

# Lecture 2 - Optimality of MDPs

Guiliang Liu

The Chinese University of Hong Kong, Shenzhen

DDA4230: Reinforcement Learning  
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# Optimality of MDPs

Reinforcement Learning seeks to find the **best policy** that achieves **the greatest value function** among the set of all possible policies.

*What do we exactly mean by finding an optimal policy?*

The **existence of an optimal policy will be assumed** throughout the course unless otherwise mentioned.



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# Optimality of MDPs

We first define precisely what it means for a policy, not necessarily stationary, to be an **optimal policy**.

## Definition

A policy  $\pi^*$  is an *optimal policy* if for every policy  $\pi$ , for **all states**  $s \in S$ ,

$$V^{\pi^*}(s) \geq V^{\pi}(s).$$

When the MDP is **non-stationary or is with a finite horizon**, the definition of optimality will be  $V_t^{\pi^*}(s) \geq V_t^{\pi}(s)$  for every  $\pi$ ,  $s$ , conditioning on each  $t$ .



# Optimality of MDPs

Is the optimal value function or policy unique?

The uniqueness of optimal value functions and policies.

- The **optimal value function** is unique for an MDP.
- The uniqueness of **optimal policies** does not hold.

Proof. Consider a counter-example to the uniqueness of optimal policy: we introduce a 'dummy' state that is never accessed, and which carries a reward value of zero. Under this hypothetical circumstance, any policy could execute arbitrary actions without influencing the overall value assessments.



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# Optimality of MDPs

In the setting of **stationary, infinite-horizon** MDPs:

- If some **not-necessarily stationary** policy is optimal, then at least one stationary policy is optimal:  $\exists \pi_t^*(a|s) \rightarrow \pi^*(a|s)$ .
- if some **not-necessarily deterministic** policy is optimal, then at least one deterministic policy is optimal.  $\exists \pi^*(a|s) \rightarrow \pi^*(s)$ .



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# Optimality of MDPs

Taking discrete state space  $\mathcal{S} = [n]$  and action space  $\mathcal{A} = [m]$  as an example,

- **Stationary and deterministic** MDP: the total number of policies is  $m^n$ .
- **Non-Stationary and deterministic** MDP: the total number of policies is  $m^{nT}$ .
- **Stochastic** MDP: the total number of policies will be infinite.

Stationary and deterministic policies can significantly **reduce the size of the universe of policies** when searching (especially the **brute-force search** that checks all policies) for an optimal policy.



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# Optimality of MDPs

After establishing the existence of an optimal policy and moreover concluding that a **deterministic stationary policy** suffices, we define:

## Definition

The **optimal state value function** for an infinite horizon MDP is defined as

$$V^*(s) = \max_{\pi \in \Pi} V^\pi(s), \quad (1)$$

and there exists a stationary deterministic policy  $\pi^* \in \Pi$ , which is an optimal policy, such that  $V^*(s) = V^{\pi^*}(s)$  for all states  $s \in \mathcal{S}$ , where  $\Pi$  is the set of all stationary deterministic policies.



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# Dynamic Programming

Sequential decision-making can be solved via dynamic programming for the finite horizon case. Denoting  $V_t^*(s)$  to be the optimal value function at time  $t$ ,

$$V_t^*(s) = \max_a \mathbb{E}[\mathcal{R}(s, a)] + \gamma \sum_{s' \in \mathcal{S}} \mathbb{P}(s' | s, a) V_{t+1}^*(s'), \quad \forall t = 0, \dots, T-1,$$

$$V_T^*(s) = 0.$$

For example, starting from  $T$  to  $T-2$ , we can compute:

$$V_T^*(s) = 0, \quad V_{T-1}^*(s) = \max_a \mathbb{E}[\mathcal{R}(s, a)],$$

$$V_{T-2}^*(s) = \max_a \mathbb{E}[\mathcal{R}(s, a)] + \gamma \sum_{s' \in \mathcal{S}} \mathbb{P}(s' | s, a) V_{T-1}^*(s').$$



# Dynamic Programming

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$$V_T^*(s) = 0.$$

However, this requires the knowledge of the world model ( $\mathcal{R}(s, a)$  and  $\mathbb{P}(s' | s, a)$ ).

Can we estimate  $\mathcal{R}(s, a)$  and  $\mathbb{P}(s' | s, a)$  for dynamic programming?

Yes, but good decisions do not mean good estimations.

For example, by empirical estimation:  $\hat{\mathbb{P}}(s' | s, a) = \frac{n_{\#}(s')}{n_{\#}(s, a)}$ .



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# The Bellman Optimality Equation

The Bellman optimality equation, named after Richard E. Bellman, is a necessary condition for a value function to be optimal:

$$V^*(s_t) = \max_a \mathbb{E}[r_t + \gamma V^*(s_{t+1}) \mid a_t = a].$$

The Bellman optimality equation  $\neq$  The Bellman equation.

- The Bellman equation describes an arbitrary policy's value function  $V(s_t) = \mathbb{E}[r_t + \gamma V(s_{t+1})]$  (expected w.r.t.  $\pi(a_t|s_t)$ ).
- The Bellman optimality equation takes the maximum overall actions (no policy in the expectation).



# The Bellman Optimality Equation

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**Value Iteration (VI).** If we replace  $V^*$  by a not-necessarily optimal value function  $V$ , VI assigns RHS to  $V$  and repeats the iteration:

$$V(s_t) \leftarrow \max_a \mathbb{E}[r_t + \gamma V(s_{t+1}) \mid a_t = a].$$

This leads to **improvements of the current value** for each iteration and  $V$  will converge to the optimal value function under some conditions.



# The Bellman Optimality Equation

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**Q-learning.** In order to satisfy the Bellman optimality equation in an alternative form ( $Q^*$  is the action-value function for an optimal policy):

$$Q^*(s_t, a_t) = \max_a \mathbb{E}[r_t + \gamma Q^*(s_{t+1}, a)]$$

Q-learning defines a Bellman error (e.g.  $\frac{1}{2}(LHS - RHS)^2$ ) and minimizes it,

$$\frac{1}{2} \left[ Q(s_t, a_t) - \max_a \mathbb{E}[r_t + \gamma Q(s_{t+1}, a)] \right]^2$$

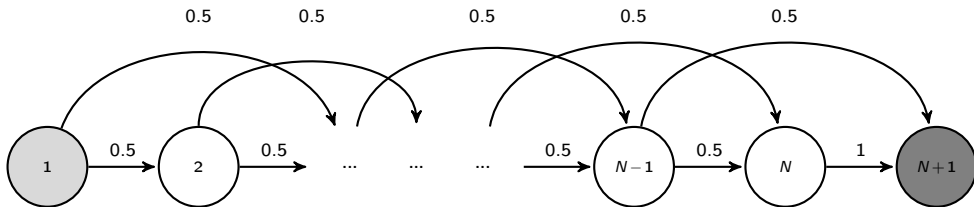


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## Examples of MDPs: Boyan chain

For the **Boyan chain**, the starting state is 1. It has a reward of  $-1$  for every step except for the terminal state and the process terminates at state  $N + 1$ . The terminal state has no reward. The transition probability shown in:



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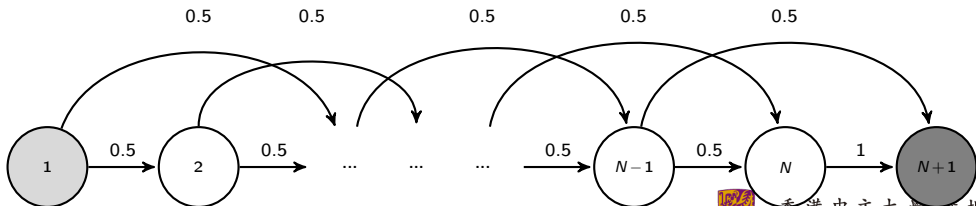
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## Examples of MDPs: Boyan chain

$V(s)$ : the negative number of steps elapsed from state  $s$  to the terminal state.

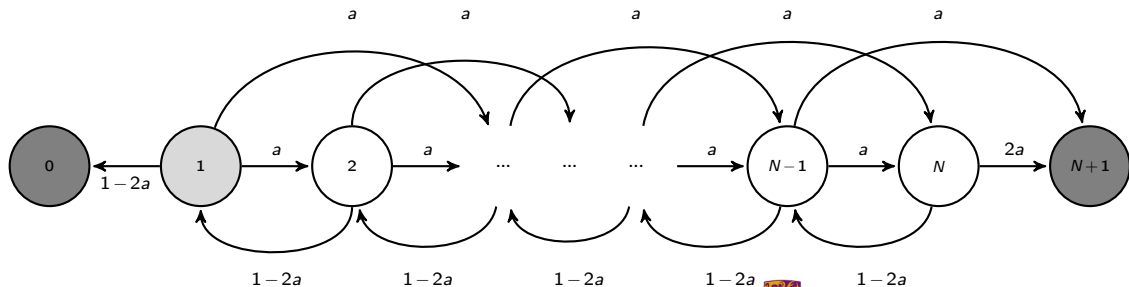
- By the linearity of expectation:  $V(s) = \frac{1}{2}V(s+1) + \frac{1}{2}V(s+2) - 1$  for  $s \leq N-1$ .
- With the boundary conditions  $V(N) = -1$  and  $V(N+1) = 0$ .

We find that  $V(s) = \frac{4}{9} - \frac{2}{3}(N-s+2) - \frac{4}{9}(-\frac{1}{2})^{N-s+2}$ .



## Examples of MDPs: The Boyan chain variant

An **action**  $a \in [0, 0.5]$  needs to be decided by the agent at every state. The starting state is 1 and the set of terminal states is  $\{0, N+1\}$ . The reward is  $-1$  for every transition. and the reward at state 0 and state  $N+1$  are 1 and  $N^2$ .



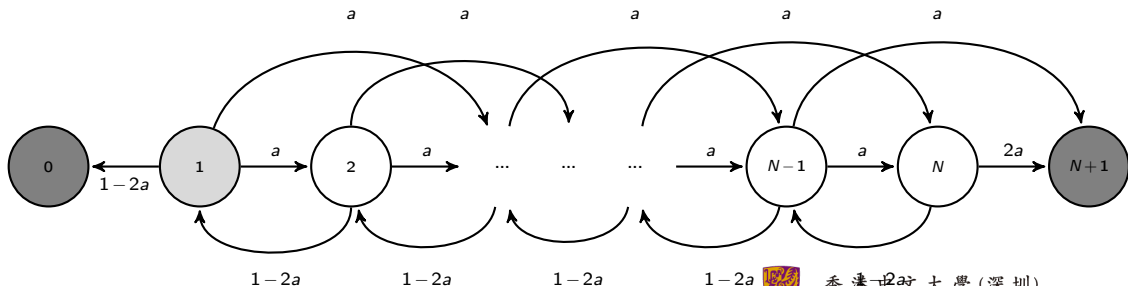
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# Examples of MDPs: The Boyan chain variant

- Finding the optimal policy is **hard**: set  $a = 0.5$  at every state.
- Finding a sub-optimal policy is **relatively easy**: set  $a = 0$  in the starting state, the algorithm can generate a return of  $-1 + \gamma$ .

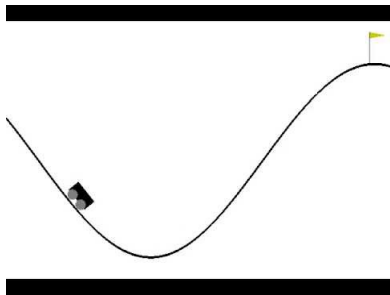


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# Examples of MDPs: Mountain Car

The problem describes the decision-making of a car driver who, starts from a valley and aims to drive to the mountain peak (the flag).

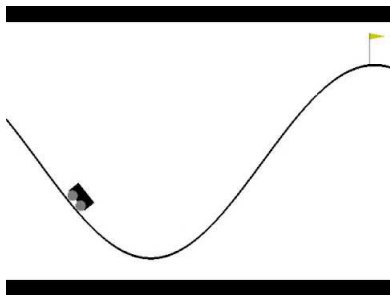


- **Credit Assignment:** Can we use  $d(car, flag)$  as the values function? If no, what should be the value function?



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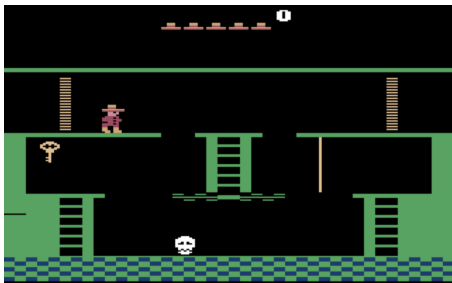


- **Credit Assignment:** Can we use  $d(car, flag)$  as the values function? If no, what should be the value function?
- The optimal policy is **state-dependent**: move left and then move right.



# Examples of MDPs: Mountain Car

Montezuma's Revenge is one of the Atari 2600 games, which compose the Atari learning environment (ALE) commonly used in reinforcement learning tests.



- In the first room, the agent must descend a ladder, jump across an open space using a rope, get the key, jump over a moving enemy...
- In the first level, there are 23 more such rooms for the agent to navigate.

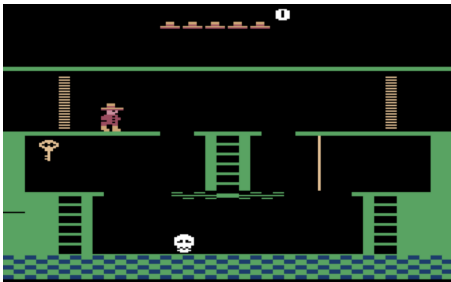


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# Examples of MDPs: Mountain Car

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- **Sparse Rewards and Long Horizon:** the agent has to ever touch some positive reward to receive a reinforcement signal.
- **Problems in Exploration and Credit Assignment:** Properly crediting the reinforce to its long sequence of actions is difficult.



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# Question and Answering (Q&A)



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