

## CS51 PROBLEM SET 5: THE SEARCH FOR INTELLIGENT SOLUTIONS

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### CONTENTS

|                                   |   |
|-----------------------------------|---|
| 1. Overview                       | 1 |
| 2. Search problems                | 2 |
| 3. Structure of the provided code | 3 |
| 3.1. Collections                  | 4 |
| 3.2. Game description             | 5 |
| 3.3. Game solving                 | 5 |
| 4. Testing, metering, and writeup | 5 |
| 5. Submission                     | 6 |

**You may work with a partner on this problem set. If you choose to work with a partner, you can find instructions for configuring GitHub Classroom in the [CS51 Reference](#) or [CSCI E-51 Reference](#).**

### 1. OVERVIEW

5 In this assignment, you will apply your knowledge of OCaml modules and functors to complete the implementation of a program for solving search problems, a core problem in the field of artificial intelligence. In the course of working on this assignment, you'll implement a more efficient queue module using two stacks; create a *higher-order functor* that abstracts away details of search algorithms and game implementations; and compare, visualize, and analyze the  
10 performance of various search algorithms on different games.

**Questions to consider:** The "questions to consider" in this writeup are not graded (though the numbered problems are!). They are provided primarily to help you assess your understanding of the material. You aren't expected to include answers to them in your submission, but the concepts they address could arise on exams. Answers to most of the  
15 questions are in the comments of the problem set.

**Testing:** Unit testing is required, as always. Please see `tests.ml` for further information on how to test.

**Partners:** You are allowed (and encouraged) to work with a partner on this assignment. You are also allowed to work alone, if you prefer. If you are an extension student, you are free

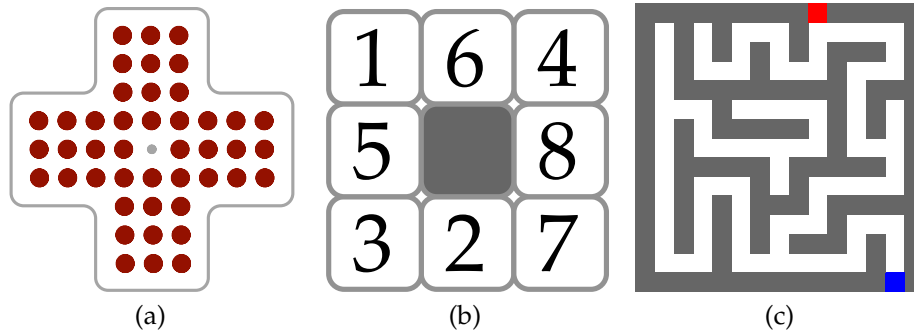


FIGURE 1. Some puzzles based on search for a goal state. (a) the peg solitaire puzzle; (b) the sliding-tile 8 puzzle; (c) a maze puzzle.

to pair up with another extension or on-campus student. For more detailed instructions, look [here](#).

**Compilation and Submitting:** As usual, make sure to commit and push early and often. By sharing your remote repository with your partner, you can more effectively collaborate on maintaining your shared code base.

**Downloading:** To download the provided materials for this problem set, first create your repository in GitHub Classroom for this homework by following [this link](#). Then, follow the GitHub Classroom instructions found [here](#). Note that, now that you are working with a partner, you should endeavor to keep up-to-date with your partner's code. Run `git pull` to fetch any changes, and `git push` to upload your changes to the repository. It's generally a good practice to `pull` before you `push`, so you can resolve any conflicts between your and your partner's code. More information about Git and its use can be found in Eddie Kohler's [guide to Git](#) and in Brian Yu's [Git video](#).

## 2. SEARCH PROBLEMS

The field of artificial intelligence pursues the computational emulation of behaviors that in humans are indicative of intelligence. A hallmark of intelligent behavior is the ability to figure out how to achieve some desired goal. Let's consider an idealized version of this behavior – puzzle solving. A puzzle can be in any of a variety of **STATES**. The puzzle starts in a specially designated **INITIAL STATE**, and we desire to reach a **GOAL STATE** by finding a sequence of **MOVES** that, when executed starting in the initial state reach the goal state. Figure 1 provides some examples of this sort of puzzle.

A good example is the 8 puzzle, depicted in Figure 2. (You may know it better as the 15 puzzle, the larger 4 by 4 version.) A 3 by 3 grid of numbered tiles, with one tile missing, allows sliding of a tile adjacent to the empty space. The goal state is to be reached by repeated moves of this sort. But which moves should you make?

Solving goal-directed problems of this sort requires a **SEARCH** among all the possible move sequences, for one that achieves the goal. You can think of this search process as a walk of a **SEARCH TREE**, where the nodes in the tree are the possible states of the puzzle and the directed

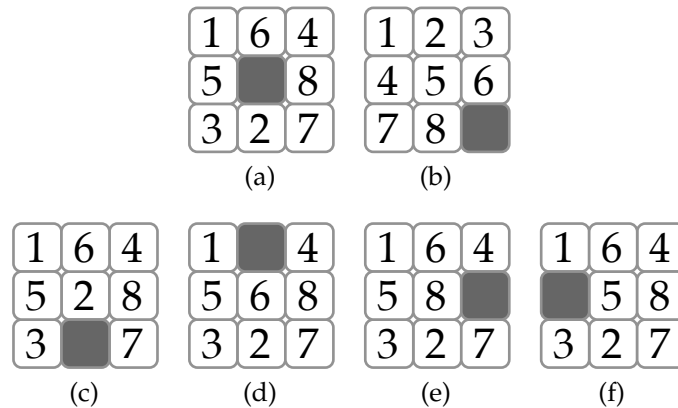


FIGURE 2. The 8 puzzle: (a) an initial state, (b) the goal state, (c-f) the states resulting from moving up, down, left, and right from the initial state, respectively.

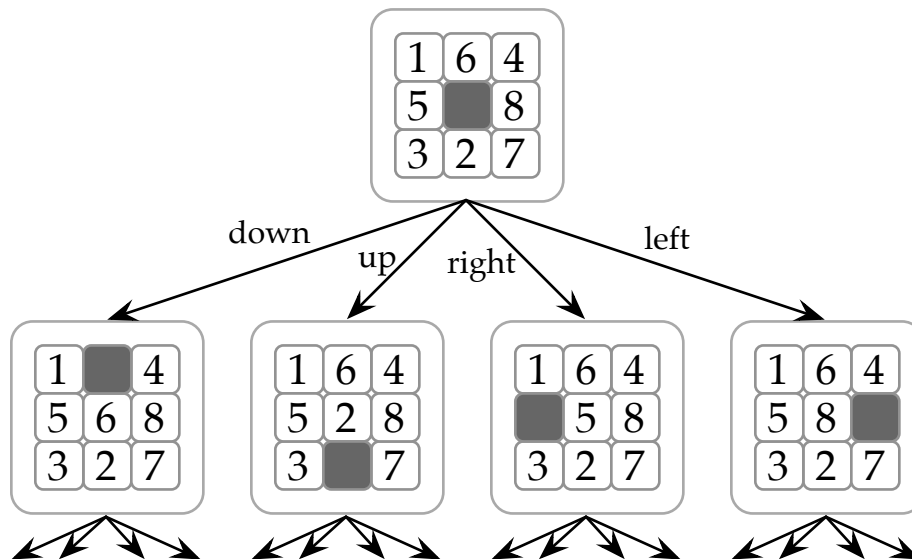


FIGURE 3. A snippet from the search tree for the 8 puzzle.

edges correspond to moves that change the state from one to another. Figure 3 depicts a small piece of the tree corresponding to the 8 puzzle.

50 To solve a puzzle of this sort, you maintain a collection of states to be searched. This collection is initialized with just the initial state. You can then take a state from the collection and test it to see if it's the goal state. If so, the puzzle has been solved. But if not, this state's NEIGHBOR states – states that are reachable in one move from the current state – are added to the collection (or at least those that have not been visited before) and the search continues.

55 Of course, much of the effectiveness of this process depends on what order states are taken from the collection of pending states as the search proceeds. If the states taken from the collection are those most recently added to the collection (last-in, first-out, that is, as a stack), the tree is being explored in a DEPTH-FIRST manner. If the states taken from the collection are those least recently

NEIGHBOR

DEPTH-FIRST

BREADTH-FIRST

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BEST-FIRST  
GREEDY

added (first-in, first-out, as a queue), the exploration is BREADTH-FIRST. Other orders are possible, for instance, the states might be taken from the collection in order of how closely they match the goal state (using some metric of closeness). This regime corresponds to BEST-FIRST or GREEDY search.

### 3. STRUCTURE OF THE PROVIDED CODE

We have provided code to start off the process of building a general puzzle-solving system that allows for different search regimes applied to different puzzle types. You'll want to  
65 familiarize yourself with the provided code.

You will work with the following signatures, modules, and functors. Some of the important components are listed by the file they are found in. Components that you will write are shown *in italics*.

- collections.ml
  - COLLECTION – A signature for collections of elements allowing adding and taking elements 70
  - MakeStackList – A functor for generating a stack Collection implemented using lists
  - MakeQueueList – A functor for generating a queue Collection implemented using lists
  - MakeQueueStack – *A functor for generating a queue Collection, where the Queue is implemented using two stacks* 75
- gamedescription.ml
  - GAMEDESCRIPTION – A signature for specifications of games, providing information about the states and moves, initial and goal states, the neighbors structure of the game, etc. 80
- gamesolve.ml
  - GAMESOLVER – A signature for game solvers
  - MakeGameSolver – *A higher-order functor for generating different game solvers*
- mazes.ml – A specification of maze puzzles
- tiles.ml – A specification of tile puzzles

3.1. **Collections.** The file collections.ml provides a signature for COLLECTION modules. A COLLECTION module, which is very similar to the OrderedCollection module in Problem Set 4, is a data structure with types `elt` and `collection`, and functions `take` and `add`. `take` removes an `elt` from a `collection`, while `add` inserts an `elt` into a `collection`. Collections generalize over a variety of data structures including stacks, queues, and priority queues. 85

Collections will be used to store the set of states reachable from the initial state that have yet to be explored, as the game solver searches the space of states, in order to find a goal state. By using different collections that implement different orderings in how elements are taken from the collection, different search regimes are manifested and different efficiencies of the search process can result. 90

We have provided two functors for especially simple implementations of COLLECTION, one that implements a stack represented internally as a list, and one that implements a queue represented internally with a list. You will implement a third functor `MakeQueueStack`, that 95

implements a queue represented internally as two stacks, similar to the approach introduced in lecture 10. (However, you should be able to provide an implementation more elegant and more purely functional than the examples from the lecture. There's no reason to introduce imperative programming techniques for `MakeQueueStack`.)

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**Problem 1.** *Implement the `MakeQueueStack` functor. You'll want to test it fully as well.* □

In theory, the implementation in `MakeQueueStack` should be more efficient than that of `MakeQueueList`. In Section 4, you will experiment with that hypothesis and provide a report on your findings as part of the problem set.

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**3.2. Game description.** A simple module signature of a game description, called `GAMEDESCRIPTION`, specifies an interface that includes data types for the states and moves, an initial state, a predicate for goal states, and functions for generating neighbors, for executing move sequences, and for visualizing the game. You will want to read and understand it to familiarize yourself with the functionality a `GAMEDESCRIPTION` provides.

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To understand the notion of moves and states, consider a simple maze. In a maze, the state would be represented as the current position in the maze, and the moves would allow you to change your position by walking up, down, left, or right. The neighbors of a state would be the positions that you could move to in one step using those moves, keeping in mind that not all four move types are possible from a given state. Similarly, in the 8 puzzle, a state is a configuration of the tiles and a move is the swapping of the empty tile with one of its four adjacent tiles, the adjacent tile moving up, down, left, or right.

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**3.3. Game solving.** In file `gamesolve.ml`, you will also implement a functor `MakeGameSolver` that maps a collection implementation (implemented as a functor that generates modules satisfying the signature `COLLECTION`) and a game description (a module satisfying the `GAMEDESCRIPTION` signature) to a module implementing the `GAMESOLVER` signature. This signature provides a `solve` function to solve the game described in the `GAMEDESCRIPTION` using a search that uses the provided collection regime.

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The type of the `solve` function is `unit -> move list * state list`. When called (by applying it to `unit`), it returns a solution to the game, a list of moves that when executed on the initial state reaches a goal state, along with the sequence of states generated along that move sequence.

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The type signature of `MakeGameSolver` is below:

```
(functor(sig type t end -> COLLECTION)) -> GAMEDESCRIPTION -> GAMESOLVER
```

Notice that `MakeGameSolver` is a functor that takes a functor as its argument! It is a higher-order functor. (You may not have realized that was even possible in OCaml.) The argument functor can be used to provide a collection of elements of any type. We recommend that you use it to store a collection of elements of type `state * (move list)`. Each such element is a state reachable by executing the associated list of moves starting from the initial state.

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The `GAMESOLVER` signature provides for an exception `CantReachGoal` for the solver to raise if it can't find a solution to the game.

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**Problem 2.** Implement the `MakeGameSolver` functor. Again, you'll want to test it fully. □

#### 4. TESTING, METERING, AND WRITEUP

We've provided two sample games, an 8-puzzle game and a maze puzzle, in files `tiles.ml` and `mazes.ml`, respectively. Once you've implemented the solver (Section 3.3) you should be able to solve simple puzzles of these sorts, and even implement your own puzzles if you're of a mind too. (Extra karma!)

You can try out both depth-first and breadth-first search for solving the puzzles by using different collection functors in the solver. With your two-stack implementation of queues, you can experiment with the relative efficiency of the two queue implementations.

In order to assess the benefit of the additional implementation of collections, you should design, develop, test, and deploy a performance testing system for timing the performance of the solver using different search regimes and implementations. Unlike in previous problem sets, we provide no skeleton code to carry out this part of the problem set. You should add a file `experiments.ml` that carries out your experiments. The design of this code is completely up to you. This part of the problem set allows you the freedom to experiment with *ab initio* design. The deliverable for this part of the problem set, in addition to any code that you write, is a report on the relative performance that you find.

You'll want to write some OCaml code to time the solving process on appropriate examples with several collection implementations. There are some timing functions that may be useful in the CS51 module (`cS51.ml`). You may also find the `time` and `gettimeofday` functions in the `Sys` and `Unix` modules useful for this purpose.

We recommend that to the extent possible any code that you write for performing your testing not change the structure of code we provide, so that our unit tests will still work. Ideally, all the code for your experimentation should be in new files, not the ones we provided.

**Problem 3.** Write up a short report outlining what you discover from your experimentation. You should submit the writeup with the rest of your code as a text file named `writeup.txt` or `writeup.md`. We recommend that you use *Markdown format* for the writeup. (See [here](#) for why.) There are many tools for writing and rendering Markdown files. Some of our favorites are: *ByWord*, *Marked*, *MultiMarkdown Composer*, *Sublime Text*, and the *Swiss army knife* of file format conversion tools, *pandoc*. If you use Markdown, you can optionally include the rendered version as a PDF file in your submission. LaTeX format is also acceptable. □

This portion of the problem set is purposefully underspecified. There is no "right answer" that we are looking for. It is up to you to determine what makes sense to evaluate the performance of the code. It is up to you to decide how to present your results in clear, well-structured, cogent prose and appropriate visualizations of the experimental results.

#### 5. SUBMISSION

Before submitting, please estimate how much time you and your partner each spent on the problem set by editing the line in `gamesolve.ml` that looks like

```
let minutes_spent () : int = failwith "not provided" ;;
```

to replace the value of the function with an approximate estimate of how long (in minutes) the problem set took you to complete. If you and your partner spent different amounts of time on a part, provide the average of the two.

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Make sure your code still compiles. Then, to submit the problem set, follow the Gradescope instructions found [here](#). Don't forget to submit the writeup as well.