Radboud University Nijmegen

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History-based Rewards for POMDPs

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Thesis MSc Computing Science

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Abstract

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Given a POMDP with a history-based reward function, obtain a policy that maximizes the expected reward.

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Chapter 2

Preliminaries

Set Theory

Let S be any countable set, then $|S|$ denotes the cardinality. We let S^* and S^ω denote the set of finite and infinite sequences over S, respectively. For a sequence $\pi \in S^*$ we can denote the length by $|\pi|$.

Let an alphabet Σ be a a finite set consisting of letters. A word is defined as a sequence of letters $w = w_1 w_2 \ldots w_n \in \Sigma^*$. A language L is a subset of all possible words given an alphabet Σ, so $L \subseteq \Sigma^*$. Let ϵ denote the empty word, so $|\epsilon| = 0$.

A regular language is a language that can be defined by a regular expression. The language accepted by a regular expressions e is denoted as $L(e)$.

Probability Theory

For any countable set S we can define a *discrete probability distribution* as $\psi : S \to [0,1]$ where $\sum_{s \in S} \psi(s) = 1$. The set of all possible probability distributions over S is denoted as $\Pi(S)$. We denote the support of a *probability distribution* as $supp(\psi) = \{s \in S \mid \psi(s) > 0\}$.

TO WRITE: random variable, expected value

Chapter 3

Background

3.1 Finite Automata

TO WRITE: introduction to dfa

Definition 3.1 (DFA)**.** A Deterministic Finite Automata is a tuple $D = (Q, q_0, \Sigma, \delta, F)$ where

- Q, the finite set of states;
- q_0, the initial state;
- Σ the input alphabet;
- $\delta : Q \times \Sigma \to Q$, the deterministic transition function;
- $F \subseteq Q$, the set of final states.

TO WRITE: introduction to lambda star

Definition 3.2. We define $\delta^* : Q \times \Sigma^* \to Q$ where $\delta^*(q, w)$ denotes the state we end up after reading word w starting from state q as follows

$$\delta^*(q, w) = \begin{cases} q & \text{if } w = \epsilon \\ \delta^*(\delta(q, a_1), a_2 \dots a_n) & \text{if } w = a_1 a_2 \dots a_n \end{cases}$$

TO WRITE: introduction to accepted words

Definition 3.3. We say the language accepted by a DFA $D = (Q, q_0, \Sigma, \delta, F)$ consists of all the words that start in the begin state and finish in any final state. Thus $L(D) = \{w \in \Sigma^* \mid \delta^*(q_0, w) \in F\}$.

3.2 Markov decision processes

TO WRITE: introduction to MDP

Definition 3.4 (MDP)**.** A Markov decision process is a tuple $M = (S, s_I, A, T)$ where

- S, the finite set of states;
- $s_I \in S$, the initial state;
- A, the finite set of actions;
- $T : S \times A \to \Pi(S)$, the probabilistic transition function.

Note that given $s \in S, a \in A$, we assign a probability distribution over S through $T(s, a)$. To obtain the probability of ending up in a certain state s' when starting in state s and performing action a, we simply calculate $T(s, a, s')$ which we obtain through $T(s, a)(s')$.

The *available actions* for a state s are given by $A(s) = \{a \in A \mid \exists s' \in S : T(s, a, s') > 0\}$. We can give the *possible successors* of state s in a similar matter through $Succ(s) = \{s \in S \mid \exists a \in A : T(s, a, s') > 0\}$.

A finite *trajectory* or *run* π of an MDP is realization of the stochastic process performed by the MDP denoted by the finite sequence $s_1 a_1 s_2 a_2 \ldots s_{n-1} a_{n-1} s_n \in (S \times A)^* \times S$. To obtain the last state of a trajectory we can use the following

$$last(\pi) = last(s_1 a_1 s_2 a_2 \ldots s_{n-1} a_{n-1} s_n) = s_n$$

.

Reward function

We can extend MDPs with a *reward function* R which assign a reward - usually in $\mathbb{R}$ for taking a certain action a in a state s.

TO WRITE: Intuitive explanation for reward function - including cost function, including a real-world example

Let us look at *Markovian reward functions*, which can determine a reward based on the current state, action and obtained state, independent of its history. The most conventional notation is $R : S \times A \to \mathbb{R}$, where we consider the current state and the taken action. Another possible definition is $R : S \times A \times S \to \mathbb{R}$, where in $R(s, a, s')$ we consider the specific transition from s to s' by using action a, or $R : S \to \mathbb{R}$ where in $R(s)$ we only consider the visited state s.

TO WRITE: Real life example of reward function with history

A reward function which is dependent of its history is called a *Non-Markovian reward function.* There are a number of different reward functions possible

- $R : S^* \to \mathbb{R}$ - which only looks at the finite states visited, or;
- $R : (S \times A)^* \to \mathbb{R}$ - which looks at the finite (sub)trajectory without the last state, or;
- $R : (S \times A)^* \times S \to \mathbb{R}$ - which looks at the finite (sub)trajectory.

The reward function we will be using is the Non-Markovian reward function which looks at trajectories of specific length k, namely $R_k : (S \times A)^k \to \mathbb{R}$.

TO WRITE: Increasing k creates increased reward

Policy

As stated above, we use reward functions over a MDP to usually argue over an optimized expected reward. After retrieving such an optimum, the question remains on how to actually obtain this value. We wish to know what strategy to apply path to take to obtain this value. For this we use strategies, or often called policies.

Definition 3.5. A policy for a MDP M is a function $\sigma : (S \times A)^* \times S \to \Pi(A)$, which maps a trajectory π to a probability distribution over all actions.

We call a policy *memoryless* if the function only considers $last(\pi)$ in deciding the actions.

TO WRITE: induced markov chain for removing non-determinism

3.3 Partial observability

TO WRITE: Introduce pomdp

Definition 3.6 (POMDP)**.** A partially observable Markov decision process (POMDP) is a tuple $\mathcal{M} = (M, \Omega, O)$ where

- $M = (S, s_I, A, T)$, the hidden MDP;
- Ω, the finite set of observations;
- $O : S \to \Omega$, the observation function.

Let $O^{-1} : \Omega \to 2^S$ be the inverse function of the observation function - $O^{-1}(o) = \{s \in \mid O(s) = o\}$ - in which we simply obtain all states in S that have observation o. Without loss of generality we assume that states with the same observations have the same set of available actions, thus $O(s_1) = O(s_2) \Rightarrow A(s_1) = A(s_2)$.

Since the actual states in a trajectory of the hidden MDP are not visible to the observes, we argue about an *observed trajectory* of the POMDP $\mathcal{M}$. This is not consist of a sequence of states and actions, but instead a sequence of observations are actions, thus an element of $(\Omega \times A)^* \times \Omega$. The set of all possible finite observed trajectories of will be denoted as $ObsSeq^{\mathcal{M}}$.

We can argue about the observed trajectory through the observation function, which will be extended over trajectories, like so

$$O(\pi) = O(s_1 a_1 s_2 a_2 \ldots s_{n-1} a_{n-1} s_n) = O(s_1) a_1 O(s_2) a_2 \ldots O(s_{n-1}) a_{n-1} O(s_n)$$

Policy

Definition 3.7. An observation-based strategy of a POMDP $\mathcal{M}$ is a function $\sigma : ObsSeq^{\mathcal{M}} \to \Pi(A)$ such that $supp(\sigma(O(\pi))) \subseteq A(last(\pi))\ \forall \pi \in (S \times A)^* \times S$.

3.4 Belief MDP

3.5 Moore machine

Based on the definition as presented in [2].

Definition 3.8. A Mealy machine is a tuple $(Q, q_0, \Sigma, O, \delta, \sigma)$ where

- Q, the finite set of states;
- $q_0 \in Q$, the initial state;
- Σ, the finite set of input characters - the input alphabet;
- O, the finite set of output characters - the output alphabet;
- $\delta : Q \times \Sigma \to Q$, the input transition function, and;
- $\sigma : Q \times O$, the output transition function.

Example

TO WRITE: example moore machine – traditional sense

Chapter 4

Reward Controllers

4.1 Definition

TO WRITE: introduction

The idea is to transform the history-based reward function into something more tangible. We transform it is so that we can obtain the reward per step instead of only at the end of a sequence.

Based on the history-based reward function $R : \Omega^* \to \mathbb{R}$ of a POMDP $\mathcal{M}$, we build a reward controller that mimics its behavior.

Definition 4.1. A reward controller $\mathcal{F}$ is a reward machine $(N, n_I, \Omega, \mathbb{R}, \delta, \lambda)$, where

- N, the finite set of memory nodes;
- $n_I \in N$, the initial memory node;
- Ω, the input alphabet;
- $\mathbb{R}$, the output alphabet;
- $\delta : N \times \Omega \to N$, the memory update;
- $\sigma : N \to \mathbb{R}$, the reward output.

TO WRITE: transition to delta star

Definition 4.2. We define $\delta^* : N \times \Omega^* \to N$ where $\delta^*(n, w)$ denotes the state we end up after reading word π starting from state n as follows

$$\delta^*(n,\pi) = \begin{cases} n & \text{if } \pi = \epsilon \\ \delta^*(\delta(n,o_1), o_2 \dots o_n) & \text{if } \pi = o_1 o_2 \dots o_n \end{cases}$$

4.2 Given a list of sequences and rewards

Let's say we are designing a model for an engineer and they want certain observation sequences to connect to a reward. Thus we are given a number of observation sequences $\pi_1, \pi_2, \dots, \pi_n$ together with their associated real valued rewards $r_1, r_2, \dots, r_n$.

Definition 4.3. Given the observation sequences $\pi_1, \pi_2, \ldots, \pi_n$ and their associated rewards $r_1, r_2, \ldots, r_n$ we define the history-based reward function $R : \Omega^* \to \mathbb{R}$, which we create as follows

$$R(w) = \begin{cases} r_i & \text{if } w = \pi_i \text{ for } i \in \{1, \ldots, n\} \\ 0 & \text{otherwise} \end{cases}$$

In R we simply connect the observation sequence π_i to their respective reward r_i and every other sequence is connected to zero.

We only want to obtain any of the rewards if their associated observation sequence has been observed in its entirety. Thus we create a reward controller in which we encode the reward in the state we end up in after reading the entire sequence. The idea is as follows: if we read the observation sequence and we end up in a certain state n, we obtain the reward $\sigma(n)$ in that state. It's important to note that if we, for example, have $R(\blacksquare\blacksquare) = 2$ and $R(\blacksquare\blacksquare\square) = 3$ and we read $\blacksquare\blacksquare\square$ we will only obtain reward 3.

Given all the sequences over which the Non-Markovian reward function is defined, let us create a reward controller through the following procedure. Note that we assume that all the sequences are unique.

Algorithm 1 Procedure for turning a list of sequences into a reward controller

procedure CreateRewardController(sequences, R)
Require: sequences
Require: $R : \Omega^* \to \mathbb{R}$
    $n_I \leftarrow$ `new Node()` ▷ initial node
    $n_F \leftarrow$ `new Node()` ▷ dump node
    `path`$(n_I) = \epsilon$
    $N \leftarrow \{n_I, n_F\}$
    for all $\pi = o_1 o_2 \ldots o_k$ in sequences **do**
        $n \leftarrow n_I$
        for $i \leftarrow 1, \ldots, k$ **do**
            if $\delta(n, o_i)$ is undefined **then**
                $n' \leftarrow$ `new Node()` ▷ create new memory node
                `path`$(n) = o_1 \ldots o_i$
                $N \leftarrow N \cup \{n'\}$
                $\delta(n, o_i) \leftarrow n'$
            $n \leftarrow \delta(n, o_i)$ ▷ update memory node
        $\sigma(n) \leftarrow R(\pi)$ ▷ set reward
    for all $n \in N$ **do** ▷ makes δ and σ deterministic
        for all $o \in \Omega$ **do**
            if $\delta(n, o)$ is undefined **then** ▷ useless transition
                $\delta(n, o) \leftarrow n_F$
        if $\sigma(n)$ is undefined **then**
            $\sigma(n) \leftarrow 0$
    return $(N, n_I, \Omega, \mathbb{R}, \delta, \sigma)$

We start by creating an initial node in Line 2 and a dump node in Line 3. The idea is that, since the reward controller is deterministic, if we need to determine the reward of a sequence that is (for example) longer than a known sequence (with reward), we don't want to end in the state in which the reward is encoded. Thus these zero-reward sequences are passed along to a node which will only consist of self-loops and will have a reward of zero encoded to them.

Then for every sequence which we are given, we walk through it. If we then come across a transition which isn't defined yet, we define it by making a new memory node in Line 10, adding it to N, and setting the transition to this new node. If the transition already existed, we simply update the memory node. After we are done with reading the sequence, we simply encode the reward into the state itself in Line 15.

Then since the reward controller needs to be deterministic, we set the other undefined values. Every other transition that hasn't been made yet, will be transferred to the dump node as mentioned above in Line 19. Furthermore, there are still nodes in which the reward is undefined. None of the given sequences ended up in these states, so per Definition 4.3 we encode those to zero in Line 21.

We observe that the number of memory nodes $|N|$ of the newly created reward controller $\mathcal{F}$ is bounded by $|\Omega|^k + 1$, where $k = \max\limits_{seq \in sequences} |seq|$.

Note that the set of nodes N without n_F together with the memory update function is represents a directed acyclic graph. This indicates for every node n there is an unique path from the initial node n_I to node n. This unique path is encoded in the function $\texttt{path}\colon N \setminus \{n_F\} \to \Omega^*$. This function is well-defined, since it's defined for n_I in Line 4. Every other time a new node is neccesary, it is created in Line 10, and `path` is then immediately defined for the new node. This `path` function is needed for proving the following lemma.

let maarten read this

Lemma 4.4. *For any sequence $\pi \in \Omega^*$, let $r = R(\pi)$ be its associated reward. Then $\sigma(\delta^*(n_I, \pi)) = r$.*

Proof. Let us state that after reading π, we end up in state n, i.e. $n = \delta^*(n_I, \pi)$. Now if $n = n_F$, we know that the associated reward is zero since $\sigma(n_F) = 0$ per construction. A sequence can only end up in n_F if it was not a part of the pre-defined sequences and following Definition 4.3 the reward is then zero.
If $n \in N \setminus \{n_F\}$, we can obtain the unique path to node n through $\texttt{path}(n)$. We know that this is equal to π, so the associated reward is thus $R(\texttt{path}(n)) = R(\pi) = r$. □

Example

Say we are given the following sequences and rewards

1. □ □ with a reward of 15
2. ■ □ ■ with a reward of 20
3. □ □ ■ □ with a reward of 12
4. ■ with a reward of 2

Following the procedure 1 we create the associated reward controller. To show how the procedure works, we will show you the intermediate reward controller after processing every sequence.

After sequence (1)

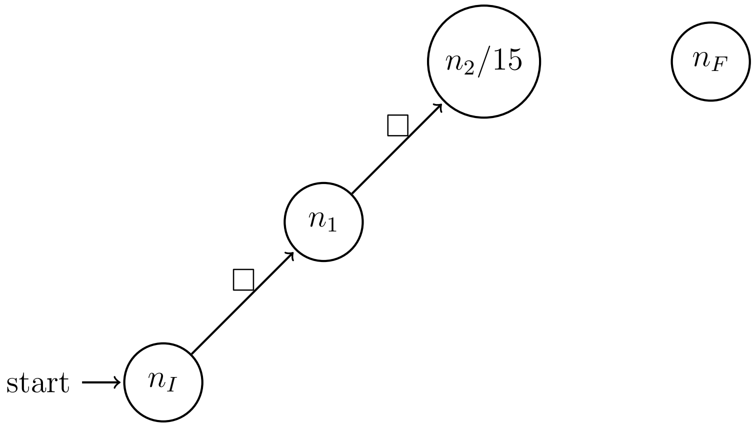

Figure 4.1: Reward controller after sequence (1)

After sequence (2)

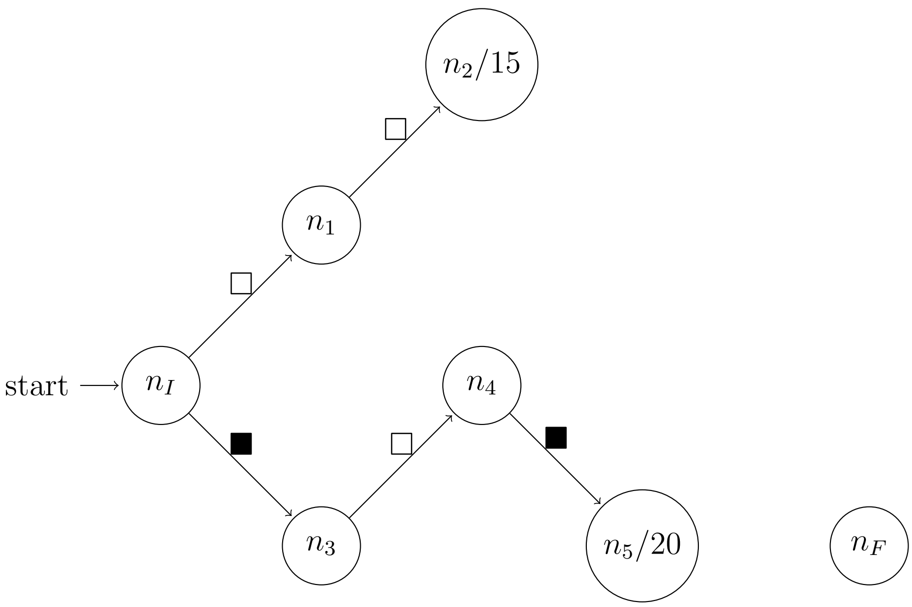

Figure 4.2: Reward controller after sequence (1) and (2)

After sequence (3)

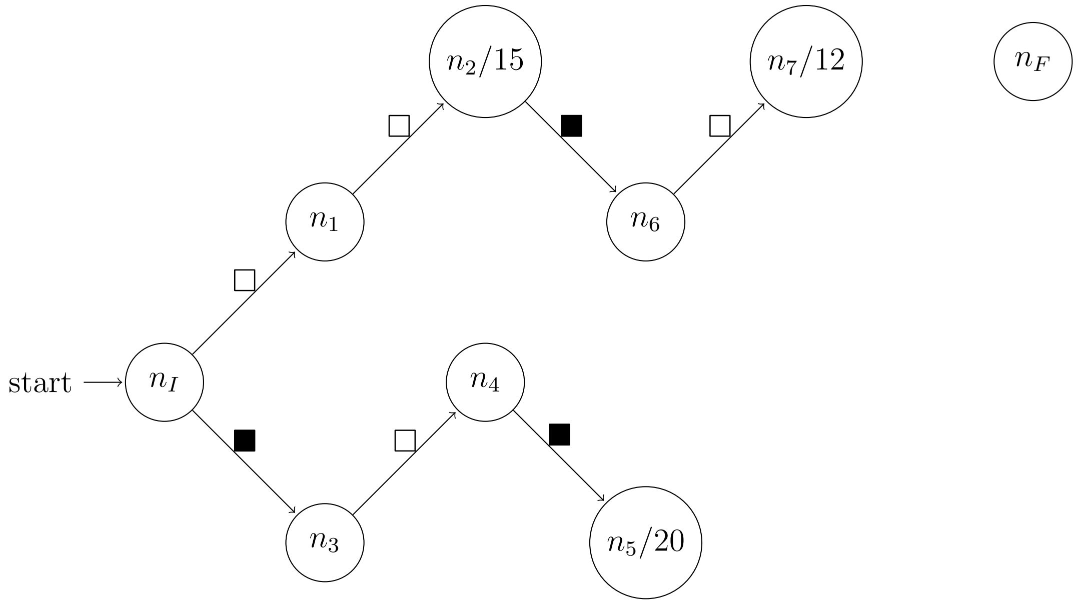

Figure 4.3: Reward controller after sequence (1), (2) and (3)

After sequence (4)

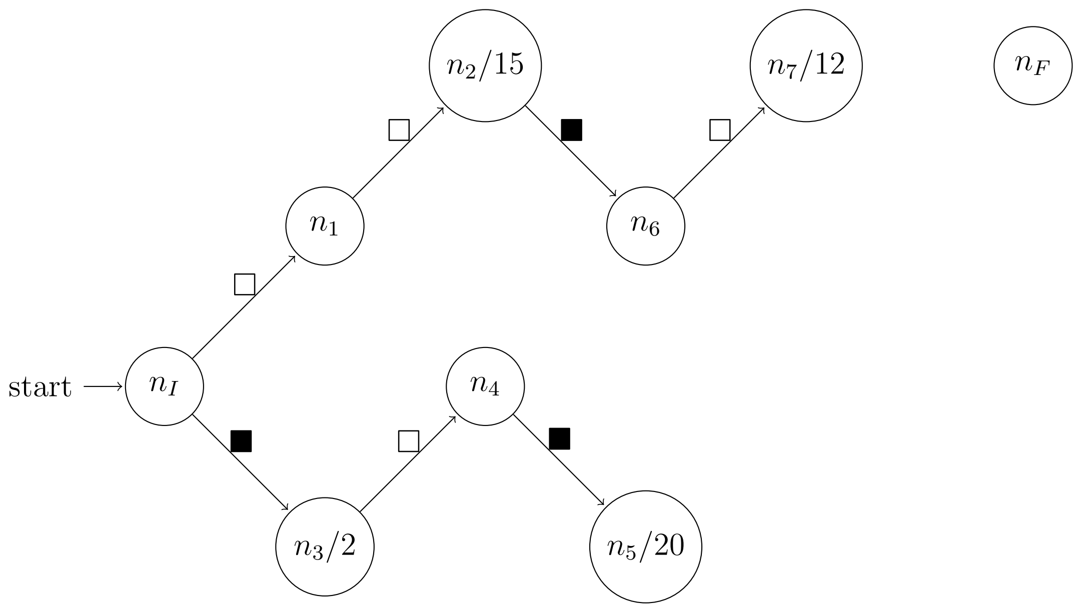

Figure 4.4: Reward controller after sequence (1), (2) and (3)

Finalized Reward Controller

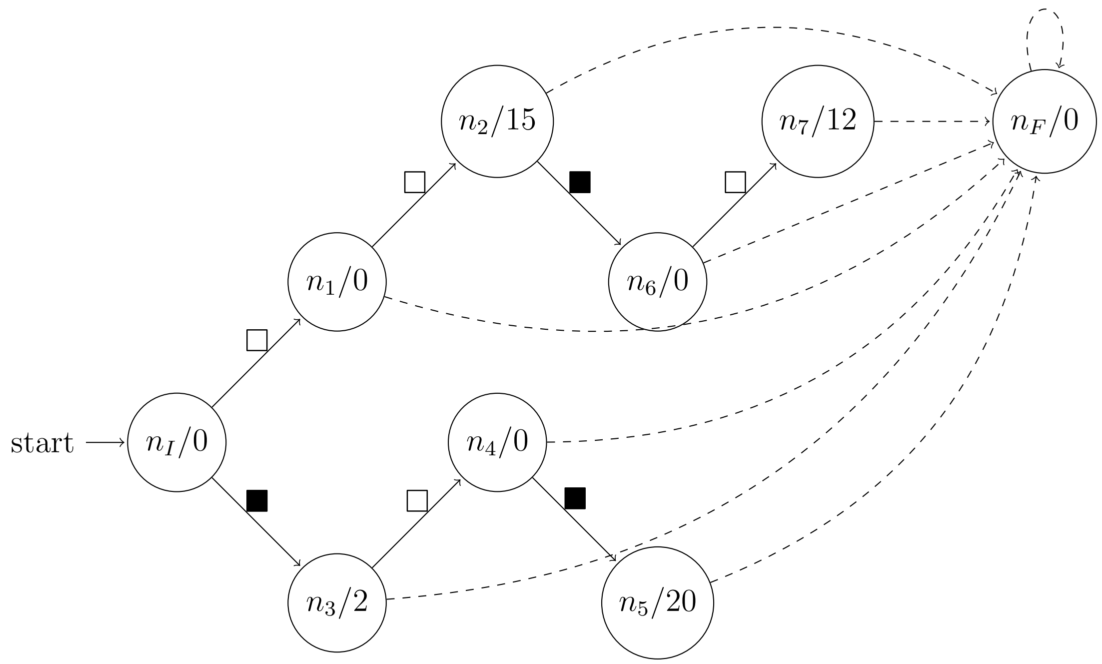

Figure 4.5: Final reward controller

In Figure 4.5 the dashed line denotes all the other possible letters for which the transition function λ wasn't defined. finish this

4.3 Given regular expressions and their rewards

Given a number of regular expressions over observations defined as $e_1, e_2, \ldots, e_n$ together with their respective rewards $r_1, r_2, \ldots, r_n \in \mathbb{R}$. Let us define a reward function R that maps the regular expression to their respective reward, in other words $R(e_i) = r_i$.

We want to create a reward controller that mimics the behaviour of several regular expressions and their associated rewards. Note that we only want a reward when the sequence of observations is accepted by the language generated by the regular expression. The first step would be is to create a DFA that is generated by the regular expression given. This can be done through simply turning the regular expression into a Non-Deterministic Finite Automaton (with ϵ-transitions) and then turning that into a DFA or using other known methods[1]. All that is left for a single regular expression is to keep track of the rewards associated to their final states.

So given the n regular expression, we create n DFAs. Let $D_i = (Q_i, q_{0,i}, \Omega, \delta_i, F_i)$ be the DFA that accepts the language generated by e_i. And then per construction we have that $L(D_i) = L(e_i)$.

Note that since we want to obtain a reward controller, we have to encode the reward in the nodes. This is solved by only encoding the reward of DFA D_i in all states of F_i. For example if $pi \in \Omega^*$ gets accepted by D_i, we have to make sure that the state it ends up in - i.e. the final state(s) - has the reward encoded in its state(s). This is done by the following definition.

Definition 4.5. Let $R_A : Q_1 \cup Q_2 \cup \cdots \cup Q_n \to \mathbb{R}$ be a function that maps any state q of all the state spaces of $D_1, D_2, \ldots, D_n$ to their respective rewards. If q is a final state of DFA D_i it should get the reward corresponding to the regular expression used for that specific DFA. In other words,

$$R_A(q) = \begin{cases} R(e_i) & \text{if } q \in F_i \\ 0 & \text{otherwise} \end{cases}$$

Having obtained all these seperate DFAs, we can now create a DFA that will accept any word that is accepted by any of the seperate DFAs as follows.

Definition 4.6. The induced product DFA for given DFAs $D_1, D_2, \ldots, D_n$ where $D_i = (Q_i, q_{0,i}, \Sigma, \delta_i, F_i)$ is a tuple $D = (Q, q_0, \Sigma, \delta, F)$ where

- $Q = Q_1 \times Q_2 \times \cdots \times Q_n$
- $q_0 = \langle q_{0,1}, q_{0,2}, \ldots, q_{0,n} \rangle$
- Ω, the same input alphabet
- $\delta(\langle q_1, q_2, \ldots, q_n \rangle, a) = \langle \delta_1(q_1, a), \delta_2(q_2, a), \ldots, \delta_n(q_n, a) \rangle$
- $F = \{\langle q_1, q_2, \ldots, q_n \rangle \mid \exists i \in \{1, 2, \ldots, n\} : q_i \in F_i\}$

Lemma 4.7. *Given n DFAs where $D_i = (Q_i, q_{0,i}, \Sigma, \delta_i, F_i)$, let D be the product automaton as obtained in Definition 4.6. Then we $L(D) = L(D_1) \cup L(D_2) \cup \ldots L(D_n)$.*

Proof.

$$\begin{aligned} w \in L(D) &\iff \delta_N^*(q_0, w) \in F \\ &\iff \langle \delta_1^*(q_{0,1}, w), \delta_2^*(q_{0,2}, w), \ldots, \delta_n^*(q_{0,n}, w) \rangle \in F \\ &\iff \exists i \in \{1, \ldots, n\} : \delta_i^*(q_{0,i}, w) \in F_i \\ &\iff \delta_1^*(q_{0,1}, w) \in F_1 \text{ or } \delta_2^*(q_{0,2}, w) \in F_2 \text{ or } \ldots \text{ or } \delta_n^*(q_{0,n}, w) \in F_n \\ &\iff w \in L(D_1) \text{ or } w \in L(D_2) \text{ or } \ldots \text{ or } w \in L(D_n) \\ &\iff w \in L(D_1) \cup L(D_2) \cup \cdots \cup L(D_n) \end{aligned}$$

□

The only step left to obtain the reward controller is to connect the obtained product DFA together with the associated rewards of the states.

Definition 4.8. Given a (product) DFA $N = (Q, q_0, \Omega, \delta, F)$ and the associated reward function R_A, we define the induced reward controller $\mathcal{F} = (N, n_I, \Omega, \mathbb{R}, \delta_{\mathcal{F}}, \sigma)$ as follows

- $N = Q$

- $n_I = q_0$
- $\delta_{\mathcal{F}} = \delta$
- $\sigma : Q \to \mathbb{R}$ where $\sigma(\langle q_1, q_2, \dots, q_n \rangle) = \sum\limits_{i=1}^{n} R_A(q_i)$

Note that the σ is defined by taking the sum over the associated rewards. This is because if we have a sequence $\pi \in \Omega^*$ that is accepted by several regular expressions given, it should then obtain all the seperate rewards associated with those regular expressions. Through the following lemma we ensure that for any sequence $\pi \in \Omega^*$ the reward controller obtains the combination of rewards depending on the final state after having read π.

Lemma 4.9. *Given $e_1, e_2, \dots, e_n$ a sequence of regular expression together with their associated rewards $r_1, r_2, \dots, r_n$, let D be the product automaton as defined in Definition 4.6 build from the DFAs D_i for which $L(D_i) = L(e_i)$. Then let $\mathcal{F} = (N, n_I, \Omega, \mathbb{R}, \delta, \sigma)$ be the reward controller as defined in Definition 4.8 given D. We say that for all possible words $\pi \in \Omega^*$ the following holds:*

$$\sigma(\delta^*(n_I, \pi)) = \sum_{e \in \{e_i | \pi \in L(e)\}} R(e_i)$$

Proof.

$$\begin{aligned}
\sigma(\delta^*(n_I, \pi)) &= \sigma(\langle q1, q2, \dots, q_n \rangle) && (4.1)\\
&= \sum_{i}^{n} R_A(q_i) && (4.2)\\
&= \sum_{\substack{i \in \{1,\dots,n\} \\ q_i \in F_i}} R_A(q_i) && (4.3)\\
&= \sum_{\substack{i \in \{1,\dots,n\} \\ q_i \in F_i}} R(e_i) && (4.4)\\
&= \sum_{\substack{i \in \{1,\dots,n\} \\ \delta^*(q_{0,i}, \pi) \in F_i}} R(e_i) && (4.5)\\
&= \sum_{\substack{i \in \{1,\dots,n\} \\ \pi \in L(D_i)}} R(e_i) && (4.6)\\
&= \sum_{\substack{i \in \{1,\dots,n\} \\ \pi \in L(e_i)}} R(e_i) && (4.7)\\
&= \sum_{e \in \{e_i | \pi \in L(e_i)\}} R(e) && (4.8)
\end{aligned}$$

For Equation (4.1) we simply use Definition 4.2 and the fact that D is deterministic, so it ends up in an unique state after reading π. For Equation (4.2) we use the definition for σ as seen in Definition 4.8. For Equation (4.3) we use that fact that in

Definition 4.5 we observe that $R_A(q_i)$ is equal to zero if $q_i \notin F_i$ and only produces a non-zero value for all $q_i \in F_i$. Thus we only look at the q_i which return a non-zero value. Since we now know we only look at the non-zero reward values, we can use Definition 4.5 again in Equation (4.4). From Definition 3.2 we can rewrite the equation in Equation (4.5). For Equation (4.6) we use Definition 3.3. Since per construction $L(e_i) = L(D_i)$ for all $i \in \{1, \ldots, n\}$, we rewrite the term in Equation (4.7). Finally in Equation (4.8) we simply rewrite the term under the sum. $\square$

Example

Let's say we are given 2 regular expressions. One is that an even number off ☐ gives a reward of 10 and the other states that an uneven number of ■ gives a reward of 15. In other words $R(e_1) = R($`even number of ☐`$) = 10$ and $R(e_2) = R($`uneven number of ■`$) = 15$

Let us first obtain the two DFAs that are generated by e_1 and e_2. Those can be seen in Figure 4.6.

(a) DFA for regular expression even number of ☐

(b) DFA for regular expression for odd number of ■

Figure 4.6

Then we create the product automaton as defined in Definition 4.6. The result can be seen in Figure 4.7.

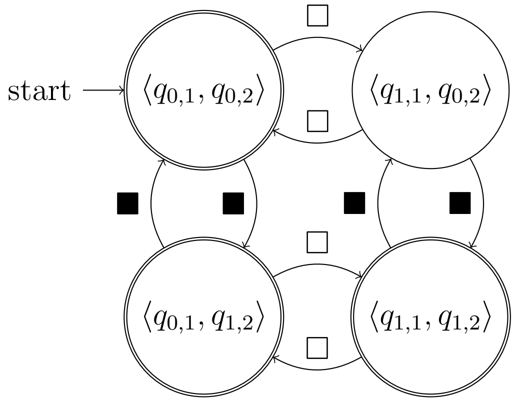

Figure 4.7: Product DFA for both regular expressions

From this we then obtain the reward controller as per Definition 4.8, and can be found in Figure 4.8. Note that

$$
\begin{aligned}
&R_A(q_{0,1}) = 10\\
&R_A(q_{1,1}) = R_A(q_{0,2}) = 0\\
&R_A(q_{1,2}) = 15
\end{aligned}
$$

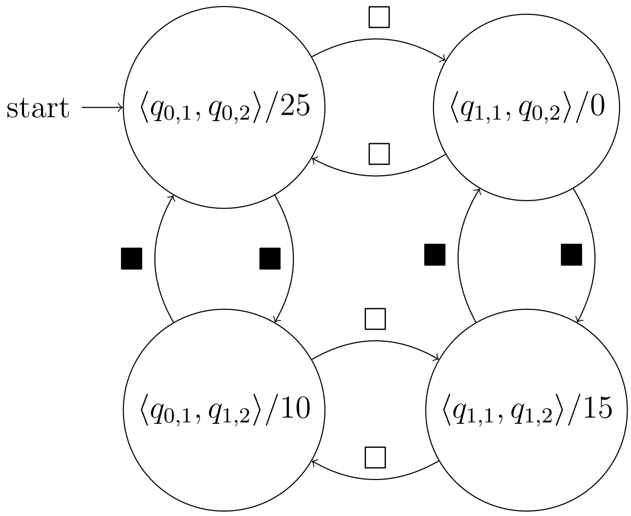

Figure 4.8: Reward Controller for R

Chapter 5

Obtaining policy

TO WRITE: introduction

Definition 5.1. The induced POMDP for reward controller $\mathcal{F} = (N, n_I, \Omega, \mathcal{R}, \delta, \lambda)$ on a POMDP $\mathcal{M} = (M, \Omega, Obs)$ where $M = (S, s_I, A, T_M)$ is a tuple $\mathcal{M}_\mathcal{F} = (M_\mathcal{F}, \Omega', Obs')$ where

- $M_\mathcal{F} = (S', s'_I, A', T_{M_\mathcal{F}}, \mathcal{R})$, the hidden MDP defined as follows
  - $S' = S \times N \cup \{s_F\}$
  - $s'_I = \langle s_I, \delta(n_I, O(s_I))\rangle$
  - $A' = A \cup \{\texttt{end}\}$
  - $T_{M_\mathcal{F}} : S' \times A' \to \Pi(S')$ where

$$T_{M_\mathcal{F}}(s, \texttt{end}, s_F) = 1 \text{ for all } s \in S'$$

$$T_{M_\mathcal{F}}(\langle s, n\rangle, a, \langle s', n'\rangle) = \begin{cases} T_M(s, a, s') & \text{if } \delta(n, O(s') = n') \\ 0 & \text{otherwise} \end{cases}$$

  - $R : S' \times A' \times S' \to \mathcal{R}$ where

$$R(s, a, s') = \begin{cases} \sigma(n) & \text{if } a = \texttt{end} \text{ and } s' = \langle s'', n\rangle \\ 0 & \text{otherwise} \end{cases}$$

- $\Omega' = \Omega \cup \{o_F\}$, the observation spate
- $Obs' : S' \to \Omega'$ where

$$Obs'(s) = \begin{cases} Obs(s') & \text{if } s = \langle s', n\rangle \\ o_F & \text{if } s = s_F \end{cases}$$

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