Week 2 Project: Search Algorithms

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INSTRUCTIONS

In this assignment you will create an agent to solve the 8**-puzzle** game. You may visit **mypuzzle.org/sliding** for a refresher of the rules of the game. You will implement and compare several search algorithms and collect some statistics related to their performances. Please read all sections of the instructions carefully:

I. Introduction

II. Algorithm Review

III. What You Need To Submit

IV. What Your Program Outputs

V. Important Information

VI. Before You Finish

NOTE: This project incorporates material learned from both **Week 2** (uninformed search) and **Week 3** (informed search). Since this project involves a fair amount of programming and design, we are releasing it now to let you get started earlier. In particular, do not worry if certain concepts (e.g. heuristics, A-Star, etc.) are not familiar at this point; you will understand everything you need to know by Week 3.

I. Introduction

An instance of the N-puzzle game consists of a **board** holding N = m^2 − 1 (m = 3, 4, 5, ...) distinct movable tiles, plus an empty space. The tiles are numbers from the set {1, …, m^2 − 1}. For any such board, the empty space may be legally swapped with any tile horizontally or vertically adjacent to it. In this assignment, we will represent the blank space with the number 0 and focus on the m = 3 case (8-puzzle).

Given an initial **state** of the board, the combinatorial search problem is to find a sequence of moves that transitions this state to the goal state; that is, the configuration with all tiles arranged in ascending order ⟨0, 1, …, m^2 − 1⟩. The search space is the set of all possible states reachable from the initial state. The blank space may be swapped with a component in one of the four directions {'Up', 'Down', 'Left', 'Right'}, one move at a time. The cost of moving from one configuration of the board to another is the same and equal to one. Thus, the total cost of path is equal to the number of moves made from the initial state to the goal state.

II. Algorithm Review

Recall from the lectures that searches begin by visiting the root node of the search tree, given by the initial state. Among other book-keeping details, three major things happen in sequence in order to visit a node:

- First, we **remove** a node from the frontier set.
- Second, we **check** the state against the goal state to determine if a solution has been found.
- Finally, if the result of the check is negative, we then **expand** the node. To expand a given node, we generate successor nodes adjacent to the current node, and add them to the frontier set. Note that if these successor nodes are already in the frontier, or have already been visited, then they should not be added to the frontier again.

This describes the life-cycle of a visit, and is the basic order of operations for search agents in this assignment—(1) remove, (2) check, and (3) expand. In this assignment, we will implement algorithms as described here. Please refer to lecture notes for further details, and review the lecture pseudocode before you begin the assignment.

IMPORTANT: Note that you may encounter implementations elsewhere that attempt to short-circuit this order by performing the goal-check on successor nodes immediately upon expansion of a parent node. For example, Russell & Norvig's implementation of breadth-first search does precisely this. Doing so may lead to edge-case gains in efficiency, but do not alter the general characteristics of complexity and optimality for each method. For simplicity and grading purposes in this assignment, **do not make such modifications to algorithms learned in lecture**.

III. What You Need To Submit

Your job in this assignment is to write `driver.py`, which solves any 8-puzzle board when given an arbitrary starting configuration. The program will be executed as follows:

```
$ python driver.py <method> <board>
```

The method argument will be one of the following. You need to implement all three of them:

`bfs` (Breadth-First Search)

`dfs` (Depth-First Search)

`ast` (A-Star Search)

The board argument will be a comma-separated list of integers containing no spaces. For example, to use the bread-first search strategy to solve the input board given by the starting configuration {0,8,7,6,5,4,3,2,1}, the program will be executed like so (with no spaces between commas):

$ python driver.py bfs 0,8,7,6,5,4,3,2,1

IMPORTANT: If you are using Python 3, please name your file `driver_3.py`, which will alert the grader to use the correct version of Python during submission and grading. If you name your file `driver.py`, the default version for our box is Python 2.

IV. What Your Program Outputs

When executed, your program will create / write to a file called `output.txt`, containing the following statistics:

`path_to_goal`: the sequence of moves taken to reach the goal

`cost_of_path`: the number of moves taken to reach the goal `nodes_expanded`: the number of nodes that have been expanded

`search_depth`: the depth within the search tree when the goal node is found

`max_search_depth`: the maximum depth of the search tree in the lifetime of the algorithm

`running_time`: the total running time of the search instance, reported in seconds

`max_ram_usage`: the maximum RAM usage in the lifetime of the process as measured by the **ru_maxrss** attribute in the **resource** module, reported in megabytes

Example #1: Breadth-First Search

Suppose the program is executed for breadth-first search as follows:

$ python driver.py bfs 1,2,5,3,4,0,6,7,8

Which should lead to the following solution to the input board:

$$parent = \begin{array}{|c|c|c|}\hline 1 & 2 & 5 \\ \hline 3 & 4 & \\ \hline 6 & 7 & 8 \\ \hline \end{array} \quad \Longrightarrow \quad child = \begin{array}{|c|c|c|}\hline 1 & 2 & \\ \hline 3 & 4 & 5 \\ \hline 6 & 7 & 8 \\ \hline \end{array}$$

$$parent = \begin{array}{|c|c|c|}\hline 1 & 2 & \\ \hline 3 & 4 & 5 \\ \hline 6 & 7 & 8 \\ \hline \end{array} \quad \Longrightarrow \quad child = \begin{array}{|c|c|c|}\hline 1 & & 2 \\ \hline 3 & 4 & 5 \\ \hline 6 & 7 & 8 \\ \hline \end{array}$$

$$parent = \begin{array}{|c|c|c|}\hline 1 & & 2 \\ \hline 3 & 4 & 5 \\ \hline 6 & 7 & 8 \\ \hline \end{array} \quad \Longrightarrow \quad child = \begin{array}{|c|c|c|}\hline & 1 & 2 \\ \hline 3 & 4 & 5 \\ \hline 6 & 7 & 8 \\ \hline \end{array}$$

The output file (example) will contain **exactly** the following lines:

path_to_goal: ['Up', 'Left', 'Left']

cost_of_path: 3

nodes_expanded: 10

search_depth: 3

max_search_depth: 4

running_time: 0.00188088

max_ram_usage: 0.07812500

Example #2: Depth-First Search

Suppose the program is executed for depth-first search as follows:

$ python driver.py dfs 1,2,5,3,4,0,6,7,8

Which should lead to the following solution to the input board:

$$parent = \begin{array}{|c|c|c|}\hline 1 & 2 & 5 \\ \hline 3 & 4 & \\ \hline 6 & 7 & 8 \\ \hline \end{array} \quad \Longrightarrow \quad child = \begin{array}{|c|c|c|}\hline 1 & 2 & \\ \hline 3 & 4 & 5 \\ \hline 6 & 7 & 8 \\ \hline \end{array}$$

$$parent = \begin{array}{|c|c|c|}\hline 1 & 2 & \\ \hline 3 & 4 & 5 \\ \hline 6 & 7 & 8 \\ \hline \end{array} \quad \Longrightarrow \quad child = \begin{array}{|c|c|c|}\hline 1 & & 2 \\ \hline 3 & 4 & 5 \\ \hline 6 & 7 & 8 \\ \hline \end{array}$$

$$parent = \begin{array}{|c|c|c|}\hline 1 & & 2 \\ \hline 3 & 4 & 5 \\ \hline 6 & 7 & 8 \\ \hline \end{array} \quad \Longrightarrow \quad child = \begin{array}{|c|c|c|}\hline & 1 & 2 \\ \hline 3 & 4 & 5 \\ \hline 6 & 7 & 8 \\ \hline \end{array}$$

The output file (example) will contain **exactly** the following lines:

path_to_goal: ['Up', 'Left', 'Left']

cost_of_path: 3

nodes_expanded: 181437

search_depth: 3

max_search_depth: 66125

running_time: 5.01608433

max_ram_usage: 4.23940217

Other test cases are available on **Week 2 Project: Implementation FAQs** page.

Note on Correctness

Of course, the specific values for `running_time` and `max_ram_usage` variables will vary greatly depending on the machine used and the specific implementation details; there is no "correct" value to look for. They are intended to enable you to check the time and space complexity characteristics of your code, and you should spend time to do so. All the other variables, however, will have **one and only one** correct answer for each algorithm and initial board specified in the sample test cases.* A good way to check the correctness of your program is to walk through small examples by hand, like the ones above.

* In general, **for any initial board whatsoever**, for BFS and DFS there is one and only one correct answer. For A*, however, your output of `nodes_expanded` may vary a little, depending on specific implementation details. You will be fine as long as your algorithm conforms to all **specifications** listed in these instructions.

V. Important Information

Please read the following information carefully. Since this is the first programming project, we are providing many hints and explicit instructions. Before you post a clarifying question on the discussion board, make sure that your question is not already answered in the following sections.

1. Implementation

You will implement the following three algorithms as demonstrated in lecture. In particular:

- **Breadth-First Search**. Use an explicit queue, as shown in lecture.
- **Depth-First Search**. Use an explicit stack, as shown in lecture.
- **A-Star Search**. Use a priority queue, as shown in lecture. For the choice of heuristic, use the Manhattan priority function; that is, the sum of the distances of the tiles from their goal positions. Note that the blanks space is not considered an actual tile here.

2. Order of Visits

In this assignment, where an arbitrary choice must be made, we always **visit** child nodes in the "**UDLR**" order; that is, [‘Up’, ‘Down’, ‘Left’, ‘Right’] in that exact order. Specifically:

- **Breadth-First Search**. Enqueue in UDLR order; dequeuing results in UDLR order.
- **Depth-First Search**. Push onto the stack in reverse-UDLR order; popping off results in UDLR order.
- **A-Star Search**. Since you are using a priority queue, what happens when there are duplicate keys? What do you need to do to ensure that nodes are retrieved from the priority queue in the desired order?

3. Submission Test Cases

You can **submit** your project any number of times before the deadline. Only the final submission will be graded. Following each submission, all three of your algorithms will be automatically run on two sample test cases each, for a total of **6** distinct tests:

Test Case #1

```
python driver.py bfs 3,1,2,0,4,5,6,7,8
```

```
python driver.py dfs 3,1,2,0,4,5,6,7,8
```

```
python driver.py ast 3,1,2,0,4,5,6,7,8
```

Test Case #2

```
python driver.py bfs 1,2,5,3,4,0,6,7,8
```

```
python driver.py dfs 1,2,5,3,4,0,6,7,8
```

```
python driver.py ast 1,2,5,3,4,0,6,7,8
```

This is provided as a sanity check for your code and the required output format. In particular, this is intended to ensure that you do not lose credit for incorrect output formatting. **Make sure your code passes at least these two test cases**. You will see that the results of each test are assessed by 8 items: 7 items are listed in**Section IV. What Your Program Outputs**. The last point is for code that executes and produces any output at all. Each item is worth 0.75 point.

4. Grading and Stress Tests

We will grade your project by running **additional test cases** on your code. In particular, there will be five test cases in total, each tested on all three of your algorithms, for a total of **15** distinct tests. Similar to the submission test cases, each test will be graded by 8 items, for a total of 90 points. **Plus, we give 10 points for code completing all 15 test cases within 10 minutes**. If you implement your code with reasonable designs of data structures, your code will solve all 15 test cases within a minute in total. We will be using a wide variety of inputs to stress-test your algorithms to check for correctness of implementation. So, we recommend that you test your own code extensively.

Do not worry about checking for **malformed input** boards, including boards of non-square dimensions, or unsolvable boards.

You will not be graded on the absolute values of your running-time or RAM usage statistics. The values of these statistics can vary widely depending on the machine. **However, we recommend that you take advantage of them in testing your code.** Try batch-running your algorithms on various inputs, and plotting your results on a graph to learn more about the space and time complexity characteristics of your code. Just because an algorithm provides the correct path to goal does not mean it has been implemented correctly.

5. Tips on Getting Started

Begin by writing a class to represent the **state** of the game at a given turn, including parent and child nodes. We suggest writing a separate **solver** class to work with the state class. Feel free to experiment with your design, for example including a **board** class to represent the low-level physical configuration of the tiles, delegating the high-level functionality to the state class. When comparing your code with pseudocode, you might come up with another class for organising specific aspects of your search algorithm elegantly.

You will not be graded on your design, so you are at a liberty to choose among your favorite programming paradigms. Students have successfully completed this project using an entirely object-oriented approach, and others have done so with a purely functional approach. Your submission will receive full credit as long as your driver program outputs the correct information.

VI. Before You Finish

- **Make sure** your code passes at least the two submission test cases.
- **Make sure** your algorithms generate the correct solution for an arbitrary solvable problem instance of 8-puzzle.

- **Make sure** your program always terminates without error, and in a reasonable amount of time. **You will receive zero points from the grader if your program fails to terminate. Running times of more than a minute or two may indicate a problem with your implementation.** If your implementation exceeds the time limit allocated (20 minutes for all test cases), your grade may be incomplete.
- **Make sure** your program output follows the specified format exactly. In particular, for the path to goal, use square brackets to surround the list of items, use single quotes around each item, and capitalize the first letter of each item. Round floating point numbers to 8 places after the decimal. You will not receive proper credit from the grader if your format differs from the provided examples above.

USE OF VOCAREUM

This assignment uses Vocareum for submission and grading. Vocareum comes equipped with an editing environment that you may use to do your development work. You are **NOT** required to use the editor. In particular, you are free to choose your favorite editor / IDE to do your development work on. When you are done with your work, you can simply upload your files onto Vocareum for submission and grading.

However, your assignments will be graded on the platform, so you **MUST** make sure that your code passes at least the submission test cases. In particular, do not use third-party libraries and packages. We do not guarantee that they will work on the platform, even if they work on your personal computer. For the purposes of this project, everything that comes with the standard Python library should be more than sufficient.

Q. My search algorithm seems correct but is too slow. How can I reduce its running time?

A. Search algorithm is perhaps one of the best learning materials for computational complexity and Python's idiosyncrasies. There are four dos and don'ts:

1. Don't store possibly-large data member such as solution `path` in search tree node class. Instead, rethink what operation should be fast.

Explanation: Storing a path from the root node in each node class achieves O(1) lookup time at the expense of O(n) creation time. For example, if the current state is visited after 60,000 intermediate states, the current state has to allocate a list of 60,000 elements, and each of the children states have to allocate a list of 60,001 elements. This would soon use up physical memory, and typically your machine's Operating System kills the search process.

A key observation is that **in the case of search algorithm, path lookup operation is executed just once after search finishes. Thus, the lookup operation is fine to be slow**. You might consider another data structure having O(n) lookup time for solution path but requiring O(1) operations during search.

2. Don't be satisfied by just using `list` as frontier. Instead, design your `Frontier` class which works faster.

Explanation: one major bottleneck of `list, deque,` or `queue` class in Python is that their **membership testing operation** is O(n). The membership testing speed is critical for search algorithm because that operation is executed for every child state. Coming up with using such list-like data structures is a good first step, but for using it with reasonable execution time, you might need one more trick.

Note that pseudocode in lecture slides does not necessarily reflect implementation details (i.e. time and space). Rather, it conceptually shows the algorithm's inputs, processing orders, and outputs. One of your missions in this assignment is to make the "frontier" thing into a reality by using Python's "low-level" primitives.

3. Don't use O(n) operation when you have another faster way to do the same thing.

Explanation: Roughly speaking, **if you set one O(n) operation under your `for neighbor in neighbors` loop, your code will be highly likely to exceed grading time limit**. In other words, it happens that your code executes drastically faster when you fix just one line of your code.

For example, merging two `set`s and checking an element is in the merged set is an expensive operation, while checking an element is in one of the two sets are O(1) operation.

4. Don't use `copy.deepcopy()` for list. Instead, use `list1 = [5,6]; list2 = list(list1)` or `list2 = list1[:]`.

Explanation: `copy.deepcopy()` handles very rare recursive edge cases and is slow. When simply copying a list or other data structures, you can construct a new list by `list()` constructor or **:** operator. Some people avoid the second notation due to readability, but it's frequently used in the real world.

Q. How can I locate the slow code block?

A. The simplest way is to execute **`python -m cProfile -s tottime driver.py <puzzle initial state>`**.

- -m : specifies module name. cProfile is a built-in profiling Python module.
- -s : sorting by the `tottime` (total execution time) statistic.
- For meaning of each statistics, see this official documentation.
- The profiling result will be shown even if you stop your driver.py by Ctrl + C command.

If you would like to see the results not on stdout but on browser, cprofilev module might help. There is a well-written tutorial here.

Having said that, sometimes cProfile does not show which part of code makes search slow. Typical case is the first top entry when sorted by tottime is your entire search function (e.g. A-STAR-SEARCH, which is called only one time), and it takes 99% of your execution time.

One approach is to make a wrapper function for an operation which you think might cause the slowness. For example, if you're suspecting **`set1 | set2`** (merging two sets) operation is slow, you can make the following wrapper function:

```
def merge_two_sets(set1, set2): # O(1)? O(n)? O(len(set1) +
len(set2))?
      return set1 | set2
```

This simple trick triggers cProfile module to show how long this one-operation function takes. In my test script, 95% of execution time is actually caused by this operation. Recall that cProfile will return profiling results even if you pause your program by Ctrl + C command.

Q. Do I need to optimize my search algorithm as much as possible?

A. You don't need to squeeze your code's performance by fancy optimization techniques such as bit shifting or reducing the number of function calls (i.e. putting every operation in one function for reducing overhead of function calls). Except `copy.deepcopy()`, most of your design choices are about choosing best data structures in terms of time/space complexity.

Q. Is there any other test cases?

A. The following two test cases might help for your stat validation. Note that long path_to_goals are truncated and running_time/max_ram_usage are removed:

python driver.py dfs 6,1,8,4,0,2,7,3,5

path_to_goal: ['Up', 'Left', 'Down', ... , 'Up', 'Left', 'Up', 'Left']

```
cost_of_path: 46142
nodes_expanded: 51015
search_depth: 46142
max_search_depth: 46142
```

python driver.py bfs 6,1,8,4,0,2,7,3,5

path_to_goal: ['Down', 'Right', 'Up', 'Up', 'Left', 'Down', 'Right', 'Down', 'Left', 'Up', 'Left', 'Up', 'Right', 'Right', 'Down', 'Down', 'Left', 'Left', 'Up', 'Up']

```
cost_of_path: 20
nodes_expanded: 54094
search_depth: 20
max_search_depth: 21
```

```
python driver.py ast 6,1,8,4,0,2,7,3,5
```

```
path_to_goal: ['Down', 'Right', 'Up', 'Up', 'Left', 'Down', 'Right',
'Down', 'Left', 'Up', 'Left', 'Up', 'Right', 'Right', 'Down', 'Down',
'Left', 'Left', 'Up', 'Up']
cost_of_path: 20
nodes_expanded: 696
search_depth: 20
max_search_depth: 20
```

```
python driver.py dfs 8,6,4,2,1,3,5,7,0
```

path_to_goal: ['Up', 'Up', 'Left', ..., , 'Up', 'Up', 'Left']

```
cost_of_path: 9612
nodes_expanded: 9869
search_depth: 9612
max_search_depth: 9612
```

python driver.py bfs 8,6,4,2,1,3,5,7,0

path_to_goal: ['Left', 'Up', 'Up', 'Left', 'Down', 'Right', 'Down', 'Left', 'Up', 'Right', 'Right', 'Up', 'Left', 'Left', 'Down', 'Right', 'Right', 'Up', 'Left', 'Down', 'Down', 'Right', 'Up', 'Left', 'Up', 'Left']

```
cost_of_path: 26
nodes_expanded: 166786
search_depth: 26
max_search_depth: 27
```

python driver.py ast 8,6,4,2,1,3,5,7,0

```
path_to_goal: ['Left', 'Up', 'Up', 'Left', 'Down', 'Right', 'Down',
'Left', 'Up', 'Right', 'Right', 'Up', 'Left', 'Left', 'Down',
'Right', 'Right', 'Up', 'Left', 'Down', 'Down', 'Right', 'Up',
'Left', 'Up', 'Left']
cost_of_path: 26
nodes_expanded: 1585
search_depth: 26
max_search_depth: 26
```

Note that these two test cases are different from ones used for grading. Coming up with tricky test cases also help you understand search algorithm behaviours deeply.

Q. (Windows Users) Is there "resource" module in Windows?

If you use Python in Cygwin, resource module is available. If otherwise, one possible workaround is to use third-party module only if the machine is Windows:

```
import sys
if sys.platform == "win32":
  import psutil
  print("psutil", psutil.Process().memory_info().rss)
```

```
else:
  # Note: if you execute Python from cygwin,
  # the sys.platform is "cygwin"
  # the grading system's sys.platform is "linux2"
  import resource
  print("resource",
resource.getrusage(resource.RUSAGE_SELF).ru_maxrss)
```

Note that **the values of max_ram_usage and running_time are not graded** as stated in project instruction page. These stats are only for helping your study on search algorithm's time/space metrics.

Q. Why does the example of `python driver.py dfs 1,2,5,3,4,0,6,7,8` return ['Up', 'Left', 'Left'] instead of ['Up', 'Left', 'Down', ...] (a solution path with 31 moves)? We are using UDLR (Up, Down, Left, Right) order, and Down move should be executed before Left move. Isn't the ['Up', 'Left', 'Left'] solution resulted from optimization forbidden in project instruction?

No, ['Up', 'Left', 'Left'] solution does not use the forbidden optimization and is a correct answer. Compared to the simpleness of the 3-move solution path, you would notice that "nodes_expanded" statistic is extremely large (181437 states). In fact, the total reachable states in (solvable) 8-puzzle is 9!/2 = 181440 states, so this statistic suggests depth first search **constantly overlooks the goal state and expands more than 99.9% of possible states in the search space**.

Why is this happening?
Please think about the reason for one minute before reading the following explanations.

There are two facts we can read from dfs pseudocode in class slides:

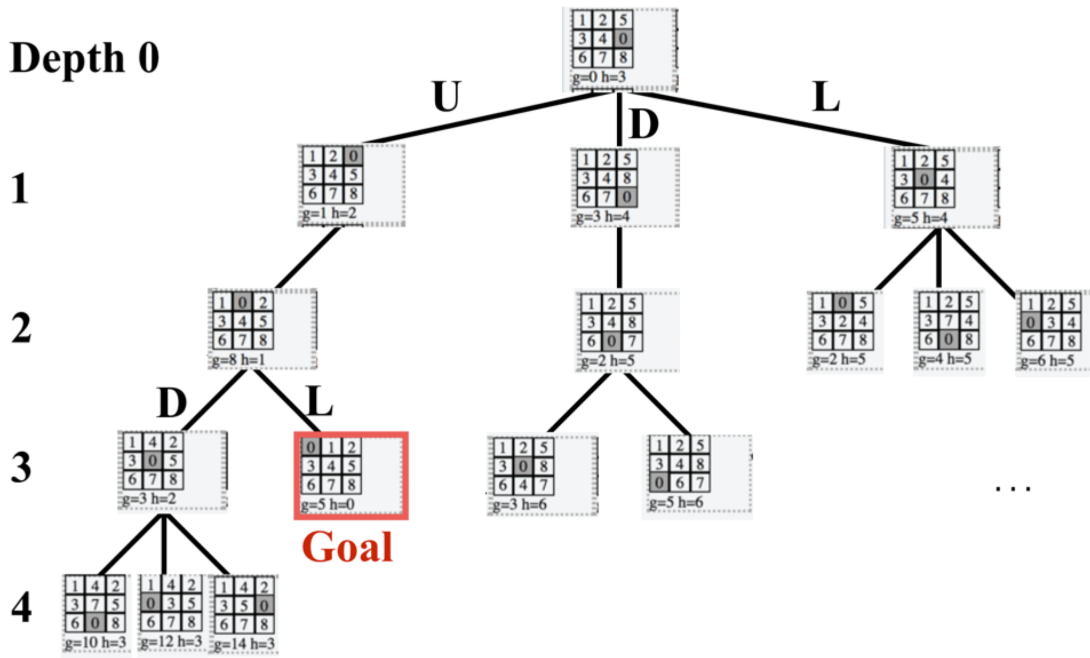
Fact 1. goalTest() function is only called for states which are just popped out from frontier. In other words, goalTest() is not applied to **neighbor** states **even if the neighbor is actually the solution state** (because we prohibited such an optimization).
Fact 2. A child state (neighbor) is only pushed into frontier when it's not already in frontier (and explored). More specifically, **the goal state** is only pushed into frontier when it's not already in frontier.

Combining those two facts reaches to the conclusion: **since the goal state is already pushed into frontier (i.e. the state corresponding to ['Up', 'Left', 'Left'] move), any subsequent encounter to the solution state cannot execute frontier.push() or goalTest() and is effectively meaningless.** Thus, the dfs algorithm extensively searches through numerous states in 8-puzzle (without putting the solution state into frontier again), gradually goes back to the previously pushed states, and finally find the solution state which is pushed at the very beginning of the search.

This question would arise when you remove/forget `neighbor in frontier` checking in your pseudocode. And if you add the checking, you will face the slowness of membership checking. In that case, please see the first question of this page ("**Q. My search algorithm seems correct but is too slow. How can I reduce its running time?**").

Q. Why the max_search_depth of python driver.py bfs 1,2,5,3,4,0,6,7,8 is 4 even though the goal state is at depth 3?

The following figure would be useful (please ignore g and h values):



Q. Why does my driver_3.py return nothing on Vocareum?

If you have default driver.py in your submission, please remove that file. Grading script does not work correctly if both of driver.py and driver_3.py exist.

Q. My `python driver.py dfs 1,2,5,3,4,0,6,7,8` returns max_search_depth as 66126 not 66125. Where does this off-by-one difference come from?

One probable reason is you are updating your max_search_depth too early. If you increase max_search_depth after generate_successor() but before checking membership, the generated child state could be actually already in frontier or explored (thus the state cannot be appended to the search tree).