

# ROB311 Quiz 3

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# 1 Overview

## Summary:

- MCTS
- $\alpha - \beta$  pruning
- Game Theory
- Exam problems are more difficult, but use past exams and over prepare.

## Partially Observable Probabilistic Decision Problems

# 2 Reinforcement Learning

**Summary:** In a RL problem,  $p(\cdot | \cdot, \cdot)$  and/or  $r(\cdot, \cdot)$  unknown, so we have to estimate q-star empirically.

### Equation

$$q^*(s, a) = \lim_{K \rightarrow \infty} \bar{R}_K$$

- $\bar{R}_K = \frac{1}{K} \sum_{k=1}^K r_k$ : empirical average reward.
- $r_k$ : reward obtained in the  $k^{\text{th}}$  simulation.
- $K$ : # of times action  $a$  taken in state  $s$  (# of simulations)
- $\gamma = 0$

$$q^*(s, a) \leftarrow q^*(s, a) + \frac{1}{N(s, a)} (r(s, a, s') - q^*(s, a))$$

- $N(s, a)$ : # of times action  $a$  taken in state  $s$ .
- $\gamma = 0$

$$q^*(s, a) \leftarrow q^*(s, a) + \frac{1}{N(s, a)} \left( \left[ r(s, a, s') + \gamma \max_{a'} q^*(s', a') \right] - q^*(s, a) \right)$$

- Using old  $q^*$  values to estimate.
- $\gamma \neq 0$

$$\pi(a | s) = \begin{cases} 1 & a = \arg \max_{a'} q^*(s, a) \\ 0 & \text{otherwise} \end{cases}$$

## 2.1 Running Average Update Rule

### Definition:

$$\bar{x} \leftarrow \bar{x} + \alpha(x_{\text{new}} - \bar{x}).$$

- $\alpha$ : learning rate

## 2.2 Q-Learning Algorithm

### Algorithm:

```

1 procedure Q_LEARNING():
2   for each episode do
3     set initial state  $s \leftarrow s_0$ 
4     while  $s \notin \mathcal{T}$  do #  $\mathcal{T}$ : terminal states
5       randomly choose an action in  $\mathcal{A}(s)$ 
6       get next state,  $s'$ , and reward  $r$ 
7       update  $N(s, a)$  and  $q^*(s, a)$  as follows:
8
9       
$$q^*(s, a) \leftarrow q^*(s, a) + \frac{1}{N(s, a)} \left( r(s, a, s') + \gamma \max_{a'} q^*(s', a') - q^*(s, a) \right)$$

10
11      
$$N(s, a) \leftarrow N(s, a) + 1$$

12
13       $s \leftarrow s'$ 
14    end while
15  end for

```

- **Note:** Possible infinite while loop if  $\mathcal{T}$  is not reached.

## 2.3 Modified Q-Learning Algorithm

### Algorithm:

```

1 procedure Q_LEARNING():
2   for each episode do
3      $l \leftarrow 0$ 
4     set initial state  $s \leftarrow s_0$ 
5     while  $s \notin \mathcal{T}$  and  $l < l_{\max}$  do
6       randomly choose an action in  $\mathcal{A}(s)$ 
7       get next state,  $s'$ , and reward  $r$ 
8       update  $N(s, a)$  and  $q^*(s, a)$  as follows:
9
10      
$$q^*(s, a) \leftarrow q^*(s, a) + \frac{1}{N(s, a)} \left( r(s, a, s') + \gamma \max_{a'} q^*(s', a') - q^*(s, a) \right)$$

11
12      
$$N(s, a) \leftarrow N(s, a) + 1$$

13
14       $l \leftarrow l + 1$ 
15       $s \leftarrow s'$ 
16    end while
17  end for

```

**Notes:** Choice of  $\gamma$  and  $l_{\max}$  are coupled:

- $\gamma \approx 1$  requires large  $l_{\max}$
- $\gamma \approx 0$  requires small  $l_{\max}$

## 2.4 Training vs. Testing

**Notes:** Episodes are classified as either:

- training (sim): reward accumulated during episode does not count
- testing (test): reward accumulated during episode counts

### 2.4.1 $K$ Sims, 1 Test

**Notes:**

1. select actions randomly during  $K$  simulations
2. extract optimal policy,  $\pi^*$
3. use  $\pi^*$  during test

### 2.4.2 $K$ Tests

**Notes:**

- maximize average reward over  $K$  tests
- must balance between exploration and exploitation
- Common ways to balance exploration and exploitation:  $\varepsilon$ -greedy strategy, UCB algorithm

Strategy	Description
$\varepsilon$ -greedy	<p>choose optimal action with probability <math>\varepsilon(k)</math></p> <ul style="list-style-type: none"> <li>• In episode <math>k</math>, choose the optimal action with probability <math>\varepsilon(k)</math>, where: <ul style="list-style-type: none"> <li>– <math>\varepsilon(0) \approx 0</math></li> <li>– <math>\varepsilon(k)</math> is increasing as you keep exploring.</li> <li>– <math>\varepsilon(k) \rightarrow 1</math> as <math>k \rightarrow \infty</math></li> </ul> </li> <li>• Common choice for <math>\varepsilon(k)</math> is <math>1 - \frac{1}{k}</math>.</li> </ul>
UCB algorithm	<p>choose action that maximizes <math>\text{UCB}(\cdot)</math></p> $\text{UCB}(s, a) = \begin{cases} q^*(s, a) + C \sqrt{\frac{\log k}{N(s, a)}}, & \text{if } N(s, a) > 0 \\ \infty, & \text{otherwise} \end{cases}$ <ul style="list-style-type: none"> <li>• In episode <math>k</math>, choose the action that maximizes <math>\text{UCB}(\cdot)</math>.</li> <li>• <math>C</math>: exploration parameter</li> <li>• <math>N(s, a)</math>: # of times <math>a</math> taken from <math>s</math>.</li> </ul>

### 3 Partially Observable MDPs (POMDPs)

**Summary:** In a POMDPs, we assume that:

- environment modelled using state space,  $\mathcal{S}$
- single agent
- $S_t$  = state after transition  $t$
- $A_t$  = action inducing transition  $t$
- stochastic state transitions with memoryless property:

$$S_T \perp S_0, A_1, \dots, A_{T-1}, S_{T-2} \mid S_{T-1}, A_T$$

- $R_t$  = reward for transition  $t$ , i.e.,  $(S_{T-1}, A_T, S_T)$
- $O_t$  = observation of  $S_t$ 
  - Measurement of a state (i.e. approximation, so may not be exact)
  - **Key:** Since actual state is unknown, so are legal actions.

Name	Function:
Initial state distribution	$p_0(s) := \mathbb{P}[S_0 = s]$
Transition distribution	$p(s' s, a) := \mathbb{P}[S_t = s'   A_t = a, S_{t-1} = s]$ <ul style="list-style-type: none"> <li>• Assume <math>\mathcal{A}(s) = \mathcal{A}(s') := \mathcal{A} \forall s, s'</math> (i.e. since actual state is unknown, so are legal actions, so assume all actions are legal): <ul style="list-style-type: none"> <li>– if <math>a \notin \mathcal{A}(s)</math>, then <math>p(s' s, a) = 0</math> for all <math>s' \neq s</math></li> </ul> </li> </ul>
Reward function	$r(s, a, s') := \text{reward for transition } (s, a, s')$ <ul style="list-style-type: none"> <li>• Assume <math>\mathcal{A}(s) = \mathcal{A}(s') := \mathcal{A} \forall s, s'</math> (i.e. since actual state is unknown, so are legal actions, so assume all actions are legal): <ul style="list-style-type: none"> <li>– if <math>a \notin \mathcal{A}(s)</math>, then <math>r(s, a, s') = 0</math> for all <math>s'</math></li> </ul> </li> </ul>
Policy for choosing actions	$\pi_t(a o_0, \dots, o_t) := \mathbb{P}[A_t = a   O_0 = o_0, \dots, O_t = o_t]$ <ul style="list-style-type: none"> <li>• Observe that policy is now time-dependent.</li> <li>• <b>Special Case:</b> If we assume the agent cannot use past observations, <math>A_t \perp O_0, \dots, O_{t-1} \mid O_t</math>, policy becomes time-independent, <math display="block">\pi_t(a o_0, \dots, o_t) = \pi_0(a o_t).</math> <ul style="list-style-type: none"> <li>– Only need to specify <math>\pi_0</math>.</li> </ul> </li> </ul>
Measurement model	$m(o s) := \mathbb{P}[O_t = o   S_t = s]$
Belief after $t$ observations	$b_t(s_t a_{1:t}, o_{0:t}) = \mathbb{P}[S_t = s_t   A_t = a_t, O_{0:t} = o_{0:t}]$ $b_t(s_t a_{1:t}, o_{0:t}) = m(o_t s_t) \sum_{s_{t-1}} p(s_t s_{t-1}, a_t) b_{t-1}(s_{t-1} a_{1:t-1}, o_{0:t-1})$ <ul style="list-style-type: none"> <li>• <math>b_t</math>: Probability distribution</li> <li>• <math>b_0(s_0) = \mathbb{P}[S_0 = s_0]</math>: Initial belief distribution</li> <li>• Only holds for <math>t \geq 1</math>. <ul style="list-style-type: none"> <li>– @<math>t</math>: Measurement before and after action for the belief is the same except at <math>t = 0</math> b/c of initial belief.</li> </ul> </li> <li>• For <math>t = 0</math> (assuming uniform prior): <math>b_0(s_0 o_0) = \frac{m(o_0 s_0)}{\sum_s m(o_0 s)}</math>.</li> </ul>

### 3.1 Bayesian Network

Notes:  $S_0, O_0, A_1, R_1, S_1, O_1, A_2, R_2, S_2, O_2, \dots$  form a Bayesian network:

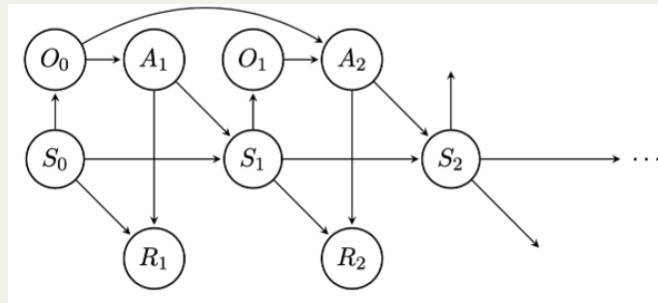


Figure 1

- Assuming  $A_t \perp O_0, \dots, O_{t-1} \mid O_t$ . WHERE DOES THIS COME INTO PLAY.

### 3.2 Belief (Probability Distribution) Over the States:

Notes: Assume actual state is the most likely state.

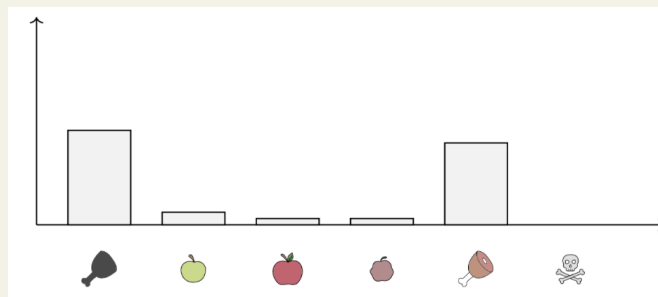


Figure 2

- Usually assume uniform distribution before you observe anything.
- Flow:** Measurement  $\rightarrow$  Take action  $\rightarrow$  Update belief  $\rightarrow$  Take action.

### 3.3 Examples

**Example:**

1. **Given:**

- Now suppose Cavemen wants to feed child:
  - Cannot know satiety of child exactly.
  - Whether apple is edible or not must be inferred from senses.
- Possible observations for the apple:



Figure 3

- Possible states for the child's satiety:

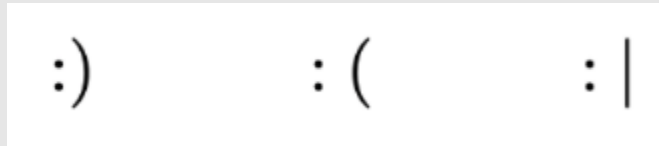


Figure 4

- Measurement distribution for the apple:












					
	1.0	0.0	0.0	0.0	0.0
	0.2	0.6	0.2	0.0	0.0
	0.0	0.3	0.4	0.3	0.0
	0.0	0.0	0.0	0.2	0.8
	1.0	0.0	0.0	0.0	0.0
	1.0	0.0	0.0	0.0	0.0

Figure 5:  $m(o_1|s) = P(o_1|s)$

- $\sum = 1$  across the rows
- What is the probability of observing a certain state of the apple given the true state?
- Measurement distribution for child's satiety:







	:)	:(	:
	0.0	0.8	0.2
	0.0	0.8	0.2
	0.0	0.8	0.2
	0.0	0.8	0.2
	0.8	0.2	0.0
	0.0	0.0	1.0

Figure 6:  $m(o_2|s) = P(o_2|s)$ 

–  $\sum = 1$  across the rows

– What is the probability of observing a certain state of the child given the true state?

- **Key:** Assume independence between the observations of the child's satiety and the apple's edibility:  
 $P(o|s) = P(o_1|s) \cdot P(o_2|s)$ .

## 2. Problem

- Initial distribution,  $b_0(s_0)$  over states is uniform.
- Action sequence is  $\langle a_1, a_2, a_3 \rangle = \langle \text{seed}, \text{wait}, \text{wait} \rangle$ .
- Observation sequence is  $\langle o_0, o_1, o_2, o_3 \rangle = \langle (:(\text{no apple}), :(\text{ga})), :(\text{ra}), :(|\text{ra})) \rangle$ .
- Find state distribution:  $b_3(s_3 | a_{1:3}, o_{0:3})$ .












						:)	:(	:
	1.0	0.0	0.0	0.0	0.0	0.0	0.8	0.2
	0.2	0.6	0.2	0.0	0.0	0.0	0.8	0.2
	0.0	0.3	0.4	0.3	0.0	0.0	0.8	0.2
	0.0	0.0	0.0	0.2	0.8	0.0	0.8	0.2
	1.0	0.0	0.0	0.0	0.0	0.0	0.8	0.2
	1.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0

Figure 7

## 3. Solution:



**Example:** FINISH THE EXAMPLE

$$b_0(s_0 | o_0) = \frac{m(o_0 | s_0)}{\sum_s m(o_0 | s)} \quad (1)$$

$$b_t(s_t | a_{1:t}, o_{0:t}) = m(o_t | s_t) \sum_{s_{t-1}} p(s_t | s_{t-1}, a_t) b_{t-1}(s_{t-1} | a_{1:t-1}, o_{0:t-1}) \quad (2)$$

s	$b_0(s)$	$b_0(s   o_0)$	$b_1(s   o_{0:1}, a_1)$	$b_2(s   o_{0:2}, a_{1:2})$	$b_3(s   o_{0:3}, a_{1:3})$
No meat	1/6	0.4545			
<ul style="list-style-type: none"> <li><math>\sum_s m((:, \text{no apple})   s) = (1.0)(0.8) + (0.2)(0.8) + (0.0)(0.8) + (0.0)(0.8) + (1.0)(0.8) + (1.0)(0.0) = 1.76</math></li> <li><math>b_0(\text{No meat}   (:, \text{no apple})) = \frac{(1.0)(0.8)}{1.76} = \frac{0.8}{1.76} = 0.4545</math></li> </ul>					
Green apple	1/6	0.0909			
<ul style="list-style-type: none"> <li><math>b_0(\text{Green apple}   o_0) = \frac{(0.2)(0.8)}{1.76} = \frac{0.16}{1.76} = 0.0909</math></li> </ul>					
Red apple	1/6	0			
<ul style="list-style-type: none"> <li><math>b_0(\text{Red apple}   o_0) = \frac{(0.0)(0.8)}{1.76} = \frac{0.0}{1.76} = 0</math></li> </ul>					
Rotten apple	1/6	0			
<ul style="list-style-type: none"> <li><math>b_0(\text{Rotten apple}   o_0) = \frac{(0.0)(0.8)}{1.76} = \frac{0.0}{1.76} = 0</math></li> </ul>					
Meat	1/6	0.4545			
<ul style="list-style-type: none"> <li><math>b_0(\text{Meat}   o_0) = \frac{(1.0)(0.8)}{1.76} = \frac{0.8}{1.76} = 0.4545</math></li> </ul>					
Dead	1/6	0			
<ul style="list-style-type: none"> <li><math>b_0(\text{Dead}   o_0) = \frac{(1.0)(0.0)}{1.76} = \frac{0.0}{1.76} = 0</math></li> </ul>					

## 4 Estimating the Optimal Quality Function

### 4.1 Estimating the Optimal Quality Function

**Motivation:** The agent need not know the model of the environment. However, it must actually make moves, even when learning.

If the agent doesn't have a model, it must estimate  $q^*$ ,  $\mathcal{A}^*$ , and  $\pi^*$ .

**Definition:** When the environment is in state  $s$ , the agent can take an action  $a$  and:

- **Update  $\hat{q}$ :**  $\hat{q}(s, a; t) \leftarrow (1 - \alpha)\hat{q}(s, a; t) + \alpha \left( r' + \gamma \max_{a'} \hat{q}(s', a'; t + 1) \right)$   
–  $0 \leq \alpha \leq 1$ : learning rate
- **Compute  $\hat{\mathcal{A}}$ :**  $\hat{\mathcal{A}}(s; t) = \arg \max_{a' \in \mathcal{A}(s)} \hat{q}(s, a'; t)$
- **Compute  $\hat{\pi}$ :**  $\hat{\pi}(a' | s; t) = 0 \ \forall a' \notin \hat{\mathcal{A}}(s; t)$

### 4.2 Exploration versus Exploitation

**Motivation:** To ensure  $\hat{q}$  converges to  $q^*$  and the agent's expected return is maximized, the agent must balance exploration and exploitation.

**Definition:**

- **Exploitation:** Choose the most promising actions based on current knowledge.  
– Use optimal policy:  $\hat{\pi}(\cdot, \cdot; t)$
- **Exploration:** Choose the least tried actions to improve current knowledge.  
– Choose actions randomly

#### 4.2.1 Simplified Case:

**Example:**

- **Given:** Assume the environment is stateless, but rewards are random.



Figure 8

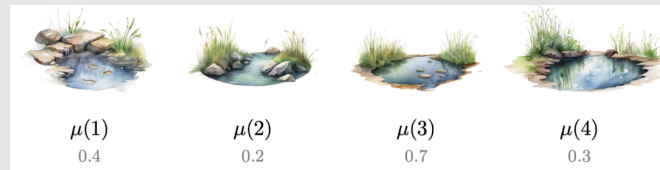


Figure 9

- $\mu(a)$ : expected reward for action  $a$  (unknown to the agent):  
–  $0 \leq \mu(a) \leq 1$  for all  $a$ .
- **Best-case expected return:** (with  $\gamma = 1$  under  $\pi^*$ ) from transition  $t$  is:

$$u^*(t) := (T - t) \max_{a'} \mu(a')$$

where in this case:

$$\pi^*(a; t) = 0 \quad \text{if } a \notin \arg \max_{a'} \mu(a').$$

- **Estimation of  $\mu(\cdot)$ .** Since the agent does not have a model, it must estimate  $\mu(\cdot)$ .

The agent can take an action  $a$  and:

1. **Update**  $n(\cdot)$  and  $\hat{\mu}(\cdot)$ :

$$n(a) \leftarrow n(a) + 1$$

$$\hat{\mu}(a) \leftarrow \left(1 - \frac{1}{n(a)}\right) \hat{\mu}(a) + \frac{1}{n(a)} r'$$

2. **Compute  $\hat{\pi}$ :**

$$\hat{\pi}(a; t) = 0 \quad \text{for all } a \notin \arg \max_{a'} \hat{\mu}(a').$$

- **Alternate Policies** We want to compare the expected return under various policies. The expected return from transition  $t$  under a policy  $\rho$  is:

$$u^\rho(t) := \mathbb{E}^\pi[G_t] = \sum_{a'} \rho(a'; t) (\mu(a') + u^\rho(t+1)).$$

### 4.3 Alternate Policies

**Summary:** To ensure the agent's expected return is maximized, the agent must strike a balance exploration and exploitation.

In the following cases, the expected return from transition  $t$  is

$$u^{\text{avg}}(t) \equiv \frac{T-t}{|\mathcal{A}|} \sum_a \mu(a)$$

We want to choose  $\rho$  so that  $u^\rho > u^{\text{avg}}$ .

Policy	Function:
Exploitation only	Choose a random action, same for all transitions
Exploration only	Choose a random action, different for each transition
Softmax	Apply a soft-max over $\hat{u}$ $\rho(a; t) = \left[ \sum_{a'} \exp \left( \frac{\hat{\mu}(a')}{\tau} \right) \right]^{-1} \exp \left( \frac{\hat{\mu}(a)}{\tau} \right)$ <ul style="list-style-type: none"> <li>Choose a temperature value decrease with <math>t</math>.</li> <li><math>\tau(t) \in [0, \infty), \tau \rightarrow 0</math></li> </ul>
$\epsilon$ -greedy	Use $\hat{\pi}$ w/ prob. $1 - \epsilon$ , otherwise take a random action $\rho(a; t) = \epsilon \frac{1}{ \mathcal{A} } + (1 - \epsilon) \hat{\pi}(a; t)$ <ul style="list-style-type: none"> <li>Choose an exploration rate decrease w/ <math>t</math>.</li> <li><math>\epsilon(t) \in [0, 1], \epsilon \rightarrow 0</math></li> </ul>
Upper confidence bound	Choose the action with the highest $\text{ucb}(\cdot)$ $\rho(a; t) = 0 \text{ if } a \notin \arg \max_{a'} \text{ucb}(a'; t)$ <ul style="list-style-type: none"> <li>Compute <math>\text{ucb}(\cdot)</math> for each action.</li> <li><math display="block">\text{ucb}(a; t) = \hat{\mu}(a) + \sqrt{\frac{\ln t}{n(a)}}</math></li> </ul>

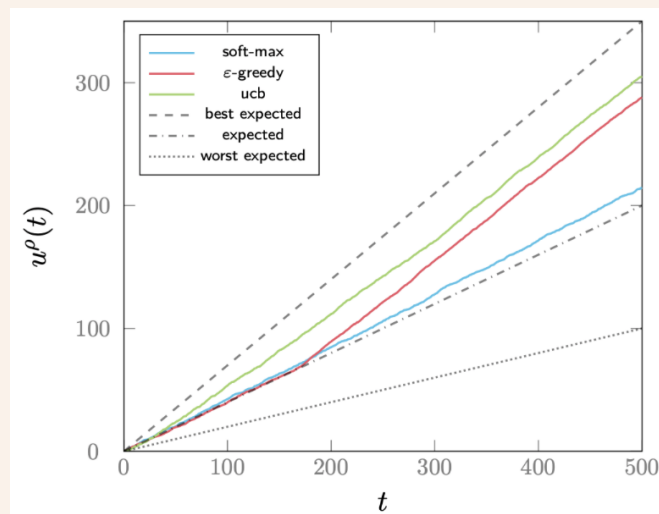


Figure 10