

14.385 Nonlinear Econometric Analysis  
Reinforcement learning

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# Outline

- Markov decision problems: Goal oriented interactions with an environment.
- Expected updates – dynamic programming.  
Familiar from economics. Requires complete knowledge of transition probabilities.
- Sample updates: Transition probabilities are unknown.
  - On policy: Sarsa.
  - Off policy: Q-learning.
- Approximation: When state and action spaces are complex.
  - On policy: Semi-gradient Sarsa.
  - Off policy: Semi-gradient Q-learning.
  - Deep reinforcement learning.
  - Eligibility traces and  $TD(\lambda)$ .

## Takeaways for this part of class

- Markov decision problems provide a general model of goal-oriented interaction with an environment.
- Reinforcement learning considers Markov decision problems where transition probabilities are unknown.
- A leading approach is based on estimating action-value functions.
- If state and action spaces are small, this can be done in tabular form, otherwise approximation (e.g., using neural nets) is required.
- We will distinguish between on-policy and off-policy learning.

# Introduction

- Many interesting problems can be modeled as Markov decision problems.
- Biggest successes in game play (Backgammon, Chess, Go, Atari games,...), where lots of data can be generated by self-play.
- Basic framework is familiar from macro / structural micro, where it is solved using dynamic programming / value function iteration.
- Big difference in reinforcement learning:  
Transition probabilities are not known, and need to be learned from data.
- This makes the setting similar to bandit problems, with the addition of changing states.
- We will discuss several approaches based on estimating action-value functions.

Markov decision problems

Expected updates - dynamic programming

Sample updates

Approximation

Eligibility traces

References

# Markov decision problems

- Time periods  $t = 1, 2, \dots$
- States  $\mathbf{S}_t \in \mathcal{S}$  (This is the part that's new relative to bandits!)
- Actions  $\mathbf{A}_t \in \mathcal{A}(\mathbf{S}_t)$
- Rewards  $R_{t+1}$
- Dynamics (transition probabilities):

$$P(\mathbf{S}_{t+1} = \mathbf{s}', R_{t+1} = r | \mathbf{S}_t = \mathbf{s}, \mathbf{A}_t = \mathbf{a}, \mathbf{S}_{t-1}, \mathbf{A}_{t-1}, \dots) = p(\mathbf{s}', r | \mathbf{s}, \mathbf{a}).$$

- The distribution depends only on the current state and action.
- It is constant over time.
- We will allow for continuous states and actions later.

# Policy function, value function, action value function

- Objective: Discounted stream of rewards,  $\sum_{t \geq 0} \gamma^t R_t$ .
- Expected future discounted reward at time  $t$ , given the state  $S_t = s$ :  
Value function,

$$V_t(s) = E \left[ \sum_{t' \geq t} \gamma^{t'-t} R_{t'} | S_t = s \right].$$

- Expected future discounted reward at time  $t$ , given the state  $S_t = s$  **and** action  $A_t = a$ :  
Action value function,

$$Q_t(a, s) = E \left[ \sum_{t' \geq t} \gamma^{t'-t} R_{t'} | S_t = s, A_t = a \right].$$

# Bellman equation

- Consider a policy  $\pi(\mathbf{a}|\mathbf{s})$ , giving the probability of choosing  $\mathbf{a}$  in state  $\mathbf{s}$ . This gives us all transition probabilities, and we can write expected discounted returns recursively

$$Q_{\pi}(\mathbf{a}, \mathbf{s}) = (\mathcal{B}_{\pi} Q_{\pi})(\mathbf{a}, \mathbf{s}) = \sum_{\mathbf{s}', r} p(\mathbf{s}', r | \mathbf{s}, \mathbf{a}) \left( r + \gamma \cdot \sum_{\mathbf{a}'} \pi(\mathbf{a}' | \mathbf{s}') Q_{\pi}(\mathbf{a}', \mathbf{s}') \right).$$

- Suppose alternatively that future actions are chosen optimally. We can again write expected discounted returns recursively

$$Q_{*}(\mathbf{a}, \mathbf{s}) = (\mathcal{B}_{*} Q_{*})(\mathbf{a}, \mathbf{s}) = \sum_{\mathbf{s}', r} p(\mathbf{s}', r | \mathbf{s}, \mathbf{a}) \left( r + \gamma \cdot \max_{\mathbf{a}'} Q_{*}(\mathbf{a}', \mathbf{s}') \right).$$



# Existence and uniqueness of solutions

- The operators  $\mathcal{B}_\pi$  and  $\mathcal{B}_*$  define contraction mappings on the space of action value functions. (As long as  $\gamma < 1$ .)
- By Banach's fixed point theorem, unique solutions exist.
- The difference between assuming a given policy  $\pi$ , or considering optimal actions  $\operatorname{argmax}_a Q(a, s)$ , is the dividing line between on policy and off policy methods in reinforcement learning.

Markov decision problems

Expected updates - dynamic programming

Sample updates

Approximation

Eligibility traces

References

## Expected updates - dynamic programming

- Suppose we know the transition probabilities  $p(s', r | s, a)$ .
- Then we can in principle just solve for the action value functions and optimal policies.
- This is typically assumed in macro, IO models.
- Solutions: Dynamic programming.  
Iteratively replace
  - $Q_\pi(a, s)$  by  $(\mathcal{B}_\pi Q_\pi)(a, s)$ , or
  - $Q_*(a, s)$  by  $(\mathcal{B}_* Q_*)(a, s)$ .
- Decision problems with terminal states: Can solve in one sweep of backward induction.
- Otherwise: Value function iteration until convergence – replace repeatedly.

Markov decision problems

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## Sample updates

- In practically interesting settings, agents (human or AI) typically don't know the transition probabilities  $p(\mathbf{s}', r | \mathbf{s}, \mathbf{a})$ .
- This is where reinforcement learning comes in.  
Learning from observation while acting in an environment.
- Observations come in the form of tuples

$$\langle \mathbf{s}, \mathbf{a}, r, \mathbf{s}' \rangle.$$

- Based on a sequence of such tuples, we want to learn  $Q_\pi$  or  $Q_*$ .

# Classification of one-step reinforcement learning methods

1. Known vs. unknown transition probabilities.
2. Value function vs. action value function.
3. On policy vs. off policy.
  - We will discuss Sarsa and Q-learning.
  - Both: unknown transition probabilities and action value functions.
  - First: “tabular” methods, where we keep track off all possible values  $(\mathbf{a}, \mathbf{s})$ .
  - Then: “approximate” methods for richer spaces of  $(\mathbf{a}, \mathbf{s})$ , e.g., deep neural nets.

Value  
estimated

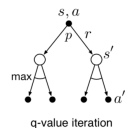
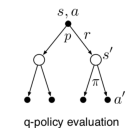
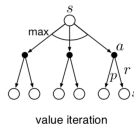
$v_{\pi}(s)$

$v_{*}(s)$

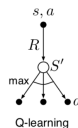
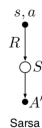
$q_{\pi}(s, a)$

$q_{*}(s, a)$

Expected updates  
(DP)



Sample updates  
(one-step TD)



# Sarsa

- On policy learning of action value functions.
- Recall Bellman equation

$$Q_{\pi}(a, s) = \sum_{s', r} p(s', r | s, a) \left( r + \gamma \cdot \sum_{a'} \pi(a' | s') Q_{\pi}(a', s') \right).$$

- Sarsa estimates expectations by sample averages.
- After each observation  $\langle \mathbf{s}, \mathbf{a}, r, \mathbf{s}', \mathbf{a}' \rangle$ , replace the estimated  $Q_{\pi}(a, s)$  by

$$Q_{\pi}(a, s) + \alpha \cdot (r + \gamma \cdot Q_{\pi}(a', s') - Q_{\pi}(a, s)).$$

- $\alpha$  is the step size / speed of learning / rate of forgetting.

## Sarsa as stochastic (semi-)gradient descent

- Think of  $Q_\pi(\mathbf{a}, \mathbf{s})$  as prediction for  $Y = r + \gamma \cdot Q_\pi(\mathbf{a}', \mathbf{s}')$ .

- Quadratic prediction error:

$$(Y - Q_\pi(\mathbf{a}, \mathbf{s}))^2.$$

- Gradient for minimization of prediction error for current observation w.r.t.  $Q_\pi(\mathbf{a}, \mathbf{s})$ :

$$-(Y - Q_\pi(\mathbf{a}, \mathbf{s})).$$

- Sarsa is thus a variant of stochastic gradient descent.
- Variant: Data are generated by actions where  $\pi$  is chosen as the optimal policy for the current estimate of  $Q_\pi$ .
- Reasonable method, but convergence guarantees are tricky.



# Q-learning

- Similar to Sarsa, but **off policy**.
- Like Sarsa, estimate expectation over  $p(\mathbf{s}', r | \mathbf{s}, \mathbf{a})$  by sample averages.
- Rather than the observed next action  $\mathbf{a}'$  consider the optimal action  **$\operatorname{argmax}_{\mathbf{a}'} Q_*(\mathbf{a}', \mathbf{s}')$** .
- After each observation  $\langle \mathbf{s}, \mathbf{a}, r, \mathbf{s}' \rangle$ , replace the estimated  $Q_*(\mathbf{a}, \mathbf{s})$  by

$$Q_*(\mathbf{a}, \mathbf{s}) + \alpha \cdot \left( r + \gamma \cdot \operatorname{max}_{\mathbf{a}'} Q_*(\mathbf{a}', \mathbf{s}') - Q_*(\mathbf{a}, \mathbf{s}) \right).$$

Markov decision problems

Expected updates - dynamic programming

Sample updates

Approximation

Eligibility traces

References

# Approximation

- So far, we have implicitly assumed that there is a small, finite number of states  $\mathbf{s}$  and actions  $\mathbf{a}$ , so that we can store  $Q(\mathbf{a}, \mathbf{s})$  in tabular form.
- In practically interesting cases, this is not feasible.
- Instead assume parametric functional form for  $Q(\mathbf{a}, \mathbf{s}; \theta)$ .
- In particular: Deep neural nets!
- Assume differentiability with gradient  $\nabla_{\theta} Q(\mathbf{a}, \mathbf{s}; \theta)$ .

# Stochastic gradient descent

- Denote our prediction target for an observation  $\langle \mathbf{s}, \mathbf{a}, r, \mathbf{s}', \mathbf{a}' \rangle$  by

$$Y = r + \gamma \cdot Q_{\pi}(\mathbf{a}', \mathbf{s}'; \theta).$$

- As before, for the on-policy case, we have the quadratic prediction error

$$(Y - Q_{\pi}(\mathbf{a}, \mathbf{s}; \theta))^2.$$

- Semi-gradient: Only take derivative for the  $Q_{\pi}(\mathbf{a}, \mathbf{s}; \theta)$  part, but not for the prediction target  $Y$ :

$$-(Y - Q_{\pi}(\mathbf{a}, \mathbf{s}; \theta)) \cdot \nabla_{\theta} Q(\mathbf{a}, \mathbf{s}; \theta).$$

- Stochastic gradient descent updating step: Replace  $\theta$  by

$$\theta + \alpha \cdot (Y - Q_{\pi}(\mathbf{a}, \mathbf{s}; \theta)) \cdot \nabla_{\theta} Q(\mathbf{a}, \mathbf{s}; \theta).$$

## Off policy variant

- As before, can replace  $\mathbf{a}'$  by the estimated optimal action.
- Change the prediction target to

$$Y = r + \gamma \cdot \max_{\mathbf{a}'} Q_*(\mathbf{a}', \mathbf{s}'; \theta).$$

- Updating step as before, replacing  $\theta$  by

$$\theta + \alpha \cdot (Y - Q_*(\mathbf{a}, \mathbf{s}; \theta)) \cdot \nabla_{\theta} Q_*(\mathbf{a}, \mathbf{s}; \theta).$$

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## Multi-step updates

- All methods discussed thus far are one-step methods.
- After observing  $\langle \mathbf{s}, \mathbf{a}, r, \mathbf{s}', \mathbf{a}' \rangle$ , only  $Q(\mathbf{a}, \mathbf{s})$  is targeted for an update.
- But we could pass that new information further back in time, since

$$Q(\mathbf{a}, \mathbf{s}) = E \left[ \sum_{t'=t}^{t+k} \gamma^{t'-t} R_{t'} + \gamma^{k+1} Q(\mathbf{A}_{t+k+1}, \mathbf{S}_{t+k+1}) \mid \mathbf{A}_t = \mathbf{a}, \mathbf{S}_t = \mathbf{s} \right].$$

- One possibility: at time  $t+k+1$ , update  $\theta$  using the prediction target

$$Y_t^k = \sum_{t'=t}^{t+k-1} \gamma^{t'-t} R_{t'} + \gamma^k Q_\pi(\mathbf{A}_{t+k}, \mathbf{S}_{t+k}).$$

- $k$ -step Sarsa: At time  $t+k$ , replace  $\theta$  by

$$\theta + \alpha \cdot \left( Y_t^k - Q_\pi(\mathbf{A}_t, \mathbf{S}_t; \theta) \right) \cdot \nabla_\theta Q_\pi(\mathbf{A}_t, \mathbf{S}_t; \theta).$$

## $TD(\lambda)$ algorithm

- Multi-step updates can result in faster learning.
- We can also weight the prediction targets for different numbers of steps, e.g. using weights  $\lambda^k$ :

$$Y_t^k = \sum_{t'=t}^{t+k} \gamma^{t'-t} R_{t'} + \gamma^{k+1} Q_{\pi}(A_{t+k+1}, S_{t+k+1}),$$
$$Y_t^{\lambda} = (1 - \lambda) \sum_{k=1}^{\infty} \lambda^k \cdot Y_t^k.$$

- But don't we have to wait forever before we can make an update based on  $Y_t^{\lambda}$ ?
- Note quite, since we can do the updating piece-wise!
- This idea leads to the so-called  $TD(\lambda)$  algorithm.



## Eligibility traces

- For  $TD(\lambda)$ , we proceed as for one-step Sarsa, using the prediction target

$$Y_t = R_t + \gamma \cdot Q_\pi(A_{t+1}, S_{t+1}; \theta).$$

- But we replace the gradient  $\nabla_\theta Q_\pi(A_t, S_t; \theta)$  by a weighted average of past gradients, the so-called eligibility trace: Let  $Z_0 = \mathbf{0}$  and

$$Z_t = \gamma\lambda \cdot Z_{t-1} + \nabla_\theta Q_\pi(A_t, S_t; \theta).$$

- Updating step: At time  $t$  replace  $\theta$  by

$$\theta + \alpha \cdot (Y_t - Q_\pi(A_t, S_t; \theta)) \cdot Z_t.$$

- This exactly implements the updating by  $Y_t^\lambda$  in the long run.
- This is one of the most popular and practically successful reinforcement learning algorithms.

# References

- *Sutton, R. S. and Barto, A. G. (2018). Reinforcement learning: An introduction. MIT press.*
- *François-Lavet, V., Henderson, P., Islam, R., Bellemare, M. G., and Pineau, J. (2018). An introduction to deep reinforcement learning. Foundations and Trends® in Machine Learning, 11(3-4):219–354.*