

## 1 Introduction

Natural scenarios in real life occur where one must sequentially make decisions under uncertainty. Quite often not only are transitions to certain states unknown but the true state of the agent as well. This is similar to that of a hidden Markov model (HMM), only in that one must make a sequence of actions instead of a single action. The classic scenario is a robot navigating a discrete environment using a GPS, and it takes action that lead to different states with various probabilities, but because of the GPS there is also inaccuracy in what its current state is.

One can formalize this, under Markovian assumptions, as a partially observable Markov decision process (POMDP). In this project we provide a software library for solving them with modular classes in order to allow for flexible extensions. More specifically, we encode a variety of basic tasks and solve them using a combination of value iteration and a variant of Thompson sampling [1], which is a Bayesian approach following a Dirichlet-multinomial posterior over each state-action pair.

## 2 Technical Background

### 2.1 POMDP

POMDP is a generalization of a Markov decision process (MDP). In an MDP, for each possible state of the process, a decision has to be made regarding which action should be executed in that state. The chosen action affects both the transition probabilities and the costs (or rewards) incurred. The goal is to choose an optimal action in every state to increase some predefined measure of performance. In a POMDP model, the agent cannot fully observe the system states. Instead, it must maintain a probability distribution over the set of possible states, based on a set of observations and observation probabilities, and the underlying MDP.

More formally, a POMDP is represented by the following variables:

- $S$  is a set of states
- $A$  is a set of actions
- $T$  is a set of transition probabilities between states. If the agent is currently in state  $s \in S$ , and it takes action  $a \in A$ . The agent will transition to some new state  $s'$  according to  $T(s' | s, a)$
- $\Omega$  is a set of observations
- $O$  is a set of conditional observation probabilities. If the agent is now in state  $s$  after taking action  $a$ , the agent then receives an observation  $o$  according to  $O(o | s, a)$
- $\gamma \in [0, 1]$  is a discount factor that determines how much rewards should be discounted over time

### 2.2 Value Iteration

### 2.3 Thompson Sampling

The posterior probabilities are updated using the transition counts.

Thompson sampling gives us two capabilities: using dynamic programming, we can find the optimal action to take at a certain state, and it allows us to learn the transition model, and reward model for a

certain environment. We tested this with Markov Decision Processes (MDPs), and extended it to be used with POMDPs.

### 3 Implementation

For use with POMDPs, we assume that the agent is given an observation model of the environment it is acting in, in the form of a conditional probability distribution  $P(\text{observation} \mid \text{state})$ . Astrom has shown that a properly updated probability distribution over the state space  $S$  is sufficient to summarize all the observable history of a POMDP agent without loss of optimality [?]. The agent, however, is unaware of its transition model, and reward model, and must learn those. Using these models, the agent keeps, and updates a distribution over the states it can be in, and chooses the action with the highest expected reward.

We ran this code in a sample environment we call gridworld: the agent has negative reward for every state/action, except when it reaches a goal state, where it has a high positive reward. Gridworld represents a maze where the agent can be in discrete locations. Certain locations are impossible for the agent, representing “walls”. Every action can move the agent between two adjacent grid locations, or fail, and keep the agent in the same location with some probability.

#### 3.1 Agent Environment Paradigm

#### 3.2 Organization of Code

We follow the directory structure specified in the problem set, with two exceptions:

- `documentation/` does not exist. Instead, documentation is written in the `README.md` inside the current working directory. Any additional documentation not purely necessary for the problem set submission is in the Github wiki.
- `source/` is named `bayesrl/` in order to follow Python convention for installing modules.

### 4 Analysis

#### 4.1 Runtime

#### 4.2 Memory

#### 4.3 Limitations

### 5 Benchmark Results

The implementation of Thompson Sampling for MDPs ran very successfully: as time progressed, the agent was able to get to the goal much faster, and get a high reward. It did not work, however, for POMDPs. As time progressed, the agent seemed to take about the same amount of time to reach the goal on every execution, not improving in performance. We hypothesize that the reason is due to a lack of a good prior on the transition model: thompson sampling relies a lot on being able to count the number of transitions between states, given an action. This is very hard in a POMDP with a weak prior on its transition model, as it may have a completely wrong idea of where it ends up at each step. The observation model is supposed to improve its accuracy, but it was not sufficient in this case.

To have an idea of how differently successful the same approach was on MDPs vs POMDPs, we show you our results:

These graphs show the cumulative reward that the agent got as time progressed. In the MDP case, the reward started low, and kept getting lower, as the agent explored. It, however, started getting higher as the

agent started acting in a more deliberate manner, to maximize reward. The POMDP agent, however, seems to be in a state where its reward just gets increasingly negative. It is unclear whether it never leaves the exploration phase, or if it simply learns a completely wrong transition model, and thus computes a very wrong policy.

## References

- [1] Malcolm Strens. A bayesian framework for reinforcement learning. In *Proceedings of the 17th International Conference on Machine Learning (ICML)*, 2000.