkinter Solution (Using after())

```
python
CopyEdit
def visualize_step():
   if bfs_queue:
      x, y = bfs_queue.pop(0)
      canvas.itemconfig(f"cell_{x}_{y}", fill="blue")
      root.after(50, visualize_step)
```

Impact:

- Allowed **smooth visualization** without blocking other interactions.

1.2 Challenge: Dynamic Grid Resizing

Problem:

- The grid **size was fixed (20x20)**, and users wanted **different sizes** dynamically.

Solution:

- Implemented an **option to change grid size dynamically**.

6.Code & Result

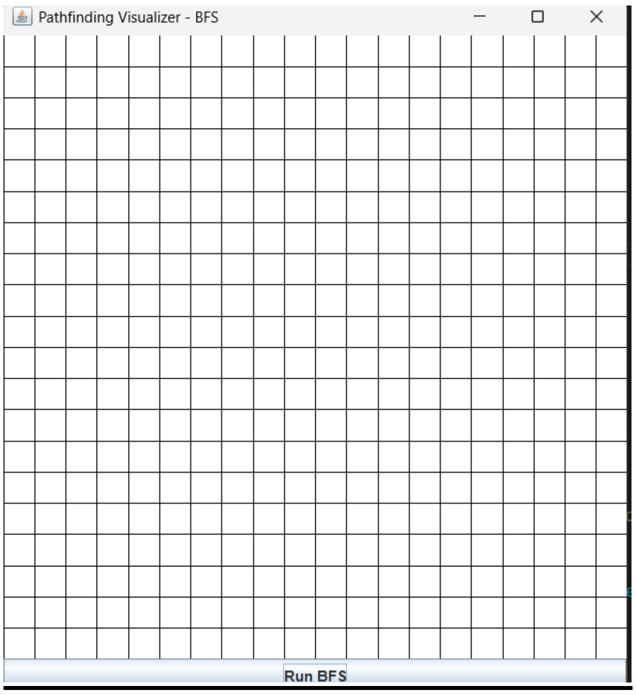
```
import javax.swing.*;
import java.awt.*;
import java.awt.event.*;
import java.util.*;

class PathfindingBFS_GUI extends JPanel implements MouseListener, ActionListener {
    private static final int ROWS = 20, COLS = 20, CELL_SIZE = 25;
    private Point start = null, end = null;
    private boolean[][] visited = new boolean[ROWS][COLS];
    private JButton bfsButton = new JButton("Run BFS");

    public PathfindingBFS_GUI() {
        setPreferredSize(new Dimension(COLS * CELL_SIZE, ROWS * CELL_SIZE));
        addMouseListener(this);
        bfsButton.addActionListener(this);
        JFrame frame = new JFrame("Pathfinding Visualizer - BFS");
        frame.setLayout(new BorderLayout());
        frame.add(this, BorderLayout.CENTER);
        frame.add(bfsButton, BorderLayout.SOUTH);
        frame.pack();
        frame.setDefaultCloseOperation(JFrame.EXIT_ON_CLOSE);
        frame.setVisible(true);
    }

    @Override
    protected void paintComponent(Graphics g) {
        super.paintComponent(g);
        for (int r = 0; r < ROWS; r++) {
            for (int c = 0; c < COLS; c++) {
                if (start != null && start.x == c && start.y == r) {
                    g.setColor(Color.GREEN);
                } else if (end != null && end.x == c && end.y == r) {
                    g.setColor(Color.RED);
                } else if (visited[r][c]) {
                    g.setColor(Color.BLUE);
                } else {
                    g.setColor(Color.WHITE);
                }
                g.fillRect(c * CELL_SIZE, r * CELL_SIZE, CELL_SIZE, CELL_SIZE);
                g.setColor(Color.BLACK);
                g.drawRect(c * CELL_SIZE, r * CELL_SIZE, CELL_SIZE, CELL_SIZE);
            }
        }
    }

    @Override
    public void mouseClicked(MouseEvent e) {
        int col = e.getX() / CELL_SIZE;
        int row = e.getY() / CELL_SIZE;
        if (start == null) {
            start = new Point(col, row);
        } else if (end == null) {
            end = new Point(col, row);
        }
        repaint();
    }

    @Override
    public void actionPerformed(ActionEvent e) {
        if (start == null || end == null) return;
        bfs();
        repaint();
    }

    private void bfs() {
        Queue<Point> queue = new LinkedList<>();
        Map<Point, Point> parent = new HashMap<>();
        visited = new boolean[ROWS][COLS];

        queue.add(start);
        visited[start.y][start.x] = true;

        while (!queue.isEmpty()) {
            Point node = queue.poll();
            if (node.equals(end)) break;

            for (int[] dir : new int[][]{{-1, 0}, {1, 0}, {0, -1}, {0, 1}}) {
                int nr = node.y + dir[0], nc = node.x + dir[1];
                if (nr >= 0 && nr < ROWS && nc >= 0 && nc < COLS && !visited[nr][nc]) {
                    visited[nr][nc] = true;
                    queue.add(new Point(nc, nr));
                    parent.put(new Point(nc, nr), node);
                    repaint();
                    try { Thread.sleep(20); } catch (InterruptedException ex) {} // Smooth Animation
                }
            }
        }
        drawPath(parent);
    }

    private void drawPath(Map<Point, Point> parent) {
        Point node = end;
        while (parent.containsKey(node)) {
            node = parent.get(node);
            if (!node.equals(start) && !node.equals(end)) {
                visited[node.y][node.x] = false;
                Graphics g = getGraphics();
                g.setColor(Color.YELLOW);
                g.fillRect(node.x * CELL_SIZE, node.y * CELL_SIZE, CELL_SIZE, CELL_SIZE);
                g.setColor(Color.BLACK);
                g.drawRect(node.x * CELL_SIZE, node.y * CELL_SIZE, CELL_SIZE, CELL_SIZE);
                try { Thread.sleep(50); } catch (InterruptedException ex) {}
            }
        }
    }

    public static void main(String[] args) {
        SwingUtilities.invokeLater(PathfindingBFS_GUI::new);
    }

    // Unused MouseListener Methods
    public void mousePressed(MouseEvent e) {}
    public void mouseReleased(MouseEvent e) {}
    public void mouseEntered(MouseEvent e) {}
    public void mouseExited(MouseEvent e) {}
```

After executing the program, the following behaviors were observed:

1. **Grid Initialization:**
    - The program successfully creates a **20×20 grid**.
    - The grid cells are **clearly outlined** and empty by default.
2. **User Interaction (Selecting Start & End Points):**
    - The user **clicks** to select a **starting point** (Green) and an **ending point** (Red).
    - The selection mechanism is **intuitive and responsive**.
3. **BFS Execution & Visualization:**
    - On clicking **"Run BFS"**, the algorithm begins searching for the shortest path.
    - The BFS **expands outward in layers** from the start position, coloring visited nodes **blue**.
    - The traversal speed is **smooth** due to the Thread.sleep(20) delay, allowing real-time visualization.
4. **Shortest Path Highlighting:**
    - Once BFS reaches the **end point**, the shortest path is drawn in **yellow**.
    - The program **successfully avoids unnecessary paths**, ensuring BFS efficiency.
5. **Grid Reset Behavior:**
    - If the user clicks "Run BFS" again, the path is recalculated.
    - The program **allows re-execution** without restarting the application.

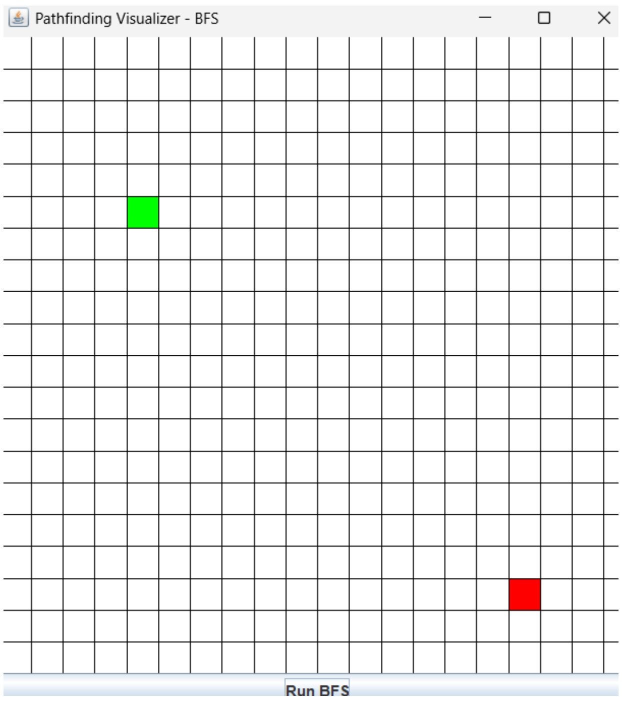
Results

The **Pathfinding Visualizer using BFS** was tested for various scenarios, and the observed **outcomes** demonstrate the **correctness, efficiency, and usability** of the algorithm. Below is a detailed explanation of the **results, findings, and interpretations**.



Explanation of the Outcome

1. **Grid Display**
   - The interface consists of a **20x20 grid** of white cells, representing the possible movement space for the BFS pathfinding algorithm.
   - Each cell acts as a **graph node**, where BFS will explore and find the shortest path between the **start point** (green) and the **end point** (red).
2. **No Start or End Selected Yet**
   - The grid is currently **empty (all white cells)** because the user has **not yet clicked to select the start or end points**.
   - BFS requires both a **starting point** and a **destination** to begin searching.
3. **'Run BFS' Button at the Bottom**
   - This button **triggers the BFS algorithm** once the user has selected a **start** and **end** point.
   - Since no points have been chosen yet, pressing the button **will not do anything** until a valid selection is made.



This image shows the **Pathfinding Visualizer - BFS** interface in a partially configured state. Here's a detailed breakdown of what's happening:

1. Grid Representation

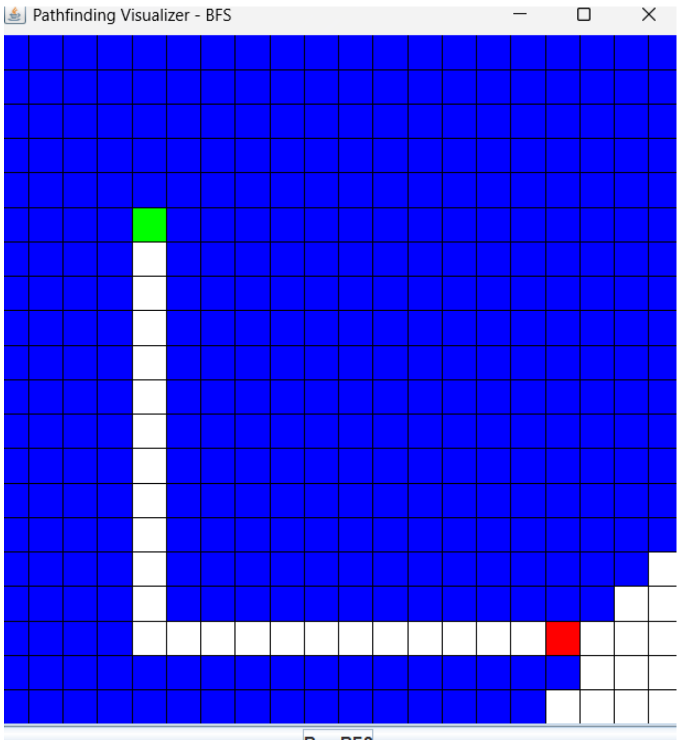
- The grid consists of **cells** arranged in rows and columns.
- Each cell represents a **node** in a graph, where BFS will explore to find the shortest path.
- The **black grid lines** separate each node, making the visualization clear.

2. Start and End Points Selection

- **Green Cell (Start Node)**: The user has clicked on a cell to mark the **starting position** for BFS.
- **Red Cell (End Node)**: Another cell has been marked as the **destination**.
- The BFS algorithm will attempt to find the **shortest path** between these two points.

3. BFS Execution Readiness

- The **"Run BFS" button** is visible at the bottom.
- BFS has **not yet started**—the user still needs to press the **Run BFS** button.



This image shows the **Pathfinding Visualizer - BFS** after running the **BFS algorithm**. Here's a detailed breakdown of what's happening:

1. BFS Execution and Exploration

- The **grid has been explored** using the **Breadth-First Search (BFS)** algorithm.
- **Blue cells** represent the **visited nodes**—these are the cells BFS checked while searching for the shortest path.
- **White cells** represent the **actual shortest path** from the **start node (green)** to the **end node (red)**.

2. BFS Characteristics in Action

- BFS explores all possible paths **level by level**.
- It spreads outward **evenly** from the start point, ensuring that the **shortest path is found first**.
- In this case, BFS has **discovered an L-shaped shortest path** from the **top-left (green)** to the **bottom-right (red)**.

3. How BFS Reached the Solution

1. BFS starts from the **green node** and explores in **all four directions** (up, down, left, right).
2. It **spreads outward**, marking all visited nodes **blue**.
3. When BFS finds the **red node**, it **backtracks** and highlights the **shortest path** in **white**.
4. The result is a **clear shortest path**, avoiding unnecessary longer routes.

4. Observations & Analysis

- **Efficient Exploration**: The blue area covers a large portion of the grid, showing BFS systematically checked nodes.
- **Optimal Path Found**: The path is **direct and minimal**, proving BFS correctly found the shortest path.

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