

CS 581 – ADVANCED ARTIFICIAL INTELLIGENCE

TOPIC: REINFORCEMENT LEARNING



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REFERENCES

- Reinforcement Learning – an Introduction
 - by Sutton & Barto
 - <http://incompleteideas.net/book/the-book-2nd.html>
- Introduction to RL lectures
 - by DeepMind; David Silver
 - <https://deepmind.com/learning-resources/-introduction-reinforcement-learning-david-silver>

REQUIRED BACKGROUND

○ MDPs

- Value function V , action-value function Q , policy π
- Bellman equations
- Value iteration
- Policy iteration

○ Multi-armed bandits

- Exploration vs exploitation trade-off
- ϵ -greedy approach

RL AND MDPs

- MDPs are building blocks for RL
- RL has the additional complexity that the agent does not have access to the full specification of the MDP. For e.g.,
 - Transition probabilities are often unknown
 - Reward function is often unknown

PREDICTION AND CONTROL

- Prediction
 - Given a policy, estimate the value function
- Control
 - Learn the optimal policy

MODEL-FREE VS MODEL-BASED

- Model-free:
 - The agent does not have and does not learn a model of the how the environment works
- Model-based:
 - The agent learns/improves a model of the environment
- Note: we are not talking about an approximate “model” of a state representation (such as DL for value estimations of states); rather, we mean model of the environment, such as transition probabilities

OUTLINE

- Prediction
 - Monte Carlo methods
 - Temporal-difference learning, specifically TD(0)
 - Unified view: TD(λ)
- Control
 - Monte Carlo methods
 - Temporal-difference learning
 - Sarsa, N-step TD, TD(λ)
 - Q-learning
- Approximate methods
 - MC prediction
 - TD prediction

MODEL-FREE PREDICTION

MONTÉ CARLO PREDICTION

- Task: prediction
 - Policy is given; compute the value functions
- Unknown environment dynamics
 - If the transition probabilities and the reward function were given, we could use the algorithms we saw earlier for complete MDPs
- Learn from *experience* – samples of episodes
- *Episode* is a sequence of state, action, reward triplets
- Assume all episodes reach a terminal state
- Basic idea: expectation = average over samples

MC PREDICTION – V

- Given a policy π
- Initialize $V(s)$ for all s
- Loop:
 - Sample an episode: $S_0, A_0, R_1, S_1, A_1, R_2, \dots, S_{T-1}, A_{T-1}, R_T$
 - For each state s in the episode, compute the cumulative discounted reward starting from that state s
- $V(s)$ is the average cumulative discounted reward starting from state s
- If s appears multiple times in a single episode (i.e., loops):
 - First-visit MC: for each episode, only the first appearance of the state s is considered
 - Every-visit MC: every appearance is considered and averaged accordingly
- Converges to the true values as the number of visits approach infinity

FIRST-VISIT MC PREDICTION

First-visit MC prediction, for estimating $V \approx v_\pi$

Input: a policy π to be evaluated

Initialize:

$V(s) \in \mathbb{R}$, arbitrarily, for all $s \in \mathcal{S}$

$Returns(s) \leftarrow$ an empty list, for all $s \in \mathcal{S}$

Loop forever (for each episode):

Generate an episode following π : $S_0, A_0, R_1, S_1, A_1, R_2, \dots, S_{T-1}, A_{T-1}, R_T$

$G \leftarrow 0$

Loop for each step of episode, $t = T-1, T-2, \dots, 0$:

$G \leftarrow \gamma G + R_{t+1}$

Unless S_t appears in S_0, S_1, \dots, S_{t-1} :

Append G to $Returns(S_t)$

$V(S_t) \leftarrow \text{average}(Returns(S_t))$

Figure from <http://incompleteideas.net/book/the-book-2nd.html>

MC PREDICTION – Q

- Given a policy π
- Initialize $Q(s, a)$ for all (s, a) pairs
- Loop:
 - Sample an episode: $S_0, A_0, R_1, S_1, A_1, R_2, \dots, S_{T-1}, A_{T-1}, R_T$
 - For each state (s, a) pair in the episode, compute the cumulative discounted reward starting from that state s and taking action a
- $Q(s, a)$ is the average cumulative discounted reward starting from state s and taking action a
- Advantage of estimating Q instead of V:
 - Can use Q values to find a better policy, i.e., for control
 - Caveat: we need to explore other actions to find a better one (remember the exploration vs exploitation trade-off)

INCREMENTAL UPDATE

- $\mu_{n+1} = \mu_n + \frac{1}{n+1} (x_{n+1} - \mu_n)$
- $\mu_{n+1} = \mu_n + \alpha (x_{n+1} - \mu_n)$
- Using a fixed α instead of $\frac{1}{n+1}$ allows us to handle non-stationary cases where the dynamics of the system changes
 - Recent experiences count more than earlier ones

MC UPDATE

- $G_t = R_{t+1} + \gamma R_{t+2} + \gamma^2 R_{t+3} + \dots + \gamma^{T-1} R_T$
- Average update
 - $V_t(S_t) = V_t(S_t) + \frac{1}{N(S_t)} (G_t - V_t(S_t))$
- Nonstationary update
 - $V_t(S_t) = V_t(S_t) + \alpha (G_t - V_t(S_t))$

TEMPORAL DIFFERENCE

- In MC, each episode had to end at a terminal state
- MC ignored the Bellman equations
- Can we learn from partial/incomplete episodes?
 - Yes, but we need estimates of the values
- The method we will use is called Temporal Difference (TD) learning

TD PREDICTION

- Given a policy π
- For an episode:
 - MC
 - $V(S_t) \leftarrow V(S_t) + \alpha[G_t - V(S_t)]$
 - Need to wait till the end to calculate G_t
 - TD: take one step and use Bellman equation
 - $V(S_t) \leftarrow V(S_t) + \alpha[R_{t+1} + \gamma V(S_{t+1}) - V(S_t)]$
- This is called TD(0) because it updates values based on a single look ahead

TD(0) PREDICTION

Tabular TD(0) for estimating v_π

Input: the policy π to be evaluated

Algorithm parameter: step size $\alpha \in (0, 1]$

Initialize $V(s)$, for all $s \in \mathcal{S}^+$, arbitrarily except that $V(\text{terminal}) = 0$

Loop for each episode:

 Initialize S

 Loop for each step of episode:

$A \leftarrow$ action given by π for S

 Take action A , observe R, S'

$V(S) \leftarrow V(S) + \alpha[R + \gamma V(S') - V(S)]$

$S \leftarrow S'$

 until S is terminal

Figure from <http://incompleteideas.net/book/the-book-2nd.html>

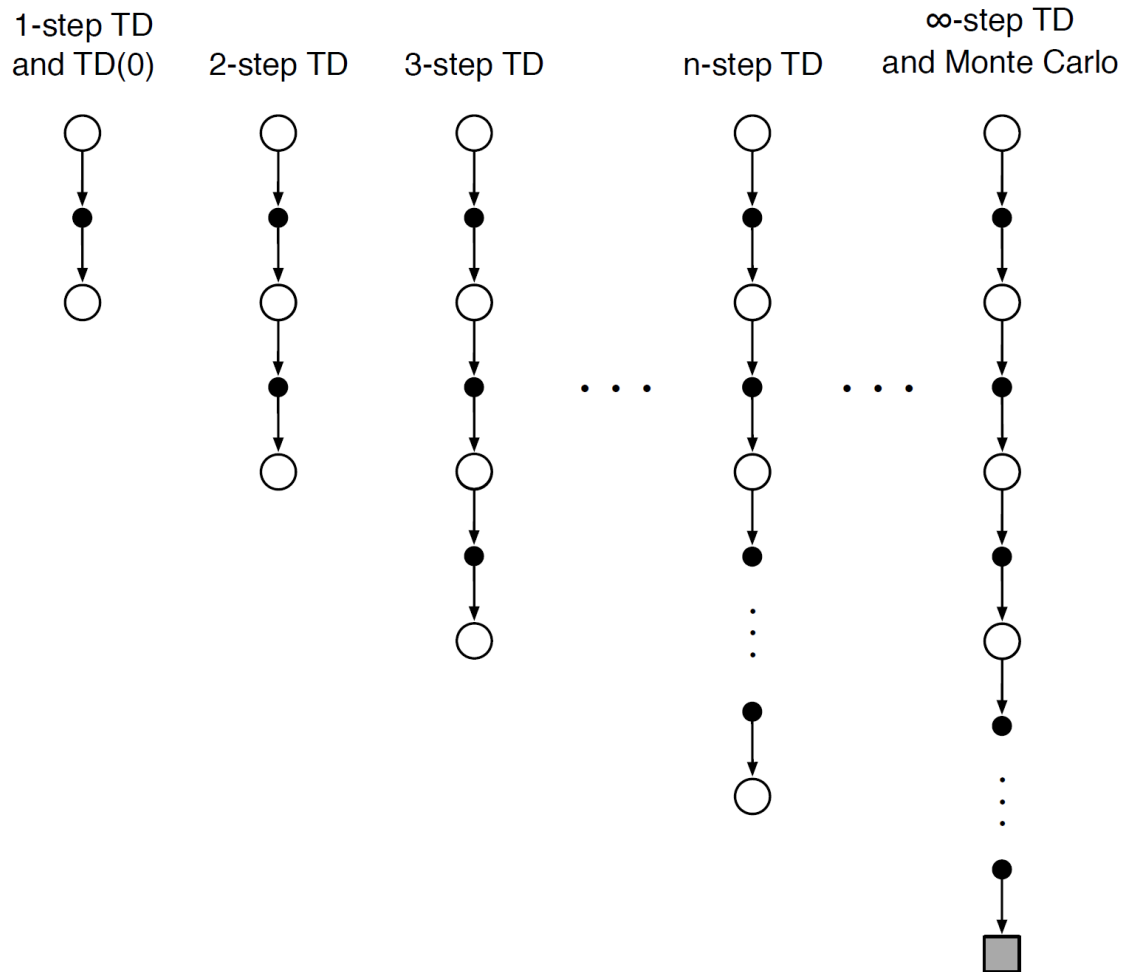
MC vs TD(0)

- Target
 - MC uses G_t ; TD(0) uses $R_{t+1} + \gamma V(S_{t+1})$
 - MC does not use the Bellman equations whereas TD(0) does
- Bootstrapping
 - MC does not need an initial estimate of V , whereas TD(0) bootstraps the V values
- Episodic vs continuing
 - MC updates the estimates after reaching the terminal state
 - TD(0) updates the estimates after each action
 - MC works on episodic tasks whereas TD(0) works for both episodic tasks and for continuing tasks
- Bias/Variance trade-off
 - MC estimate is unbiased but is high variance
 - TD(0) estimate is biased but is low variance
- Convergence
 - Both converge to the true values (in the simplest case of tabular state representation)
 - TD typically converges faster than MC

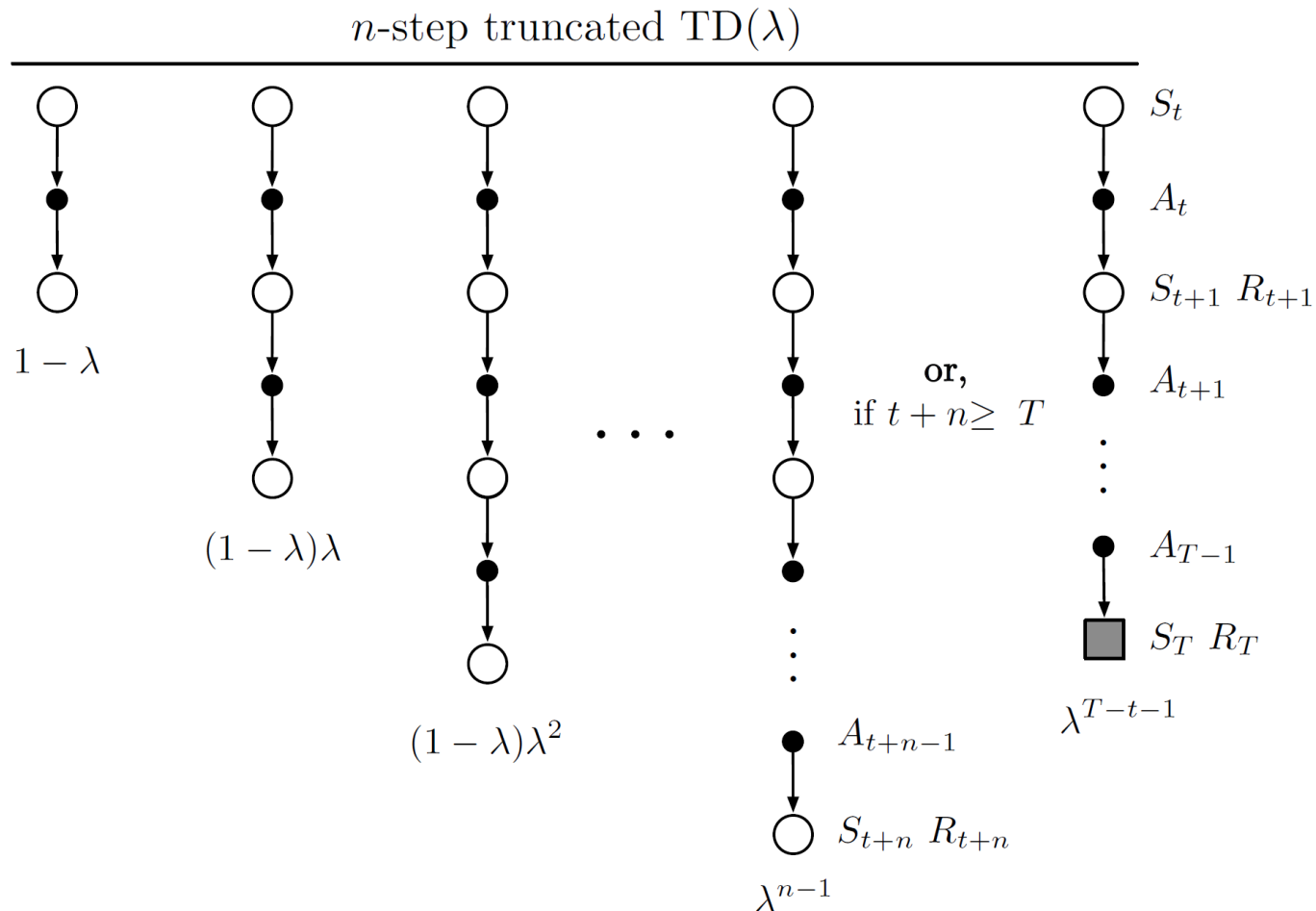
N-STEP TD

- TD(0) bootstraps the value functions and looks at one step in the future
- TD(n) is generalization that looks at $n+1$ steps to the future
- TD(∞) is equivalent to MC
- TD(λ) considers all steps with proper weighting

N-STEP TD



TD(λ)



MODEL-FREE CONTROL

ON-POLICY VS OFF-POLICY CONTROL

- On-policy control
 - The behavior/experience is generated by the same policy π that we are trying to improve
- Off-policy control
 - The behavior/experience is generated by a behavior policy b and we are trying to learn/improve policy π

ON-POLICY CONTROL

MC CONTROL

- Unlike prediction, we are not given a policy
- The environment dynamics are unknown
- The agent needs to find an optimal policy through experience
 - samples of episodes
- Can't we combine policy iteration of MDPs and MC sampling?
 - Yes, but
 - We need to learn a Q function; V function would not be useful because we do not have the transition function to read the policy from V values
 - We cannot sample from a deterministic policy; otherwise, the agent does not learn
 - We need to balance exploration vs exploitation
 - We will use ϵ -greedy approach
 - During sampling an episode:
 - With ϵ probability, choose a random action
 - Otherwise, choose the action recommended by the policy

MC CONTROL – PSEUDOCODE

- Initialize $Q(s, a)$ for all (s, a) pairs
- Initialize a policy π
- Loop:
 - Sample an episode: $S_0, A_0, R_1, S_1, A_1, R_2, \dots, S_{T-1}, A_{T-1}, R_T$
 - For choosing an action A_i at state S_i :
 - With ϵ probability, choose a random action
 - Otherwise, choose the action recommended by the current policy
 - For each state (s, a) pair in the episode, compute the cumulative discounted reward starting from that state s and taking action a
 - Update Q using the sample averages
 - Update π using the updated Q

TD CONTROL – SARSA

- Like MC Control, except we use the one step look ahead instead of waiting till the episode terminates
- $Q(S_t, A_t) \leftarrow Q(S_t, A_t) + \alpha[R_{t+1} + \gamma Q(S_{t+1}, A_{t+1}) - Q(S_t, A_t)]$
- Because we use $S_t, A_t, R_{t+1}, S_{t+1}, A_{t+1}$, this algorithm is also called SARSA
- Like MC Control, we need to introduce randomness into choosing actions, rather than strictly following a deterministic policy
 - Use ϵ -greedy approach

SARSA ALGORITHM

Sarsa (on-policy TD control) for estimating $Q \approx q_*$

Algorithm parameters: step size $\alpha \in (0, 1]$, small $\varepsilon > 0$

Initialize $Q(s, a)$, for all $s \in \mathcal{S}^+, a \in \mathcal{A}(s)$, arbitrarily except that $Q(\text{terminal}, \cdot) = 0$

Loop for each episode:

 Initialize S

 Choose A from S using policy derived from Q (e.g., ε -greedy)

 Loop for each step of episode:

 Take action A , observe R, S'

 Choose A' from S' using policy derived from Q (e.g., ε -greedy)

$Q(S, A) \leftarrow Q(S, A) + \alpha[R + \gamma Q(S', A') - Q(S, A)]$

$S \leftarrow S'; A \leftarrow A';$

 until S is terminal

Figure from <http://incompleteideas.net/book/the-book-2nd.html>

OFF-POLICY CONTROL

Q-LEARNING

Q-learning (off-policy TD control) for estimating $\pi \approx \pi_*$

Algorithm parameters: step size $\alpha \in (0, 1]$, small $\varepsilon > 0$

Initialize $Q(s, a)$, for all $s \in \mathcal{S}^+$, $a \in \mathcal{A}(s)$, arbitrarily except that $Q(\text{terminal}, \cdot) = 0$

Loop for each episode:

 Initialize S

 Loop for each step of episode:

 Choose A from S using policy derived from Q (e.g., ε -greedy)

 Take action A , observe R, S'

$Q(S, A) \leftarrow Q(S, A) + \alpha [R + \gamma \max_a Q(S', a) - Q(S, A)]$

$S \leftarrow S'$

 until S is terminal

Figure from <http://incompleteideas.net/book/the-book-2nd.html>

APPROXIMATE METHODS

$$s \begin{bmatrix} \cdot \\ \vdots \\ \cdot \end{bmatrix}$$

$$s \begin{bmatrix} \cdot & A \end{bmatrix}$$

- So far, we assumed we could represent the V and Q functions as tables
- This is unrealistic in real-world settings
- When the state and/or action space is large, we need to approximate the V and Q functions
- $v(s; \mathbf{w}) \approx v_{\pi}(s)$
 - \mathbf{w} can be the weights of linear model, a neural network, etc.
- A good/useful model allows one to generalize from one state to another
- We can use supervised learning methods, with some caveats
 - For e.g., the data is not stationary, the sequences in an episode are not i.i.d., etc.

PREDICTION

- MSVE = $\sum_s P(s)[v_\pi(s) - v(s; \mathbf{w})]^2$
- Gradient-based approach
 - $\mathbf{w}_{i+1} = \mathbf{w}_i - \frac{1}{2}\alpha \nabla [v_\pi(s) - v(s; \mathbf{w}_i)]^2$
 - $\mathbf{w}_{i+1} = \mathbf{w}_i - \alpha [v_\pi(s) - v(s; \mathbf{w})] \nabla v(s; \mathbf{w}_i)$
- Replace $v_\pi(s)$ with its MC or TD estimate

MC PREDICTION

Gradient Monte Carlo Algorithm for Estimating $\hat{v} \approx v_\pi$

Input: the policy π to be evaluated

Input: a differentiable function $\hat{v} : \mathcal{S} \times \mathbb{R}^d \rightarrow \mathbb{R}$

Algorithm parameter: step size $\alpha > 0$

Initialize value-function weights $\mathbf{w} \in \mathbb{R}^d$ arbitrarily (e.g., $\mathbf{w} = \mathbf{0}$)

Loop forever (for each episode):

 Generate an episode $S_0, A_0, R_1, S_1, A_1, \dots, R_T, S_T$ using π

 Loop for each step of episode, $t = 0, 1, \dots, T - 1$:

$\mathbf{w} \leftarrow \mathbf{w} + \alpha [G_t - \hat{v}(S_t, \mathbf{w})] \nabla \hat{v}(S_t, \mathbf{w})$

Figure from <http://incompleteideas.net/book/the-book-2nd.html>

TD PREDICTION

Semi-gradient TD(0) for estimating $\hat{v} \approx v_\pi$

Input: the policy π to be evaluated

Input: a differentiable function $\hat{v} : \mathcal{S}^+ \times \mathbb{R}^d \rightarrow \mathbb{R}$ such that $\hat{v}(\text{terminal}, \cdot) = 0$

Algorithm parameter: step size $\alpha > 0$

Initialize value-function weights $\mathbf{w} \in \mathbb{R}^d$ arbitrarily (e.g., $\mathbf{w} = \mathbf{0}$)

Loop for each episode:

 Initialize S

 Loop for each step of episode:

 Choose $A \sim \pi(\cdot|S)$

 Take action A , observe R, S'

$\mathbf{w} \leftarrow \mathbf{w} + \alpha [R + \gamma \hat{v}(S', \mathbf{w}) - \hat{v}(S, \mathbf{w})] \nabla \hat{v}(S, \mathbf{w})$

$S \leftarrow S'$

 until S is terminal

Figure from <http://incompleteideas.net/book/the-book-2nd.html>

OTHER TOPICS

- Control with approximate functions
 - Estimate the Q function instead of the V function
- Policy gradient methods
 - The policy is a parameterized function that can select actions without going indirectly through the value functions
- Eligibility traces
 - Efficient and iterative implementation of TD(n)
- Off policy learning
 - Two policies: a *target policy* – the policy being learned, and a *behavior policy* – the policy that generates the sequences