

Artificial Intelligence

CS 165A

May 10, 2022

Instructor: Prof. Yu-Xiang Wang

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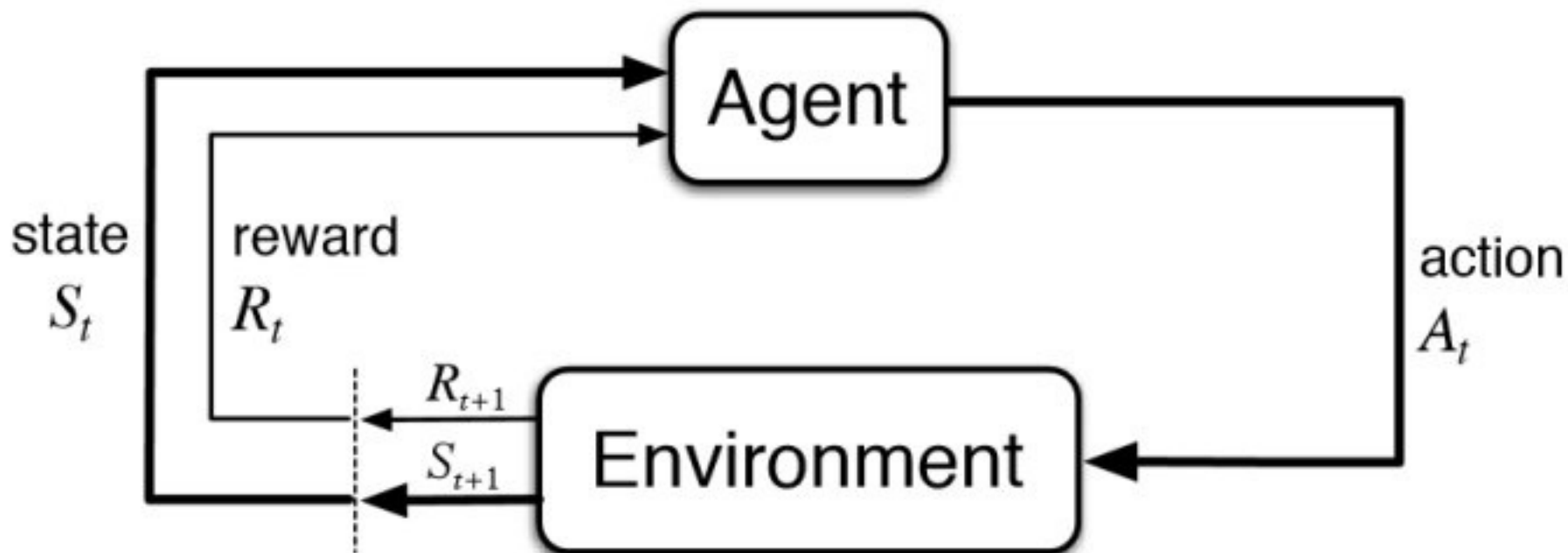
→ Markov Decision Processes

Announcement

- Project 1 grades published on Gradescope
 - Most students got full or nearly full grades
 - Bonus question still open (try them to make up for the losses in the midterm?)
- Project 2 due on Thursday midnight
 - Additional instructor OH: Today 2pm at Henley Hall 2013
 - Project 2 bonus questions submission allowed until end of the quarter (I suggest you do them now! They are fun.)

Recap: Reinforcement learning problem setup

- State, Action, Reward
- Unknown reward function, unknown state-transitions.
- Agents might not even observe the state



Recap: Frozen Lake.

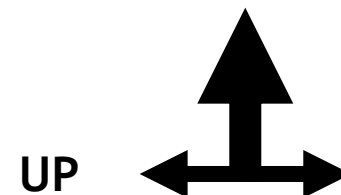
↑	→		+1
↑		↓	-1
	←	↓	→

$$T_{i2} S \rightarrow A$$

$$S \rightarrow P_A$$

actions: UP, DOWN, LEFT, RIGHT

e.g.,



State-transitions with action **UP**:

80% move up

10% move left

10% move right

- reward +1 at [4,3], -1 at [4,2]
- reward -0.04 for each step
- what's the strategy to achieve max reward?
- what if the transitions were deterministic?

*If you bump into a wall,
you stay where you are.

Recap: Tabular MDP

- **Discrete** State, **Discrete** Action, Reward and Observation

$$S_t \in \mathcal{S} \quad A_t \in \mathcal{A} \quad R_t \in \mathbb{R} \quad \text{---} \quad \mathcal{O}_t \in \mathcal{O}$$

- Policy:

– When the state is observable: $\pi : \mathcal{S} \rightarrow \mathcal{A}$

~~– Or when the state is not observable~~

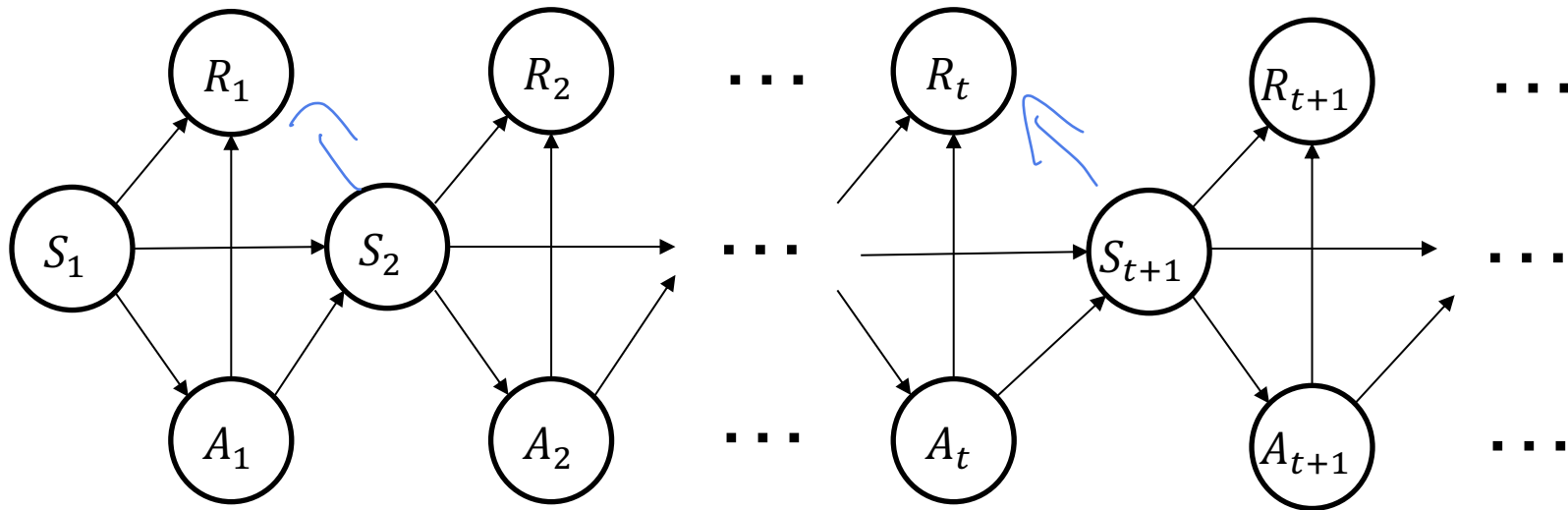
$$\text{---} \quad \pi_t : (\mathcal{O} \times \mathcal{A} \times \mathbb{R})^{t-1} \rightarrow \mathcal{A}$$

- Learn the best policy that maximizes the expected reward

– Finite horizon (episodic) RL: $\pi^* = \arg \max_{\pi \in \Pi} \mathbb{E} \left[\underbrace{\sum_{t=1}^T R_t}_{T: \text{horizon}} \right]$

– Infinite horizon RL: $\pi^* = \arg \max_{\pi \in \Pi} \mathbb{E} \left[\sum_{t=1}^{\infty} \underbrace{\gamma^{t-1} R_t}_{\gamma: \text{discount factor}} \right]$

Recap: Parameters of an MDP are the CPTs



- Initial state distribution
- Transition dynamics
- Reward distribution

$$P(S_1) \in \mathbb{R}^{|S|}$$

$$P(S_{t+1} | S_t, A_t) \in \mathbb{R}^{|S| \times |S| \times |A|}$$

$$P(R_t | S_t, A_t) \text{ or } P(R_t | S_t, A_t, S_{t+1})$$

$$E[R_t | S_t, A_t, S_{t+1}] = \gamma(S_t, A_t, S_{t+1}) = r(S_t, a, s')^6$$

Recap: Reward function and Value functions

- Immediate reward function $r(s,a,s')$

- **expected immediate** reward

$$r(s, a, s') = \mathbb{E}[R_1 | S_1 = s, A_1 = a, S_2 = s']$$

$$r^\pi(s) = \mathbb{E}_{a \sim \pi(a|s)}[R_1 | S_1 = s]$$

- state value function: $V^\pi(s)$

- **expected long-term** return when starting in s and following π

$$V^\pi(s) = \mathbb{E}_\pi[R_1 + \gamma R_2 + \dots + \gamma^{t-1} R_t + \dots | S_1 = s]$$

- state-action value function: $Q^\pi(s,a)$

- **expected long-term** return when starting in s , performing a , and following π

$$Q^\pi(s, a) = \mathbb{E}_\pi[R_1 + \gamma R_2 + \dots + \gamma^{t-1} R_t + \dots | S_1 = s, A_1 = a]$$

This lecture

- Bellman equations
- Algorithms for solving MDPs
 - Value iterations / Policy Iterations
- Exploration and Bandit problem

Bellman equations – the fundamental equations of MDP and RL

$$V^\pi(s) = \mathbb{E}_\pi [R_1 + \gamma R_2 + \dots \mid S_1 = s]$$

- An alternative, recursive and more useful way of defining the V-function and Q function

$$\begin{aligned}
 V^\pi(s) &= \sum_a \pi(a|s) \sum_{s'} P(s'|s, a) [r(s, a, s') + \gamma V^\pi(s')] = \sum_a \pi(a|s) Q^\pi(s, a) \\
 &= \mathbb{E}_{A \sim \pi(a|s)} \mathbb{E}_{S' \sim P(S'|s, a)} [r(s, A, S') + \gamma V^\pi(S')] \\
 &= \mathbb{E}_{A \sim \pi(a|s)} \mathbb{E}_{S' \sim P(S'|s, A)} \left[\mathbb{E}[R_1 | S_1, A, S'] + \gamma \mathbb{E}_{\pi} [R_1 + \gamma R_2 + \gamma^2 R_3 + \dots \mid S_1 = S'] \right] \\
 &= \text{---} + \gamma \mathbb{E}_a [R_2 + \gamma R_3 + \gamma^2 R_4 + \dots \mid S_2 = s] \\
 &= \mathbb{E} [R_1 + \gamma R_2 + \gamma^2 R_3 + \dots \mid S_1 = s] := V^\pi(s)
 \end{aligned}$$

Bellman equations – the fundamental equations of MDP and RL

- An alternative, recursive and more useful way of defining the V-function and Q function

$$V^\pi(s) = \sum_a \pi(a|s) \sum_{s'} P(s'|s, a) [r(s, a, s') + \gamma V^\pi(s')] = \sum_a \pi(a|s) Q^\pi(s, a)$$

(Handwritten blue annotations: a circle around $V^\pi(s)$, a circle around the right-hand side, and a double-headed arrow between them. A bracket under the right-hand side is labeled $Q^\pi(s, a)$.)

- Quiz:
 - Prove Bellman equation from the definition (why are the two definitions the same?). ✓

- Write down the Bellman equation using Q function alone.

$$Q^\pi(s, a) = ? \sum_{s'} P(s'|s, a) \left[r(s, a, s') + \gamma \sum_{a'} \pi(a'|s') Q^\pi(s', a') \right]$$

(Handwritten blue annotations: a bracket under the right-hand side, and a red question mark before the summation.)

Let's work out the Value function for a specific policy

→	→	→	+1
↑		→	-1
↑	→	←	←

actions: UP, DOWN, LEFT, RIGHT

e.g., UP

state-transitions with action **UP**:

80% move UP

10% move LEFT

10% move RIGHT

*If you bump into a wall, you stay where you are.

- reward +1 at [4,3], -1 at [4,2]
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+

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1.0 +

+

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1.0 + 0.8 * +

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$$1.0 + 0.8 * (+1 - 0.04) + \dots$$

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1.0 + 0.8 * (+1-0.04 + 0) + 0.1 *

Let's work out the Value function for a specific policy

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 &= 1.0 + 0.8 * (+1 - 0.04 + 0) + 0.1 * (-0.04 + V^\pi([3,2])) + \dots
 \end{aligned}$$

Let's work out the Value function for a specific policy

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 \end{aligned}$$

Let's work out the Value function for a specific policy

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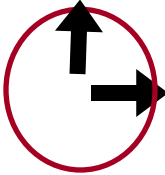






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 &= 1.0 \cdot 0.8 \cdot (+1 - 0.04 + 0) \\
 &\quad + 0.1 \cdot (-0.04 + \gamma V^\pi([3,2])) \\
 &\quad + 0.1 \cdot (-0.04 + \gamma V^\pi([3,3]))
 \end{aligned}$$

$\gamma = 1.0$

Another example: Value function of a randomized policy?

			+1
			-1
			

actions: UP, DOWN, LEFT, RIGHT

e.g., UP

state-transitions with action **UP**:

80% move UP

10% move LEFT

10% move RIGHT

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$[3,3]$

$$V^\pi(s) = \sum_a \pi(a|s) \sum_{s'} P(s'|s, a) [r(s, a, s') + \gamma V^\pi(s')] = \sum_a \pi(a|s) Q^\pi(s, a)$$

"Right"
prev slide
0.5

$$+ 0.5 \left(0.8 \cdot (-0.04 + V([3,3])) + 0.1 \cdot (-0.04 + V([2,3])) + 0.1 \cdot (-0.04 + V([4,3])) \right)$$

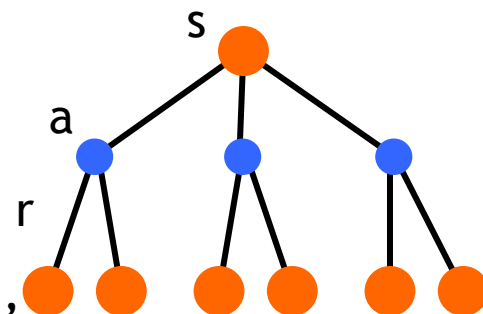
Optimal value functions

- there's a set of *optimal* policies
 - V^π defines partial ordering on policies
 - they share the same optimal value function

$$\underline{V^*(s)} = \max_{\pi} V^\pi(s)$$

$\exists \pi^* \text{ s.t. } \pi^* = \arg \max_{\pi} V^\pi(s)$

$\forall s \in S$



- Bellman optimality equation

$$E[R_t + \gamma V^*(S_{t+1}) | S_t = s]$$

$$\underline{V^*(s)} = \max_a \sum_{s'} P(s'|s, a) [r(s, a, s') + \gamma V^*(s')]$$

- system of n non-linear equations
- solve for $V^*(s)$
- easy to extract the optimal policy

!!
 $Q^*(s, a)$

- having $Q^*(s, a)$ makes it even simpler

$$\underline{\pi^*(s)} = \arg \max_a Q^*(s, a)$$

Inference problem: given an MDP, how to compute its optimal policy?

- It suffices to compute its Q^* function, because:

$$\pi^*(s) = \arg \max_a Q^*(s, a)$$

- It suffices to compute its V^* function, because:

$$Q^*(s, a) = \sum_{s'} P(s'|s, a) [r(s, a, s') + \gamma V^*(s')]$$

Summary of Bellman equations – the fundamental equations of MDP and RL

- V-function and Q function

- V^π function Bellman equation

$$V^\pi(s) = \sum_a \pi(a|s) \sum_{s'} P(s'|s, a) [r(s, a, s') + \gamma V^\pi(s')]$$

- Q $^\pi$ function Bellman equation

$$Q^\pi(s, a) = \sum_{s'} P(s'|s, a) [r(s, a, s') + \gamma \sum_{a'} \pi(a'|s') Q^\pi(s', a')]$$

- V^* function Bellman (optimality) equation

$$V^*(s) = \max_a \sum_{s'} P(s'|s, a) [r(s, a, s') + \gamma V^*(s')]$$

- Q* function Bellman (optimality) equation

$$Q^*(s, a) = \sum_{s'} P(s'|s, a) [r(s, a, s') + \gamma \max_{a'} Q^*(s', a')]$$

Algorithms for calculating the V^* function

- Policy evaluation, policy-improvement
- Policy iterations
- Value iterations

Dynamic programming

- main idea
 - use value functions to structure the search for good policies
 - need a known model of the environment

- two main components



- policy evaluation: compute V^π from π
- policy improvement: improve π based on V^π



- start with an arbitrary policy $\pi_0 \rightarrow V^{\pi_0}$ then update $\pi_0 \rightarrow \pi_1$
- repeat evaluation/improvement until convergence

Policy evaluation/improvement

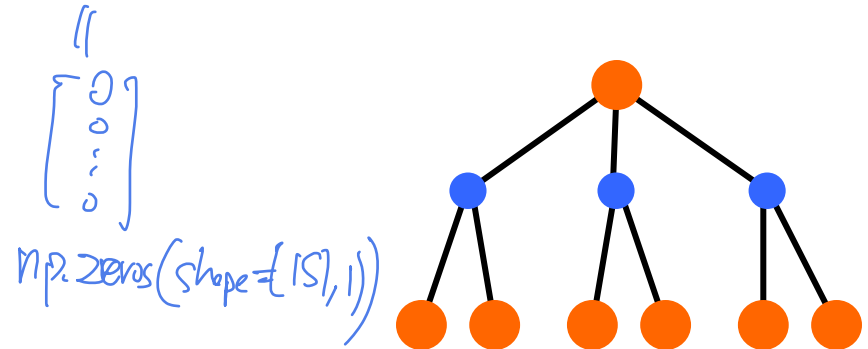
- policy evaluation: $\pi \rightarrow V^\pi$

- Bellman eqn's define a system of n eqn's
- could solve, but will use iterative version

$$V_{k+1}^\pi(s) \leftarrow \sum_a \pi(a|s) \sum_{s'} P(s'|s, a) [r(s, a, s') + \gamma V_k^\pi(s')]$$

Handwritten annotations:
- \uparrow $P(s'|s, a)$
- \downarrow $V_k^\pi(s')$
- \uparrow $r(s, a, s')$

- start with an arbitrary value function V_0 , iterate until V_k converges



Policy evaluation/improvement

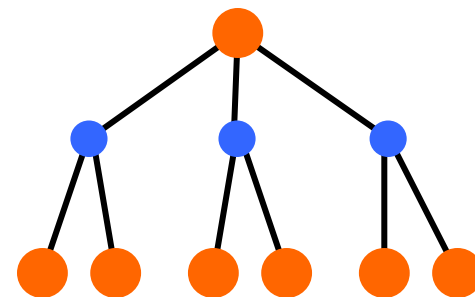
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- start with an arbitrary value function V_0 , iterate until V_k converges

- policy improvement: $V^\pi \rightarrow \pi'$



Policy evaluation/improvement

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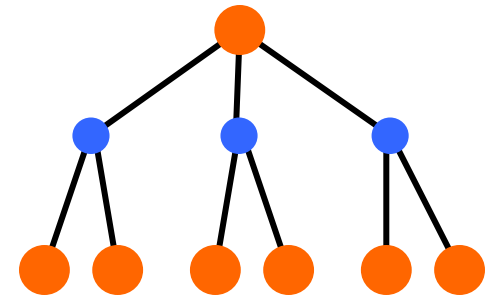
- policy improvement: $V^\pi \rightarrow \pi'$

$$\pi'(s) = \arg \max_a Q^\pi(s, a)$$

$$= \arg \max_a \sum_{s'} P(s'|s, a) [r(s, a, s') + \gamma V_k^\pi(s')]$$

either $\pi' = \pi^*$

or $\pi' \neq \pi$ and $V^{\pi'}(s) \geq V^\pi(s) \forall s$ and $V^{\pi'}(s) > V^\pi(s)$ some s



Policy evaluation/improvement

- policy evaluation: $\pi \rightarrow V^\pi$

- Bellman eqn's define a system of n eqn's
- could solve, but will use iterative version

$$V_{k+1}^\pi(s) \leftarrow \sum_a \pi(a|s) \sum_{s'} P(s'|s, a) [r(s, a, s') + \gamma V_k^\pi(s')]$$

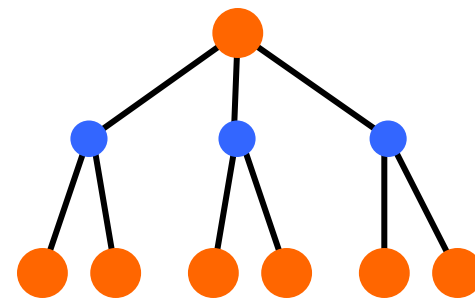
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$$= \arg \max_a \sum_{s'} P(s'|s, a) [r(s, a, s') + \gamma V_k^\pi(s')]$$

- π' either strictly better than π , or π' is optimal (if $\pi = \pi'$)

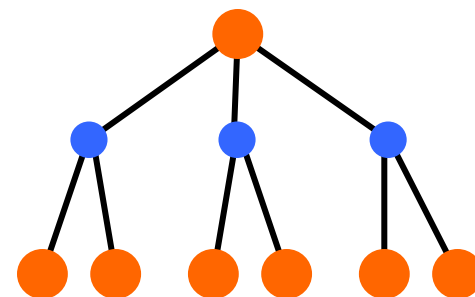


Policy/Value iteration

- Policy iteration

$$\pi_0 \xrightarrow{\underline{E}} V^{\pi_0} \xrightarrow{I} \pi_1 \xrightarrow{\underline{E}} V^{\pi_1} \xrightarrow{I} \dots \xrightarrow{I} \underline{\pi^*} \xrightarrow{\underline{E}} \underline{V^*}$$

- two nested iterations; too slow
- don't need to converge to V^{π_k}
 - just move towards it



Policy/Value iteration

- Policy iteration

$$\pi_0 \xrightarrow{E} V^{\pi_0} \xrightarrow{I} \pi_1 \xrightarrow{E} V^{\pi_1} \xrightarrow{I} \dots \xrightarrow{I} \pi^* \xrightarrow{E} V^*$$

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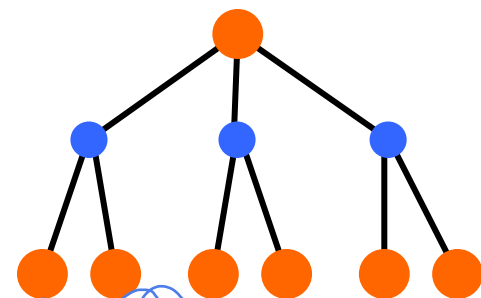
- Value iteration

$$V_{k+1}(s) \leftarrow \max_a \sum_{s'} P(s'|s, a) [r(s, a, s') + \gamma V_k(s')]$$

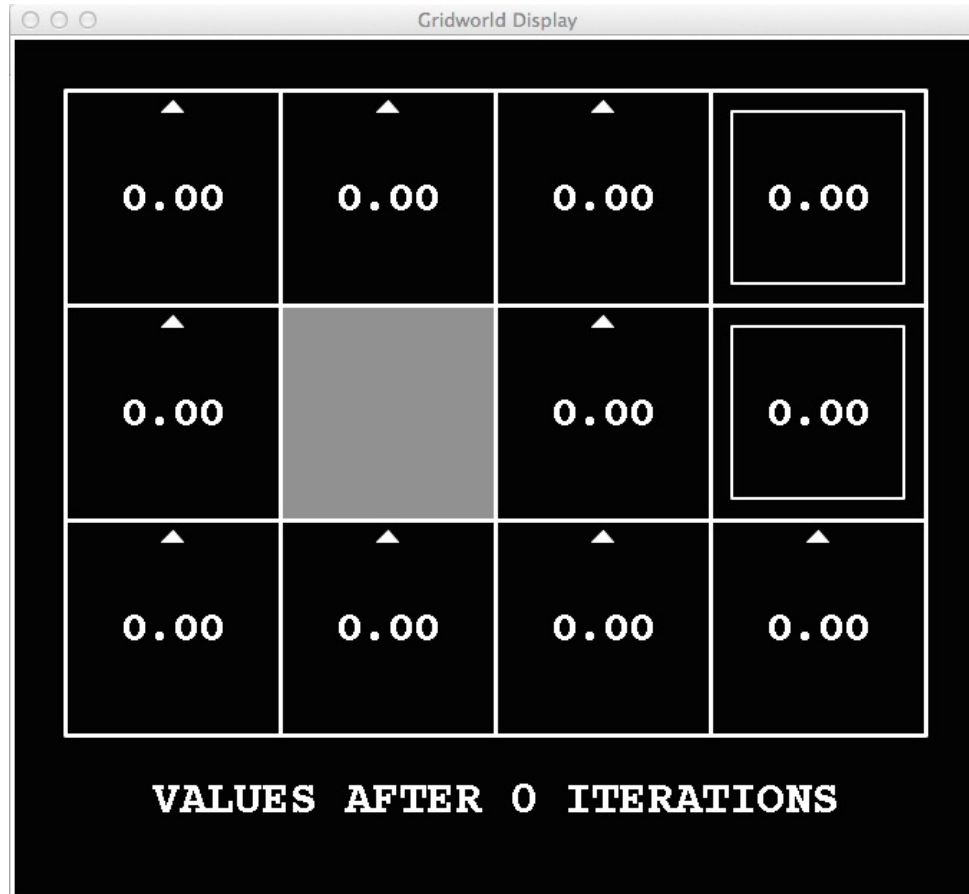
one-step Policy Eval from V_k

- use Bellman optimality equation as an update
- converges to V^*

$$V^*(s) = \max_a \sum_{s'} P(s'|s, a) [r(s, a, s') + \gamma V^*(s')]$$



$k=0$

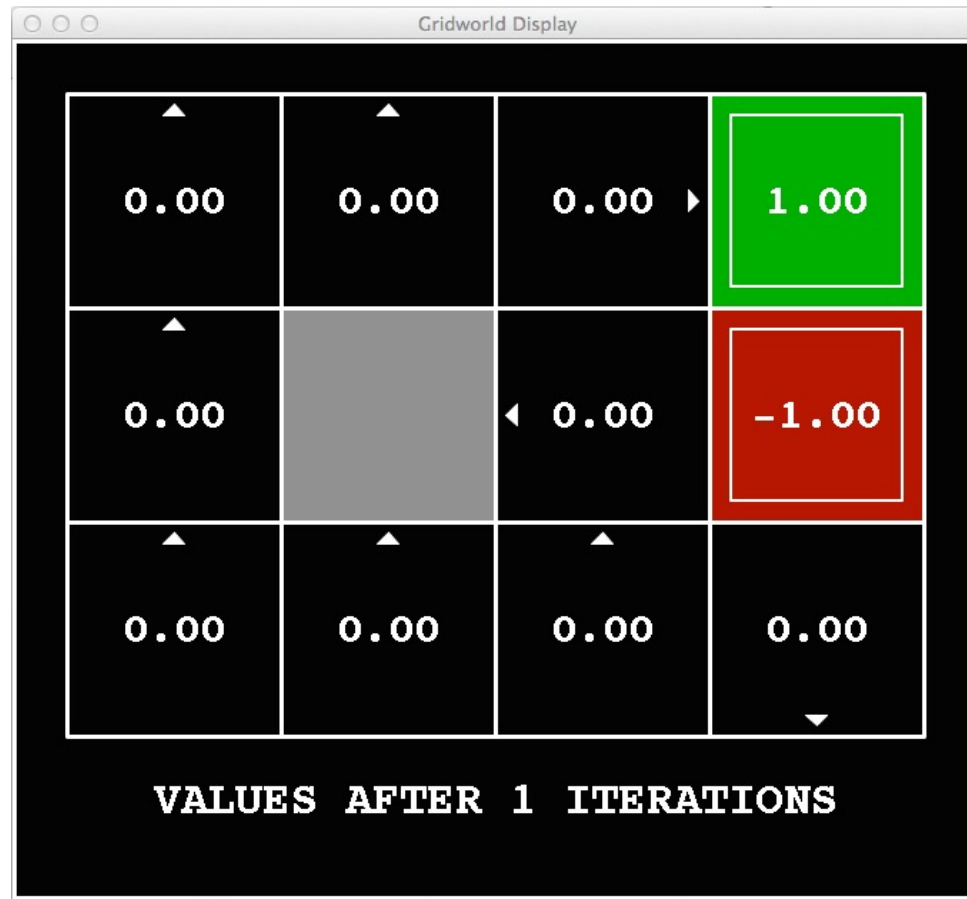


Noise = 0.2

Discount = 0.9

Living reward = 0

$k=1$



Noise = 0.2

Discount = 0.9

Living reward = 0

$k=2$

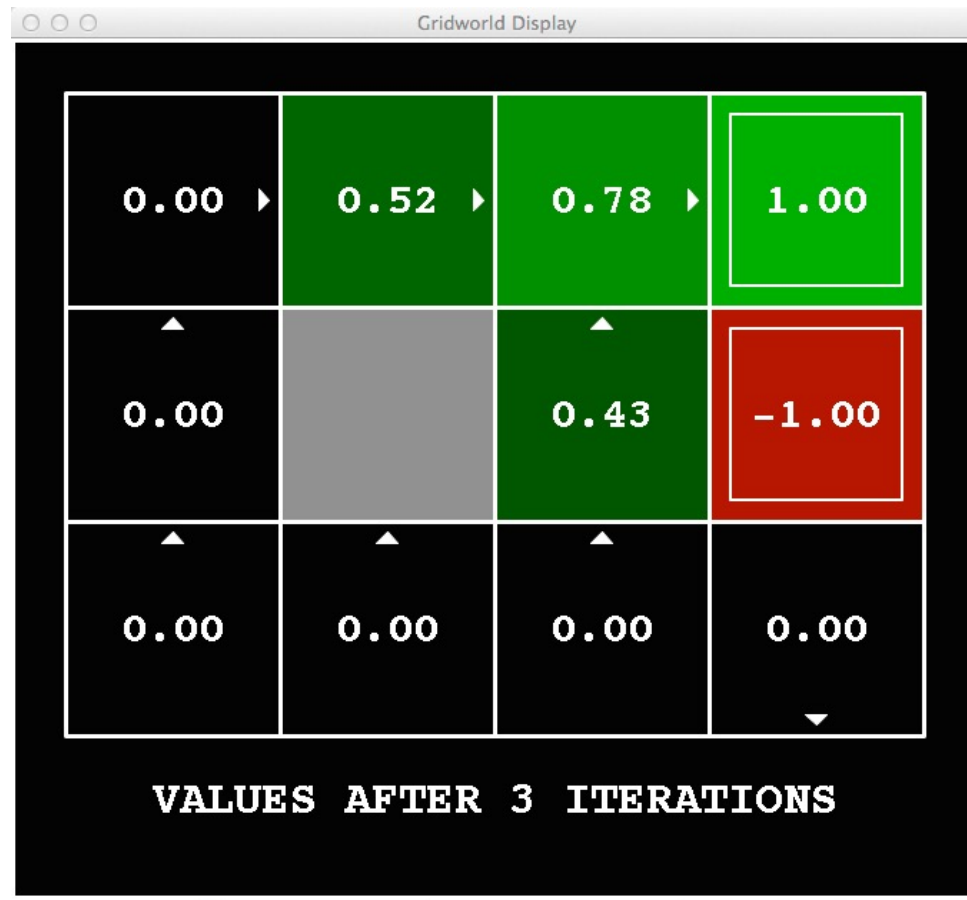


Noise = 0.2

Discount = 0.9

Living reward = 0

$k=3$



Noise = 0.2

Discount = 0.9

Living reward = 0

$k=4$

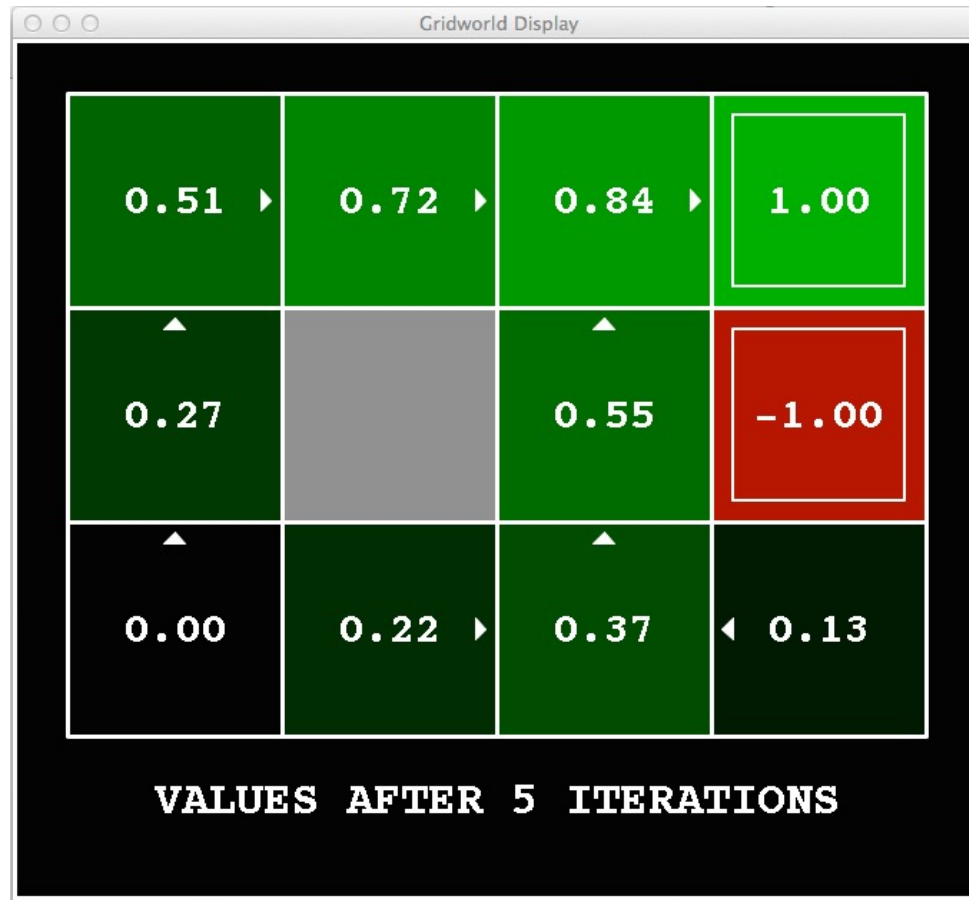


Noise = 0.2

Discount = 0.9

Living reward = 0

$k=5$



Noise = 0.2

Discount = 0.9

Living reward = 0

$k=6$



Noise = 0.2

Discount = 0.9

Living reward = 0

$k=7$



Noise = 0.2

Discount = 0.9

Living reward = 0

$k=8$



Noise = 0.2

Discount = 0.9

Living reward = 0

$k=9$



Noise = 0.2

Discount = 0.9

Living reward = 0

$k=10$



Noise = 0.2

Discount = 0.9

Living reward = 0

k=11

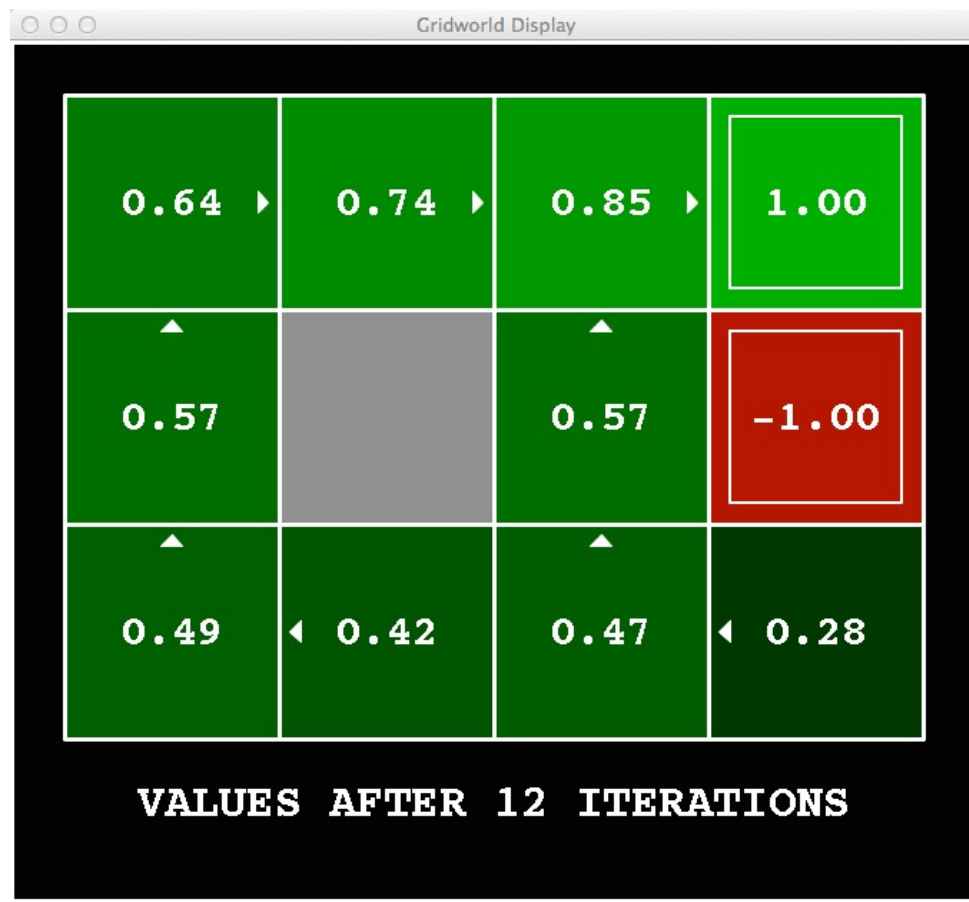


Noise = 0.2

Discount = 0.9

Living reward = 0

k=12



Noise = 0.2

Discount = 0.9

Living reward = 0

$k=100$



Noise = 0.2

Discount = 0.9

Living reward = 0

Q-iteration

- Updating Q functions instead of V functions

$$Q_{k+1}(s, a) \leftarrow \sum_{s'} P(s'|s, a) [r(s, a, s') + \gamma \max_{a'} Q_k(s', a')]$$

$$Q = \begin{bmatrix} & G & R(s/A) \\ & & \end{bmatrix}$$
$$V = \begin{bmatrix} & G & R(s) \\ & & \end{bmatrix}$$

- Quiz: What is the difference from the following extended version of value iteration? *Value iteration*

$$V_{k+1}(s) \leftarrow \max_a \sum_{s'} P(s'|s, a) [r(s, a, s') + \gamma V_k(s')]$$

$$Q_{k+1}(s, a) \leftarrow \sum_{s'} P(s'|s, a) [r(s, a, s') + \gamma V_{k+1}(s')]$$

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$$Q_{k+1}(s, a) \leftarrow \sum_{s'} P(s'|s, a) [r(s, a, s') + \gamma V_{k+1}(s')]$$

Ans: They are identical!

Demo: grid worlds

0.00 ↘	0.00 ↘	0.00 ↘	0.00 ↘	0.00 ↘	0.00 ↘	0.00 ↘	0.00 ↘	0.00 ↘	0.00 ↘
0.00 ↖	0.00 ◆	0.00 ◆	0.00 ◆	0.00 ◆	0.00 ◆	0.00 ◆	0.00 ◆	0.00 ◆	0.00 ◆
0.00 ↖					0.00 ◆				0.00 ◆
0.00 ↖	0.00 ◆	0.00 ◆	0.00 ◆ R-1.0		0.00 ◆	0.00 ◆	0.00 ◆	0.00 ◆	0.00 ◆
0.00 ↖	0.00 ◆	0.00 ◆	0.00 ◆		0.00 ◆ R-1.0	0.00 ◆ R-1.0	0.00 ◆	0.00 ◆	0.00 ◆
0.00 ↖	0.00 ◆	0.00 ◆	0.00 ◆		0.00 ◆ R-1.0	0.00 ◆ R-1.0	0.00 ◆	0.00 ◆ R-1.0	0.00 ◆
0.00 ↖	0.00 ◆	0.00 ◆	0.00 ◆		0.00 ◆	0.00 ◆	0.00 ◆	0.00 ◆ R-1.0	0.00 ◆
0.00 ↖	0.00 ◆	0.00 ◆	0.00 ◆ R-1.0		0.00 ◆ R-1.0	0.00 ◆ R-1.0	0.00 ◆	0.00 ◆	0.00 ◆
0.00 ↖	0.00 ◆	0.00 ◆	0.00 ◆	0.00 ◆	0.00 ◆	0.00 ◆	0.00 ◆	0.00 ◆	0.00 ◆
0.00 ↘	0.00 ↖	0.00 ↖	0.00 ↖	0.00 ↖	0.00 ↖	0.00 ↖	0.00 ↖	0.00 ↖	0.00 ↖

https://cs.stanford.edu/people/karpathy/reinforcejs/gridworld_dp.html

MDP summary

- Tabular MDP
- Episodic vs. infinite horizon (discounted)
- Immediate reward vs long-term reward
- Value functions: V functions, Q functions
- Bellman equations, Bellman optimality equations
- How to solve MDP? Policy iterations, value iterations

MDP Summary

Standard expectimax: $V(s) = \max_a \sum_{s'} P(s'|s, a) V(s')$

Bellman equations: $V(s) = \max_a \sum_{s'} P(s'|s, a) [r(s, a, s') + \gamma V(s')]$

Value iteration: $V_{k+1}(s) = \max_a \sum_{s'} P(s'|s, a) [r(s, a, s') + \gamma V_k(s')], \quad \forall s$

$$Q_{k+1}(s, a) = \sum_{s'} P(s'|s, a) [r(s, a, s') + \gamma \max_{a'} Q_k(s', a')], \quad \forall s, a$$

$$V_{k+1}^\pi(s) = \sum_{s'} P(s'|s, \pi(s)) [r(s, \pi(s), s') + \gamma V_k^\pi(s')], \quad \forall s$$

$$\pi_{new}(s) = \operatorname{argmax}_a \sum_{s'} P(s'|s, a) [r(s, a, s') + \gamma V^{\pi_{old}}(s')], \quad \forall s$$

MDP Summary

Standard expectimax: $V(s) = \max_a \sum_{s'} P(s'|s, a) V(s')$

Bellman equations: $V(s) = \max_a \sum_{s'} P(s'|s, a) [r(s, a, s') + \gamma V(s')]$

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Q-iteration: $Q_{k+1}(s, a) = \sum_{s'} P(s'|s, a) [r(s, a, s') + \gamma \max_{a'} Q_k(s', a')], \quad \forall s, a$

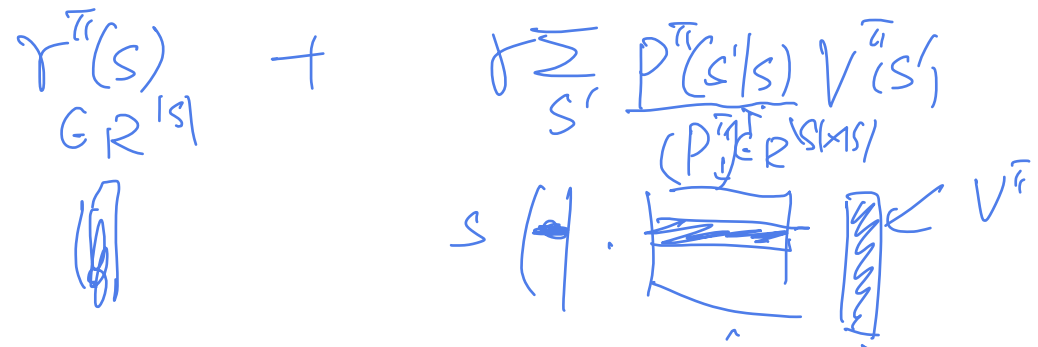
Policy evaluation: $V_{k+1}^\pi(s) = \sum_{s'} P(s'|s, \pi(s)) [r(s, \pi(s), s') + \gamma V_k^\pi(s')], \quad \forall s$

Policy improvement: $\pi_{new}(s) = \operatorname{argmax}_a \sum_{s'} P(s'|s, a) [r(s, a, s') + \gamma V^{\pi_{old}}(s')], \quad \forall s$

Matrix-form of Bellman Equations and VI

$$\begin{aligned}
 \underbrace{V^\pi(s)}_{\in \mathbb{R}^{|S|}} &= \sum_a \pi(a|s) \sum_{s'} P(s'|s, a) [r(s, a, s') + \gamma \underbrace{V^\pi(s')}_{\in \mathbb{R}^{|S|}}] \\
 &= \underbrace{\mathbb{E}_{a \sim \pi(a|s)}}_{\in \mathbb{R}^{|S|}} \underbrace{\mathbb{E}_{s' \sim P(s'|s, a)}}_{\in \mathbb{R}^{|S|}} [r(s, a, s')] + \gamma \mathbb{E} [V^\pi(s')]
 \end{aligned}$$

$$\begin{aligned}
 &V^\pi = r^\pi + (P^\pi)^\top V^\pi \\
 &\underline{(I - \gamma(P^\pi)^\top)} V^\pi = r^\pi
 \end{aligned}$$



$$V_{k+1}^\pi(s) \leftarrow \sum_a \pi(a|s) \sum_{s'} P(s'|s, a) [r(s, a, s') + \gamma V_k^\pi(s')]$$

$$\boxed{Ax = b}$$

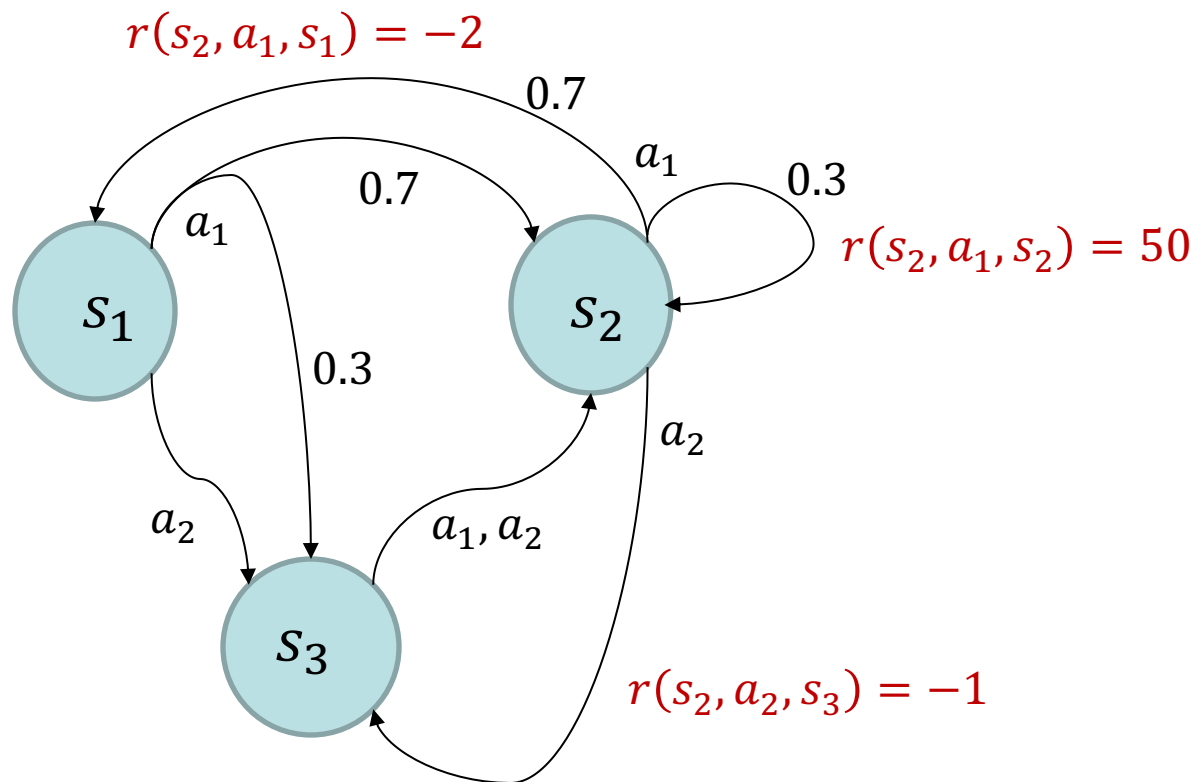
$x = A^{-1}b$, np. lin. alg. solve (A, b)

$$V_{k+1} \leftarrow r^\pi + \gamma (P^\pi)^\top V_k$$

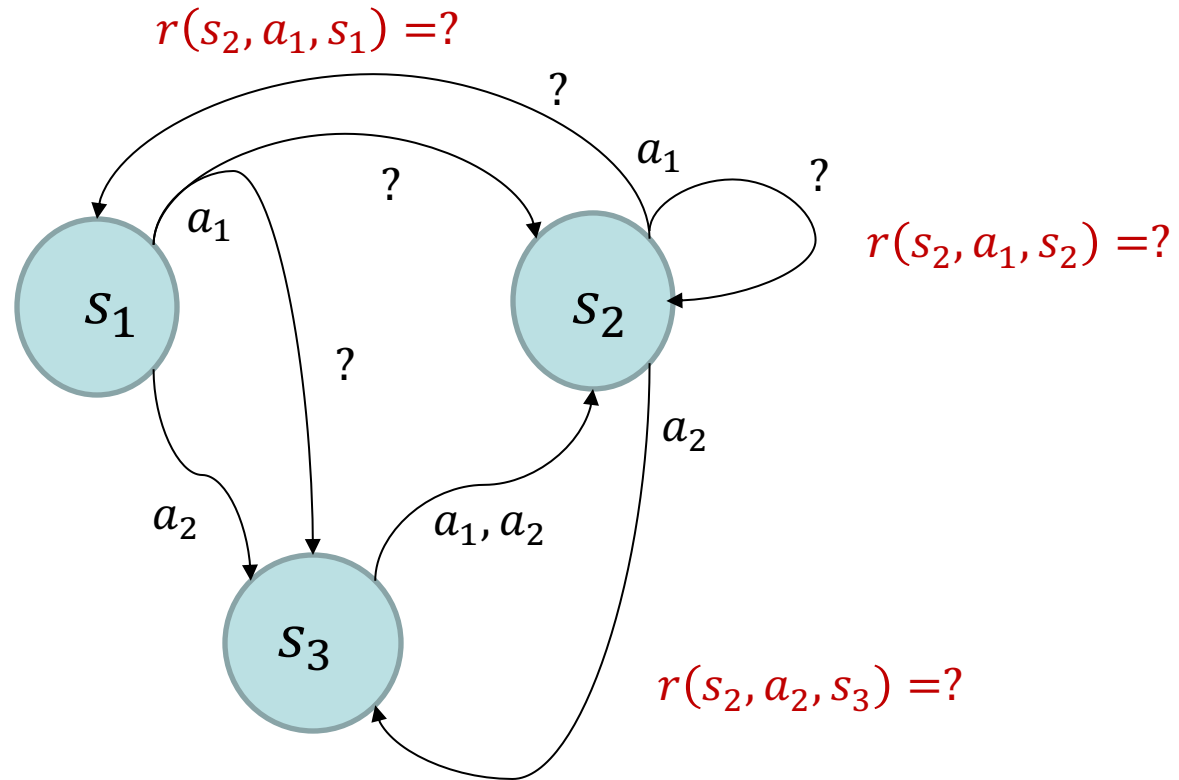
Solving MDP with VI or PI is offline planning

- The agent is given how the environment works
- The agent works out the optimal policy in its mind.
- The agent never really starts to play at all.
- No learning is happening.

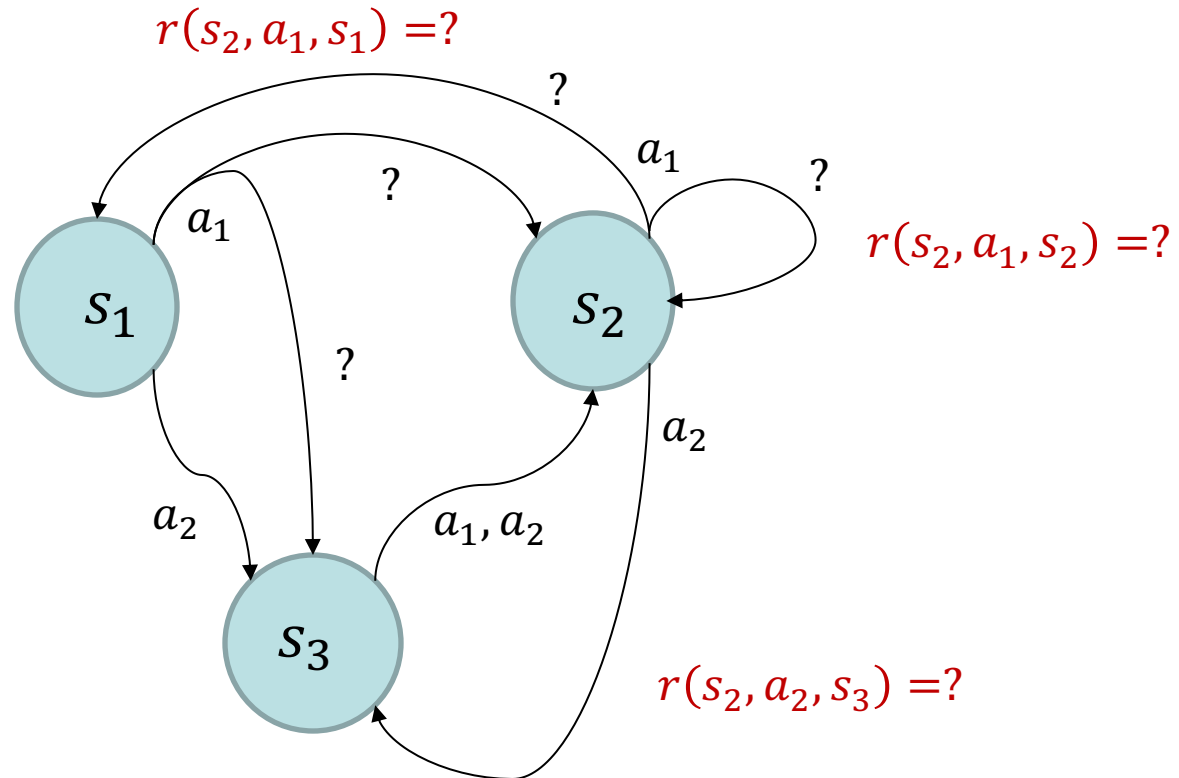
State-space diagram representation of an MDP: An example with 3 states and 2 actions.



What happens if you do not know the rewards / transition probabilities?



What happens if you do not know the rewards / transition probabilities?



Then you have to learn by interacting with the unknown environment.

You cannot use only offline planning!

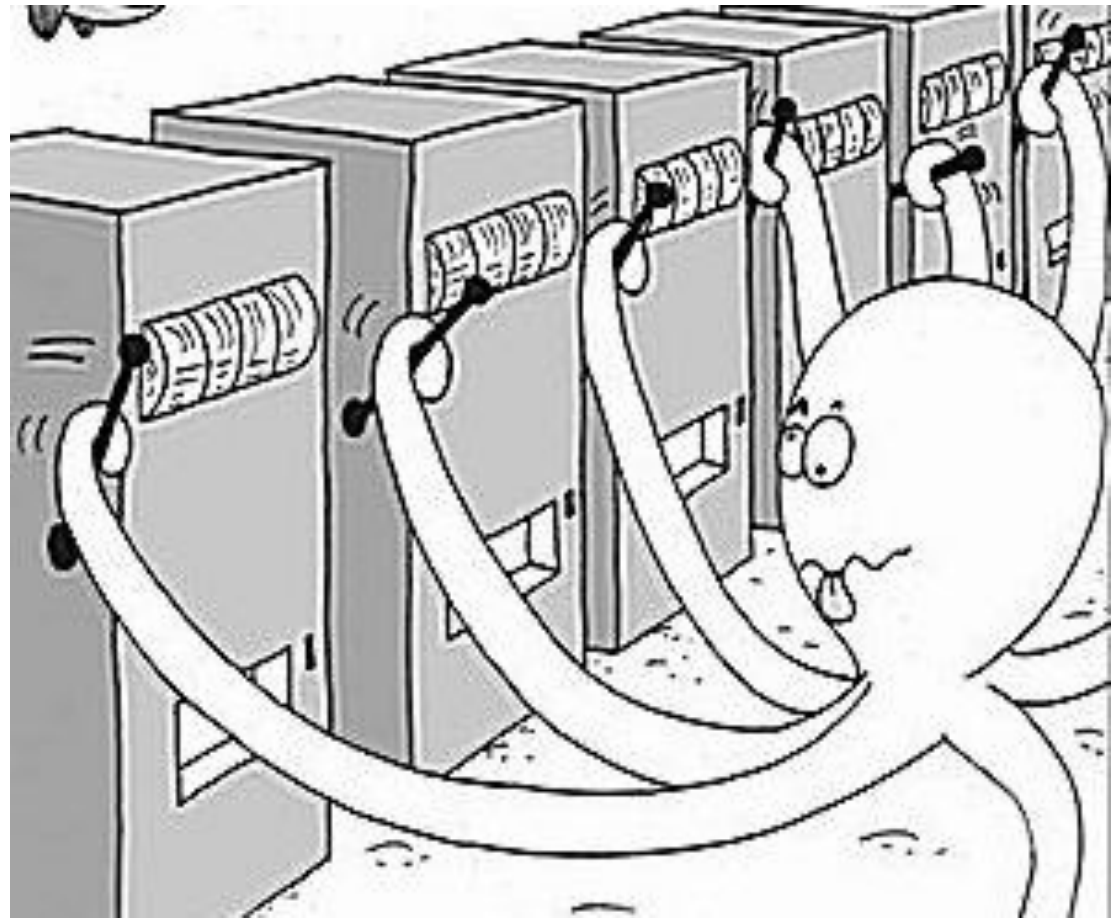
Exploration: Try unknown actions to see what happens.

Exploitation: Maximize utility using what we know.

Let us tackle different aspects of the RL problem one at a time

- Markov Decision Processes:
 - Dynamics are given no need to learn
- **Bandits: Explore-Exploit in simple settings**
 - RL without dynamics
- Full Reinforcement Learning
 - Learning MDPs

Slot machines and Multi-arm bandits



Multi-arm bandits: Problem setup

- No state. k -actions $a \in \mathcal{A} = \{1, 2, \dots, k\}$

- You decide which arm to pull in every iteration

$$A_1, A_2, \dots, A_T$$

- You collect a cumulative payoff of $\sum_{t=1}^T R_t$

- The goal of the agent is to maximize the expected payoff.
 - For future payoffs?
 - For the expected cumulative payoff?

Key differences from MDPs

- Simplified:
 - No state-transitions

- But:
 - We are not given the expected reward $r(s, a, s')$
 - We need to learn the optimal policy by trials-and-errors.

A 10-armed bandits example

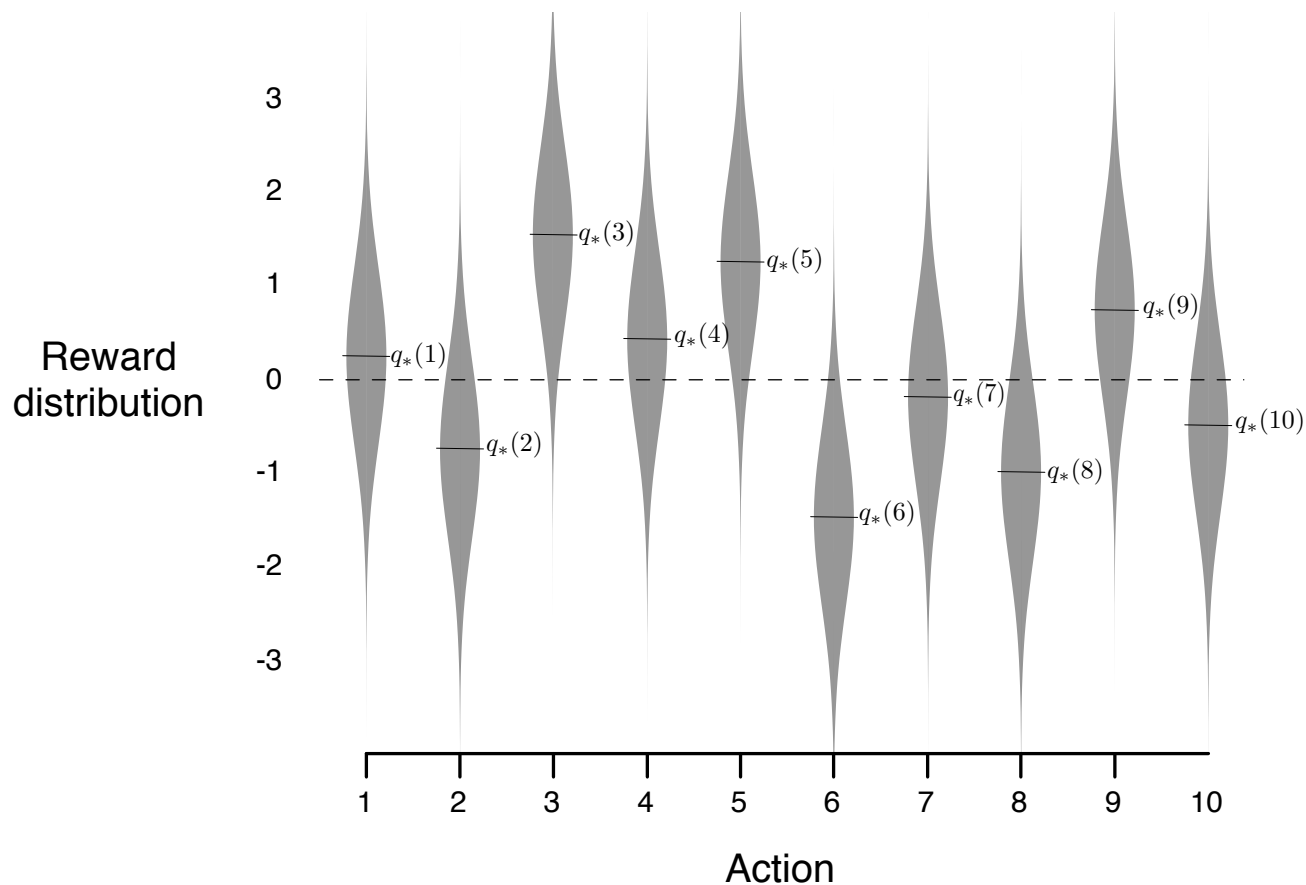


Figure 2.1: An example bandit problem from the 10-armed testbed. The true value $q_*(a)$ of each of the ten actions was selected according to a normal distribution with mean zero and unit variance, and then the actual rewards were selected according to a mean $q_*(a)$ unit variance normal distribution, as suggested by these gray distributions.

How do we measure the performance of an **online learning agent**?

- The notion of “Regret”:
 - I wish I have done things differently.
 - Comparing to the best actions in the hindsight, how much worse did I do.

- For MAB, the regret is defined as follow

$$T \max_{a \in [k]} \mathbb{E}[R_t | a] - \sum_{t=1}^T \mathbb{E}_{a \sim \pi} [\mathbb{E}[R_t | a]]$$

Greedy strategy

- Expected reward

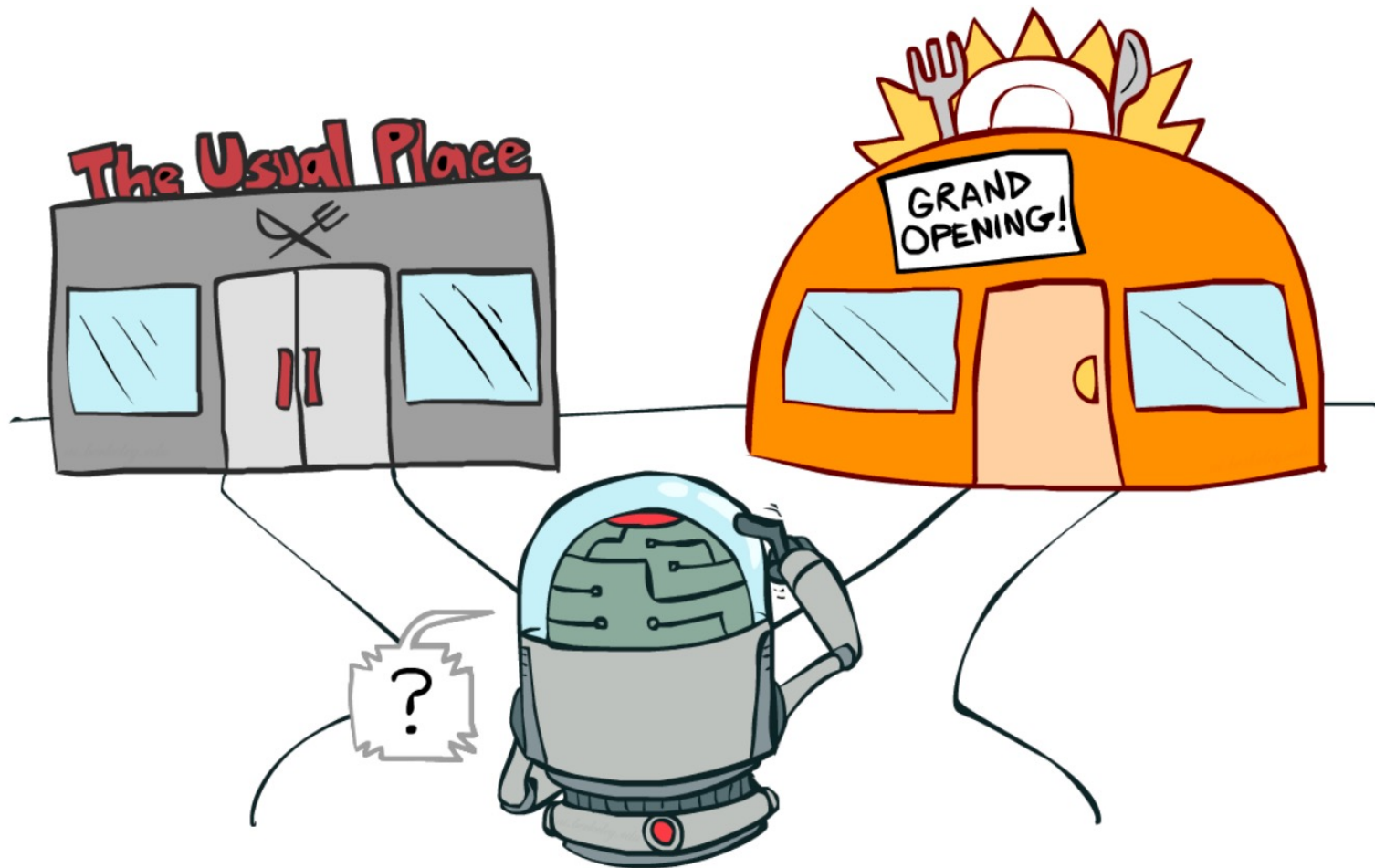
$$q_*(a) \doteq \mathbb{E}[R_t \mid A_t = a] .$$

- Estimate the expected reward

$$\begin{aligned} Q_t(a) &\doteq \frac{\text{sum of rewards when } a \text{ taken prior to } t}{\text{number of times } a \text{ taken prior to } t} \\ &= \frac{\sum_{i=1}^{t-1} R_i \cdot \mathbb{1}_{A_i=a}}{\sum_{i=1}^{t-1} \mathbb{1}_{A_i=a}} \end{aligned}$$

- Choose $A_t \doteq \arg \max_a Q_t(a)$,

Exploration vs. Exploitation



(Illustration from Dan Klein and Pieter Abbeel's course in UC Berkeley)

Next Tuesday

- Bandits algorithms
 - Explore-first
 - epsilon-greedy
 - Upper confidence bound