

CMPT 419/983: Theoretical Foundations of Reinforcement Learning

Lecture 6

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- We have studied algorithms (VI/PI/LP) that use knowledge of the transition probabilities \mathcal{P} and rewards r to compute the optimal policy.
- These quantities are difficult to obtain in practical scenarios, and hence we need methods that can compute the optimal policy without explicitly relying on this information.
- Today, we will consider evaluating a fixed policy π without explicit knowledge of \mathcal{P} and r .

Policy Evaluation

For a fixed policy π and starting state s_0 , $v^\pi(s_0) = \mathbb{E}[X|S_0 = s_0]$ where $X := \sum_{t=0}^{\infty} \gamma^t R_t$.

$$\begin{aligned}\mathbb{E}[X|S_0 = s_0] &= \mathbb{E}_{A_0|S_0} [\mathbb{E}[X|S_0 = s_0, A_0]] = \mathbb{E}_{A_0|S_0} [\mathbb{E}_{S_1|\{S_0, A_0\}} [\mathbb{E}[X|S_0 = s_0, A_0, S_1]]] \\ &\quad \text{(Using that } \mathbb{E}[X] = \mathbb{E}_Y[\mathbb{E}[X|Y]]\text{)} \\ &= \mathbb{E}_{A_0|S_0} \mathbb{E}_{S_1|\{S_0, A_0\}} \mathbb{E}_{A_1|\{S_0, A_0, S_1\}} \cdots \mathbb{E}_{S_t|\{S_0, A_0, \dots, S_{t-1}, A_{t-1}\}} \mathbb{E}[X|\{S_0, A_0, \dots, S_{t-1}, A_{t-1}\}] \\ &\quad \text{(Unrolling recursively)} \\ &= \mathbb{E}_{A_0|S_0} \mathbb{E}_{S_1|\{S_0, A_0\}} \mathbb{E}_{A_1|\{S_0, A_0, S_1\}} \cdots \mathbb{E}_{S_t|\{S_{t-1}, A_{t-1}\}} \mathbb{E}[X|\{S_0, A_0, \dots, S_{t-1}, A_{t-1}\}] \\ &\quad \text{(Markov assumption)} \\ &= \mathbb{E}_{A_0|S_0} \mathbb{E}_{S_1|\{S_0, A_0\}} \mathbb{E}_{A_1|S_1} \cdots \mathbb{E}_{S_t|\{S_{t-1}, A_{t-1}\}} \mathbb{E}[X|\{S_0, A_0, \dots, S_{t-1}\}] \\ &\quad \text{(Restricting to Markov policies)} \\ &= \mathbb{E}_{A_0|S_0} [R_0 + \mathbb{E}_{S_1|\{S_0, A_0\}} \mathbb{E}_{A_1|S_1} [\gamma R_1 + \cdots \mathbb{E}_{S_t|\{S_{t-1}, A_{t-1}\}} [\gamma^t R_t + \cdots]]] \\ &\quad \text{(Distributing the sum)}\end{aligned}$$

Policy Evaluation

The unrolling on the previous slide suggests a Monte-Carlo sampling scheme:

- Starting from s_0 , for $t \geq 0$, sample $a_t \sim \pi(\cdot|s_t)$, the environment transitions to s_{t+1} (equivalent to sampling $s_{t+1} \sim \mathcal{P}(\cdot|s_t, a_t)$). This generates a trajectory $\tau = (s_0, a_0, s_1, \dots)$.
- Collect rewards $r_t = r(s_t, a_t)$, calculate $R(\tau) = \sum_{t=0}^{\infty} \gamma^t r_t$. Note that $\mathbb{E}[R(\tau)] = v^\pi(s_0)$.
- In order to reduce the variance, generate m trajectories $\{\tau_i\}_{i=1}^m$, calculate $R(\tau_i)$ and output the empirical average: $\hat{v} := \frac{\sum_{i=1}^m R(\tau_i)}{m}$ as an approximation to $v^\pi(s_0)$.

Q: What is the problem with this approach?

Solution 1: Truncate the trajectory to H steps, i.e. calculate $R(\tau) = \sum_{t=0}^{H-1} \gamma^t r_t$.

$$\begin{aligned} R(\tau) &= \sum_{t=0}^{\infty} \gamma^t r_t - \sum_{t=H}^{\infty} \gamma^t r_t \implies \mathbb{E}[R(\tau)] = \mathbb{E} \left[\sum_{t=0}^{\infty} \gamma^t r_t \right] - \mathbb{E} \left[\sum_{t=H}^{\infty} \gamma^t r_t \right] = v^\pi(s_0) - \sum_{t=H}^{\infty} \gamma^t r_t \\ &\implies |v^\pi(s_0) - \mathbb{E}[R(\tau)]| \leq \frac{\gamma^H}{1-\gamma} \quad (r_t \leq 1, \text{ Sum of geometric series.}) \end{aligned}$$

Policy Evaluation

Claim: Using $m = \frac{\ln(2/\delta)}{2\epsilon^2(1-\gamma)^2}$ trajectories with $H \geq \frac{\ln(1/\epsilon(1-\gamma))}{\ln(1/\gamma)}$ guarantees that $|\hat{v} - v^\pi(s_0)| \leq \epsilon$ with probability $1 - \delta$.

Proof: Recall that $\hat{v} = \frac{\sum_{i=1}^m R(\tau_i)}{m}$.

$$\begin{aligned} |v^\pi(s_0) - \mathbb{E}[\hat{v}]| &= \left| v^\pi(s_0) - \frac{\sum_{i=1}^m \mathbb{E}[R(\tau_i)]}{m} \right| = \left| \frac{\sum_{i=1}^m [v^\pi(s_0) - \mathbb{E}[R(\tau_i)]]}{m} \right| \\ &\leq \frac{\sum_{i=1}^m |v^\pi(s_0) - \mathbb{E}[R(\tau_i)]|}{m} \leq \frac{\gamma^H}{1-\gamma} \\ |\hat{v} - v^\pi(s_0)| &= |\hat{v} - \mathbb{E}[\hat{v}] + \mathbb{E}[\hat{v}] - v^\pi(s_0)| \leq |\hat{v} - \mathbb{E}[\hat{v}]| + |\mathbb{E}[\hat{v}] - v^\pi(s_0)| \\ &\leq |\hat{v} - \mathbb{E}[\hat{v}]| + \frac{\gamma^H}{1-\gamma} \leq |\hat{v} - \mathbb{E}[\hat{v}]| + \frac{\epsilon}{2} \quad (\text{Using } H \geq \frac{\ln(1/\epsilon(1-\gamma))}{\ln(1/\gamma)}) \\ |\hat{v} - \mathbb{E}[\hat{v}]| &= \left| \frac{X_m - \mathbb{E}[X_m]}{m} \right| \quad (X_m := \sum_{i=1}^m R(\tau_i)) \end{aligned}$$

Since the $R(\tau_i)$ r.v's are i.i.d, we can use Hoeffding's inequality.

Policy Evaluation

Recall that $|\hat{v} - v^\pi(s_0)| \leq |\hat{v} - \mathbb{E}[\hat{v}]| + \frac{\epsilon}{2}$. Here, $|\hat{v} - \mathbb{E}[\hat{v}]| = \left| \frac{X_m - \mathbb{E}[X_m]}{m} \right|$ where $X_m := \sum_{i=1}^m R(\tau_i)$.

Hoeffding's Inequality: For m i.i.d. r.v's such that $X_i \in [a_i, b_i]$. For $t > 0$,

$$\Pr[|X_m - \mathbb{E}[X_m]| \geq t] \leq 2 \exp \left(\frac{-2t^2}{\sum_{i=1}^m (b_i - a_i)^2} \right)$$

$R(\tau_i) \in [0, 1/(1-\gamma)]$. Setting $t = m\epsilon$,

$$\begin{aligned} \Pr \left[\left| \frac{X_m - \mathbb{E}[X_m]}{m} \right| \geq \epsilon \right] &\leq 2 \exp(-2m\epsilon^2(1-\gamma)^2) \\ \implies \Pr \left[\left| \frac{X_m - \mathbb{E}[X_m]}{m} \right| \geq \epsilon \right] &\leq \delta \quad \left(\text{Setting } m = \frac{\ln(2/\delta)}{2\epsilon^2(1-\gamma)^2} \right) \end{aligned}$$

Putting everything together, with probability $1 - \delta$, $|\hat{v} - v^\pi(s_0)| \leq \epsilon$. \square

Solution 2: Randomly truncate the trajectory i.e. sample H from a geometric distribution with parameter $1 - \gamma$, return $R(\tau) = \sum_{t=0}^{H-1} r_t$. Eliminates the bias from using a fixed truncation.

Claim: $\mathbb{E}_H \mathbb{E}_\tau[R(\tau)] = v^\pi(s_0)$. Prove in Assignment 2!

- **Problem 1:** To estimate $v^\pi \in \mathbb{R}^S$, we need fresh trajectories for estimating $v^\pi(s)$ for each $s \in \mathcal{S}$. We need to restart the sampling each time, which may not always be possible.
- *Sol:* Sample a single trajectory, estimate $v^\pi(s)$ as the cumulative discounted sum of rewards following the first time state s is visited. This is referred to as “first visit” Monte-Carlo. Can also average the returns following “every visit” to state s . Both strategies can be shown to produce unbiased estimates of v^π . For more details, see [SB18, Chapter 5].
- If \hat{v}_k is the empirical average after sampling $k \in [1, m]$ trajectories, we can update it in an online fashion: $\hat{v}_k = \hat{v}_{k-1} + \frac{R(\tau_k) - \hat{v}_{k-1}}{k-1}$.
- **Problem 2:** Hence, \hat{v}_k is updated only after observing the rewards from the entire trajectory. This could be slow when the trajectories are long. Moreover, Monte-Carlo estimation does not exploit the MDP structure effectively.
- *Sol:* Temporal Difference Learning

Temporal Difference Learning

Idea: Exploit the Bellman equation and combine it with Monte-Carlo estimation.

Recall that, for starting state s , for a fixed policy π ,

$$\begin{aligned} v^\pi(s) &= \mathbf{r}_\pi(s) + \gamma \sum_{s'} \mathbf{P}_\pi[s, s'] v^\pi(s') = \sum_{a \in \mathcal{A}} r(s, a) \pi[a|s] + \gamma \sum_{s' \in \mathcal{S}} \sum_{a \in \mathcal{A}} \mathcal{P}[s'|s, a] \pi[a|s] v^\pi(s') \\ &= \sum_{a \in \mathcal{A}} \pi[a|s] \left[r(s, a) + \gamma \sum_{s' \in \mathcal{S}} \mathcal{P}[s'|s, a] v^\pi(s') \right] = \mathbb{E}_{a \sim \pi(\cdot|s)} [r(s, a) + \gamma \mathbb{E}_{s' \sim \mathcal{P}(\cdot|s, a)} [v^\pi(s')]] \\ \implies v^\pi(s) &= \mathbb{E}_{a \sim \pi(\cdot|s)} \mathbb{E}_{s' \sim \mathcal{P}(\cdot|s, a)} [r(s, a) + \gamma v^\pi(s')] \end{aligned}$$

Sampling a from $\pi(\cdot|s)$ and the environment samples $s' \sim \mathcal{P}(\cdot|s, a)$, $\hat{v}^\pi(s) = r(s, a) + \gamma v^\pi(s')$.

Since we do not know $v^\pi(s')$ either, we can use the estimate instead, implying that, $\hat{v}^\pi(s) = r(s, a) + \gamma \hat{v}^\pi(s')$. This is known as *bootstrapping* since we are using an estimate at s' to estimate the value function at state s .

Using this idea, we can design an iterative algorithm – TD(0).

Temporal Difference Learning

Algorithm Temporal Difference Learning. [TD(0)]

- 1: **Input:** MDP $M = (\mathcal{S}, \mathcal{A}, \rho)$, $v_0 = 0$, Policy π . Step-sizes $\{\alpha_t\}_{t=0}^{T-1}$.
 - 2: Sample state $s_0 \sim \rho$.
 - 3: **for** $t = 0 \rightarrow T - 1$ **do**
 - 4: Take action $a_t \sim \pi(\cdot | s_t)$, observe reward $r(s_t, a_t)$ and transition to state s_{t+1} .
 - 5: Update $v_{t+1}(s_t) = (1 - \alpha_t) v_t(s_t) + \alpha_t [r(s_t, a_t) + \gamma v_t(s_{t+1})]$.
 - 6: $\forall s \neq s_t, v_{t+1}(s) = v_t(s)$
 - 7: **end for**
-

- Unlike Monte-Carlo estimation, TD(0) does not require waiting until the end of trajectories to start updating the value function estimates.
- Unlike using \mathcal{T}_π , TD(0) does not require knowledge of \mathcal{P} and r .
- Under some technical assumptions, TD(0) will converge, i.e. $\lim_{t \rightarrow \infty} v_t = v^\pi$.
- TD(0) can handle linear function approximation and has non-asymptotic theoretical convergence guarantees. We will prove this next.

Linear Temporal Difference Learning

Linear TD(0)

Assumption: Have access to features $\Phi \in \mathbb{R}^{S \times d}$ such that for every policy π , there exists a $\theta \in \mathbb{R}^d$ such that $v^\pi = \Phi\theta$. For the specific policy π being evaluated, there exists a unique θ^* such that $v^\pi = \Phi\theta^* = v_{\theta^*}$ where $v_\theta := \Phi\theta$.

Define $\phi(s)$ as the feature vector corresponding to state s . Hence, $v_\theta(s) = \langle \phi(s), \theta \rangle$. For convenience, we will assume that $\forall s, \|\phi(s)\| \leq 1$.

Algorithm TD(0) with linear function approximation

- 1: **Input:** MDP $M = (\mathcal{S}, \mathcal{A}, \rho)$, Features $\Phi \in \mathbb{R}^{S \times d}$, Policy π . $\theta_0 \in \mathbb{R}^d$, Step-sizes $\{\alpha_t\}_{t=0}^{T-1}$.
 - 2: Sample state $s_0 \sim \rho$
 - 3: **for** $t = 0 \rightarrow T - 1$ **do**
 - 4: Take action $a_t \sim \pi(\cdot | s_t)$, observe reward $r(s_t, a_t)$ and transition to state s_{t+1} .
 - 5: Define $g_t(\theta) = [r_t + \gamma \langle \theta, \phi(s_{t+1}) \rangle - \langle \theta, \phi(s_t) \rangle] \phi(s_t)$
 - 6: Update $\theta_{t+1} = \theta_t + \alpha_t g_t(\theta_t)$
 - 7: **end for**
-

If $d = S$ and $\phi(s)$ correspond to one-hot vectors, then we recover TD(0) from the previous slide.

Linear TD(0) Analysis

The TD(0) update is $\theta_{t+1} = \theta_t + \alpha_t g_t(\theta)$ where $g_t(\theta) = [r_t + \gamma \langle \theta, \phi(s_{t+1}) \rangle - \langle \theta, \phi(s_t) \rangle] \phi(s_t)$.

Q: Could we use a Gradient Descent type analysis?

We will analyze Linear TD(0) in 4 steps:

- (1) Warmup: Analyze a hypothetical algorithm that performs GD on $f(\theta) := \frac{1}{2} \|v_{\theta^*} - v_{\theta}\|_D^2$.
- (2) Mean-path: Make an analogy between Linear TD(0) and GD, and analyze Linear TD(0) assuming access to the stationary distribution.
- (3) IID: Analyze Linear TD(0) assuming access to (s_t, s_{t+1}) sampled i.i.d from the stationary distribution.
- (4) Markovian: Analyze *Projected* Linear TD(0) assuming access to (s_t, s_{t+1}) that are gathered from a “fast-mixing” Markov chain (will not cover this in detail).

Linear TD(0) Analysis

Define $P(s'|s)$ to be the probability of transitioning from s to s' when acting according to π .

Assumption: The Markov chain induced by policy π is ergodic (can visit every state) with a unique stationary distribution $\omega \in \Delta_S$. For $s \in S$, $\omega(s) = \lim_{t \rightarrow \infty} \Pr[s_t = s]$. Hence, $\omega \mathbf{P}^\pi = \omega$ meaning that if $s \sim \omega$ and $s' \sim P(\cdot|s)$, then the marginal distribution of s' is ω .

Define a diagonal matrix $D \in \mathbb{R}^{S \times S}$ such that $D_{i,i} = \omega(i)$. For any $u, w \in \mathbb{R}^S$, define $\|u - w\|_D^2 = \sum_s \omega(s) [u(s) - w(s)]^2$.

For v_θ and $v_{\theta'}$, define $\Sigma := \sum_s \omega(s) \phi(s) \phi(s)^T \in \mathbb{R}^{d \times d}$ and $\lambda := \lambda_{\min}[\Sigma]$.

$$\begin{aligned} \|v_\theta - v_{\theta'}\|_D^2 &= \sum_s \omega(s) [v_\theta(s) - v_{\theta'}(s)]^2 = \sum_s \omega(s) [\langle \phi(s), \theta - \theta' \rangle]^2 \\ &= (\theta - \theta')^T \sum_s \omega(s) \phi(s) \phi(s)^T (\theta - \theta') = \|\theta - \theta'\|_\Sigma^2 \end{aligned}$$

Q: Prove that $\lambda_{\max}[\Sigma] \leq 1$

Hence, for any θ , $\sqrt{\lambda} \|\theta\| \leq \|v_\theta\|_D \leq \|\theta\|$ (by setting $\theta' = 0$ above).

Linear TD(0) Analysis – Warmup

Define $f(\theta) := \frac{1}{2} \|v_{\theta^*} - v_{\theta}\|_D^2 = \frac{1}{2} \|\theta^* - \theta\|_{\Sigma}^2$. Consider a hypothetical algorithm that performs GD on $f(\theta)$ i.e. at iteration t , $\theta_{t+1} = \theta_t - \alpha \nabla f(\theta_t)$. Note that $\nabla f(\theta) = \Sigma(\theta - \theta^*)$.

$$\begin{aligned}\|\theta_{t+1} - \theta^*\|^2 &= \|\theta_t - \alpha \nabla f(\theta_t) - \theta^*\|^2 = \|\theta_t - \theta^*\|^2 + 2\alpha \langle \nabla f(\theta_t), \theta^* - \theta_t \rangle + \alpha^2 \|\nabla f(\theta_t)\|^2 \\ \langle \nabla f(\theta_t), \theta^* - \theta_t \rangle &= \langle \Sigma(\theta_t - \theta^*), \theta^* - \theta_t \rangle = -\|\theta_t - \theta^*\|_{\Sigma}^2 = -\|v_{\theta_t} - v_{\theta^*}\|_D^2\end{aligned}$$

For any vector u s.t. $\|u\| \leq 1$,

$$\langle u, \nabla f(\theta) \rangle = \langle u, \Sigma(\theta - \theta^*) \rangle \leq \left\| \Sigma^{1/2} u \right\| \left\| \Sigma^{1/2} (\theta - \theta^*) \right\| \quad (\text{Cauchy Schwarz})$$

$$= \|u\|_{\Sigma} \|\theta - \theta^*\|_{\Sigma} \leq \lambda_{\max}[\Sigma] \|u\| \|\theta - \theta^*\|_{\Sigma} \leq \|v_{\theta} - v_{\theta^*}\|_D \quad (\lambda_{\max}[\Sigma] \leq 1, \|u\| \leq 1)$$

$$\implies \|\nabla f(\theta)\|^2 \leq \|v_{\theta} - v_{\theta^*}\|_D^2 \quad (\text{Setting } u = \nabla f(\theta) / \|\nabla f(\theta)\|)$$

$$\implies \|\theta_{t+1} - \theta^*\|^2 \leq \|\theta_t - \theta^*\|^2 - 2\alpha \|v_{\theta_t} - v_{\theta^*}\|_D^2 + \alpha^2 \|v_{\theta_t} - v_{\theta^*}\|_D^2$$

$$\|\theta_{t+1} - \theta^*\|^2 \leq \|\theta_t - \theta^*\|^2 - \|v_{\theta_t} - v_{\theta^*}\|_D^2 \leq (1 - \lambda) \|\theta_t - \theta^*\|^2 \quad (\text{Set } \alpha = 1, \lambda = \lambda_{\min}[\Sigma])$$

$$\implies \|\theta_T - \theta^*\|^2 \leq (1 - \lambda)^T \|\theta_0 - \theta^*\|^2 \quad (\text{Recurring from } t = 0 \text{ to } T - 1)$$

Linear TD(0) Analysis – Mean-path

The previous analysis relied on bounding two key quantities: (i) $\langle \nabla f(\theta_t), \theta^* - \theta_t \rangle$ and (ii) $\|\nabla f(\theta)\|^2$. We now consider analyzing Mean-path TD. For this, define $\bar{g}(\theta)$ and the corresponding update as:

$$\begin{aligned}\bar{g}(\theta) &:= \mathbb{E}_{s \sim \omega} \mathbb{E}_{s' \sim P(\cdot|s)} [r(s, \pi(s)) + \gamma \langle \theta, \phi(s') \rangle - \langle \theta, \phi(s) \rangle] \phi(s) \\ \theta_{t+1} &= \theta_t + \alpha \bar{g}(\theta)\end{aligned}$$

- Intuitively, $\bar{g}(\theta)$ is the Linear TD update in expectation if s was sampled from the stationary distribution, and the Markov chain transitioned to s' .
- Importantly, recall that the marginal distribution of s' is the stationary distribution ω .
- If \mathcal{T}_π is the policy evaluation operator for π , then, $\bar{g}(\theta) = \Phi^T D [\mathcal{T}_\pi \Phi \theta - \Phi \theta]$ (Prove in Assignment 3!).

Similar to the warm-up, we will show two important properties for $\bar{g}(\theta)$. For all θ ,

- (1) $\langle \bar{g}(\theta), \theta^* - \theta \rangle \geq (1 - \gamma) \|\mathbf{v}_\theta - \mathbf{v}_{\theta^*}\|_D^2$
- (2) $\|\bar{g}(\theta)\| \leq 2\sqrt{2} \|\mathbf{v}_\theta - \mathbf{v}_{\theta^*}\|_D$

Linear TD(0) Analysis – Mean-path

Claim: $\langle \bar{g}(\theta), \theta^* - \theta \rangle \geq (1 - \gamma) \|v_\theta - v_{\theta^*}\|_D^2$.

Proof: Since $\bar{g}(\theta) = \Phi^T D [\mathcal{T}_\pi \Phi \theta - \Phi \theta]$, using the definition of θ^* ,
 $\bar{g}(\theta^*) = \Phi^T D [\mathcal{T}_\pi \Phi \theta^* - \Phi \theta^*] = \Phi^T D [\mathcal{T}_\pi v^\pi - v^\pi] = 0$. Hence,

$$\begin{aligned}\bar{g}(\theta) &= \bar{g}(\theta) - \bar{g}(\theta^*) \\ &= \mathbb{E}_{s,s'} [[(r(s, \pi(s)) + \gamma \langle \theta, \phi(s') \rangle - \langle \theta, \phi(s) \rangle) - (r(s, \pi(s)) + \gamma \langle \theta^*, \phi(s') \rangle - \langle \theta^*, \phi(s) \rangle)] \phi(s)] \\ &= \mathbb{E}_{s,s'} [(\langle \phi(s), \theta^* - \theta \rangle - \gamma \langle \phi(s'), \theta^* - \theta \rangle) \phi(s)]\end{aligned}$$

Define $\zeta_s := \langle \theta^* - \theta, \phi(s) \rangle$ and $\zeta_{s'} := \langle \theta^* - \theta, \phi(s') \rangle$

$$\implies \bar{g}(\theta) = \mathbb{E}_{s,s'} [(\zeta_s - \gamma \zeta_{s'}) \phi(s)]$$

$$\begin{aligned}\langle \bar{g}(\theta), \theta^* - \theta \rangle &= \langle \mathbb{E}_{s,s'} [(\zeta_s - \gamma \zeta_{s'}) \phi(s)], \theta^* - \theta \rangle = \mathbb{E}_{s,s'} [(\zeta_s - \gamma \zeta_{s'}) \langle \phi(s), \theta^* - \theta \rangle] \\ &= \mathbb{E}_{s,s'} [(\zeta_s - \gamma \zeta_{s'}) \zeta_s] = \mathbb{E}_{s,s'} [\zeta_s^2 - \gamma \zeta_{s'} \zeta_s]\end{aligned}$$

$$\implies \langle \bar{g}(\theta), \theta^* - \theta \rangle = \mathbb{E}_{s \sim \omega} \mathbb{E}[\zeta_s^2] - \gamma \mathbb{E}_{s \sim \omega, s' \sim P(\cdot|s)} [\zeta_{s'} \zeta_s]$$

Linear TD(0) Analysis – Mean-path

Recall that $\langle \bar{g}(\theta), \theta^* - \theta \rangle = \mathbb{E}_{s \sim \omega} \mathbb{E}[\zeta_s^2] - \gamma \mathbb{E}_{s \sim \omega, s' \sim P(\cdot|s)} [\zeta_{s'} \zeta_s]$ where $\zeta_s := \langle \theta^* - \theta, \phi(s) \rangle$.

$$\begin{aligned} \langle \bar{g}(\theta), \theta^* - \theta \rangle &= \mathbb{E}_{s \sim \omega} [\zeta_s^2] - \gamma \mathbb{E}_{s \sim \omega, s' \sim P(\cdot|s)} [\zeta_{s'} \zeta_s] \\ &\geq \mathbb{E}_{s \sim \omega} \mathbb{E}[\zeta_s^2] - \gamma \sqrt{\mathbb{E}_{s \sim \omega, s' \sim P(\cdot|s)} [\zeta_s^2]} \sqrt{\mathbb{E}_{s \sim \omega, s' \sim P(\cdot|s)} [\zeta_{s'}^2]} \\ &\hspace{25em} \text{(Cauchy Schwarz)} \end{aligned}$$

$$= \mathbb{E}_{s \sim \omega} [\zeta_s^2] - \gamma \sqrt{\mathbb{E}_{s \sim \omega} [\zeta_s^2]} \sqrt{\mathbb{E}_{s' \sim \omega} [\zeta_{s'}^2]} \quad (\omega \text{ is the stationary distribution})$$

$$= (1 - \gamma) \mathbb{E}_{s \sim \omega} [\zeta_s^2] = (1 - \gamma) \sum_s \omega(s) \zeta^2(s)$$

$$= (1 - \gamma) \sum_s \omega(s) (\theta^* - \theta)^T \phi(s) \phi(s)^T (\theta^* - \theta) \quad \text{(By def. of } \zeta_s \text{)}$$

$$= (1 - \gamma) \|\theta - \theta^*\|_{\Sigma}^2 \quad \text{(By def. of } \Sigma \text{)}$$

$$\implies \langle \bar{g}(\theta), \theta^* - \theta \rangle \geq (1 - \gamma) \|\nu_{\theta} - \nu_{\theta^*}\|_D^2 \quad \square \quad \text{(Since } \|\theta - \theta^*\|_{\Sigma} = \|\nu_{\theta} - \nu_{\theta^*}\|_D \text{)}$$

Linear TD(0) Analysis – Mean-path

Claim: $\|\bar{g}(\theta)\| \leq 2\sqrt{2} \|v_\theta - v_{\theta^*}\|_D$.

Proof: Since $\bar{g}(\theta) = \mathbb{E}_{s,s'} [(\zeta_s - \gamma\zeta_{s'}) \phi(s)]$,

$$\|\bar{g}(\theta)\| = \|\mathbb{E}_{s,s'} [(\zeta_s - \gamma\zeta_{s'}) \phi(s)]\| \leq \mathbb{E}_{s,s'} \|[(\zeta_s - \gamma\zeta_{s'}) \phi(s)]\| \quad (\text{Jensen's inequality})$$

$$= \mathbb{E}_{s,s'} [|\zeta_s - \gamma\zeta_{s'}| \|\phi(s)\|] \leq \sqrt{\mathbb{E}[(\zeta_s - \gamma\zeta_{s'})^2]} \sqrt{\mathbb{E}[\|\phi(s)\|^2]} \quad (\text{Cauchy Schwarz})$$

$$\leq \sqrt{\mathbb{E}[(\zeta_s - \gamma\zeta_{s'})^2]} \quad (\text{Since } \|\phi(s)\| \leq 1)$$

$$\leq \sqrt{2} \sqrt{\mathbb{E}[\zeta_s^2 + \gamma^2 \zeta_{s'}^2]} \leq \sqrt{2} \sqrt{\mathbb{E}_{s \sim \omega}[\zeta_s^2]} + \sqrt{2} \sqrt{\gamma^2 \mathbb{E}_{s \sim \omega, s' \sim P(\cdot|s)}[\zeta_{s'}^2]}$$

$$(\text{Since } (a+b)^2 \leq 2(a^2 + b^2) \text{ and } \sqrt{a+b} \leq \sqrt{a} + \sqrt{b} \text{ for all } a \geq 0, b \geq 0)$$

$$= \sqrt{2} \sqrt{\mathbb{E}_{s \sim \omega}[\zeta_s^2]} + \sqrt{2} \gamma \sqrt{\mathbb{E}_{s' \sim \omega}[\zeta_{s'}^2]} = \sqrt{2} (1 + \gamma) \sqrt{\mathbb{E}[\zeta_s^2]}$$

$$(\text{Since } \omega \text{ is the stationary distribution})$$

$$\leq 2\sqrt{2} \sqrt{\mathbb{E}[\zeta_s^2]} \quad (\text{Since } 1 + \gamma < 2)$$

$$\implies \|\bar{g}(\theta)\| \leq 2\sqrt{2} \|v_\theta - v_{\theta^*}\|_D \quad \square \quad (\text{Using the bound on } \mathbb{E}[\zeta_s^2])$$

Linear TD(0) Analysis – Mean-path

Claim: $\|\theta_T - \theta^*\|^2 \leq \left(1 - \frac{(1-\gamma)^2 \lambda}{8}\right)^T \|\theta_0 - \theta^*\|^2$.

Proof: We have proven (1) $\langle \bar{g}(\theta), \theta^* - \theta \rangle \geq (1-\gamma) \|v_\theta - v_{\theta^*}\|_D^2$ and (2) $\|\bar{g}(\theta)\| \leq 2\sqrt{2} \|v_\theta - v_{\theta^*}\|_D$.

$$\begin{aligned} \|\theta_{t+1} - \theta^*\|^2 &= \|\theta_t + \alpha \bar{g}(\theta) - \theta^*\|^2 = \|\theta_t - \theta^*\|^2 + 2\alpha \langle \bar{g}(\theta_t), \theta_t - \theta^* \rangle + \alpha^2 \|\bar{g}(\theta_t)\|^2 \\ &\leq \|\theta_t - \theta^*\|^2 - 2\alpha(1-\gamma) \|v_{\theta_t} - v_{\theta^*}\|_D^2 + 8\alpha^2 \|v_{\theta_t} - v_{\theta^*}\|_D^2 \\ &\leq \|\theta_t - \theta^*\|^2 - \frac{(1-\gamma)^2}{8} \|v_{\theta_t} - v_{\theta^*}\|_D^2 \quad (\text{Setting } \alpha = \frac{1-\gamma}{8}) \\ &= \|\theta_t - \theta^*\|^2 - \frac{(1-\gamma)^2}{8} \|\theta_t - \theta^*\|_\Sigma^2 \quad (\text{Since } \|v_\theta - v_{\theta^*}\|_D^2 = \|\theta - \theta^*\|_\Sigma^2) \\ &\leq \|\theta_t - \theta^*\|^2 - \lambda_{\min}[\Sigma] \frac{(1-\gamma)^2}{8} \|\theta_t - \theta^*\|^2 \\ \|\theta_{t+1} - \theta^*\|^2 &\leq \left(1 - \frac{(1-\gamma)^2 \lambda}{8}\right) \|\theta_t - \theta^*\|^2 \quad (\text{Since } \lambda = \lambda_{\min}[\Sigma]) \\ \implies \|\theta_T - \theta^*\|^2 &\leq \left(1 - \frac{(1-\gamma)^2 \lambda}{8}\right)^T \|\theta_0 - \theta^*\|^2 \quad \square \quad (\text{Recurring from } t = 0 \text{ to } T-1) \end{aligned}$$

Linear TD(0) Analysis – IID

The previous analysis requires $\bar{g}(\theta) = \mathbb{E}_{s \sim \omega} \mathbb{E}_{s' \sim P(\cdot|s)} [r(s, \pi(s)) + \gamma \langle \theta, \phi(s') \rangle - \langle \theta, \phi(s) \rangle] \phi(s)$.

Since we do not have access to the expectation, we will adapt the previous proof.

We will assume that (s_t, s_{t+1}) are sampled i.i.d. from the stationary distribution, i.e. $s_t \sim \omega$ and $s_{t+1} \sim P(\cdot|s_t) \implies \Pr[s_t = s, s_{t+1} = s'] = \omega(s) P(s'|s)$. Hence, taking the expectation over the randomness in s_t, s_{t+1} , we have that for all t and θ ,

$$\begin{aligned} \mathbb{E}[g_t(\theta)] &= \mathbb{E}_{s_t, s_{t+1}} [[r(s_t, \pi(s_t)) + \gamma \langle \theta, \phi(s_{t+1}) \rangle - \langle \theta, \phi(s_t) \rangle] \phi(s_t)] \\ &= \sum_{s, s'} [r(s, \pi(s)) + \gamma \langle \theta, \phi(s') \rangle - \langle \theta, \phi(s) \rangle] \phi(s) \Pr[s_t = s, s_{t+1} = s'] = \bar{g}(\theta) \end{aligned}$$

Similar to the previous proofs, we will rely on two important properties for $g_t(\theta)$. For a fixed t and θ independent of the randomness in (s_t, s_{t+1}) ,

- (1) $\mathbb{E}[\langle g_t(\theta), \theta^* - \theta \rangle] = \langle \bar{g}(\theta), \theta^* - \theta \rangle \geq (1 - \gamma) \|v_\theta - v_{\theta^*}\|_D^2$.
- (2) $\mathbb{E}[\|g_t(\theta)\|^2] \leq 2\sigma^2 + 8 \|v_\theta - v_{\theta^*}\|_D^2$ where $\sigma^2 := \mathbb{E}_{s_t, s_{t+1}} \|g_t(\theta^*)\|^2$ is the variance in $g_t(\theta^*)$.

(Prove in Assignment 3!)

Linear TD(0) Analysis – IID

Claim: Assuming (s_t, s_{t+1}) are sampled i.i.d from the stationary distribution, the update $\theta_{t+1} = \theta_t + \alpha_t g_t(\theta)$ with $\alpha_t = \frac{1-\gamma}{8\sqrt{T}}$ has the following convergence,

$$\mathbb{E} \|v_{\bar{\theta}_T} - v_{\theta^*}\|_D^2 \leq \frac{8 \|\theta_0 - \theta^*\|^2}{(1-\gamma)^2 \sqrt{T}} + \frac{\sigma^2}{4\sqrt{T}},$$

where the expectation is w.r.t. $\{s_t, s_{t+1}\}_{t=0}^{T-1}$ and $\bar{\theta}_T := \frac{\sum_{t=0}^{T-1} \theta_t}{T}$ is the average iterate.

Proof: We have proved that (1) $\mathbb{E}[\langle g_t(\theta), \theta^* - \theta \rangle] \geq (1-\gamma) \|v_\theta - v_{\theta^*}\|_D^2$ and (2) $\mathbb{E}[\|g_t(\theta)\|^2] \leq 2\sigma^2 + 8 \|v_\theta - v_{\theta^*}\|_D^2$. Proceeding similar to the previous proof,

$$\|\theta_{t+1} - \theta^*\|^2 = \|\theta_t - \theta^*\|^2 + 2\alpha_t \langle g_t(\theta_t), \theta_t - \theta^* \rangle + \alpha_t^2 \|g_t(\theta)\|^2$$

Taking expectation w.r.t the randomness at iteration t

$$\begin{aligned} \mathbb{E} \|\theta_{t+1} - \theta^*\|^2 &= \|\theta_t - \theta^*\|^2 + 2\alpha_t \mathbb{E}[\langle g_t(\theta_t), \theta_t - \theta^* \rangle] + \alpha_t^2 \mathbb{E} \|g_t(\theta)\|^2 \\ &\leq \|\theta_t - \theta^*\|^2 - 2\alpha_t (1-\gamma) \|v_{\theta_t} - v_{\theta^*}\|_D^2 + \alpha_t^2 \mathbb{E} \|g_t(\theta)\|^2 \\ &\quad \text{(Using Property (1))} \end{aligned}$$

Linear TD(0) Analysis – IID

We have shown that $\mathbb{E} \|\theta_{t+1} - \theta^*\|^2 \leq \|\theta_t - \theta^*\|^2 - 2\alpha_t (1 - \gamma) \|\nu_{\theta_t} - \nu_{\theta^*}\|_D^2 + \alpha_t^2 \mathbb{E} \|g_t(\theta)\|^2$. Using Property (2),

$$\begin{aligned} \mathbb{E} \|\theta_{t+1} - \theta^*\|^2 &\leq \|\theta_t - \theta^*\|^2 - 2\alpha_t (1 - \gamma) \|\nu_{\theta_t} - \nu_{\theta^*}\|_D^2 + \alpha_t^2 \left[2\sigma^2 + 8 \|\nu_{\theta_t} - \nu_{\theta^*}\|_D^2 \right] \\ &\leq \|\theta_t - \theta^*\|^2 - \alpha_t (1 - \gamma) \|\nu_{\theta_t} - \nu_{\theta^*}\|_D^2 + 2\alpha_t^2 \sigma^2 \quad (\text{For } \alpha_t \leq \frac{1-\gamma}{8}) \\ \implies (1 - \gamma) \|\nu_{\theta_t} - \nu_{\theta^*}\|_D^2 &\leq \frac{\mathbb{E}[\|\theta_t - \theta^*\|^2 - \|\theta_{t+1} - \theta^*\|^2]}{\alpha_t} + 2\alpha_t \sigma^2 \end{aligned}$$

Using constant step-size $\alpha_t = \frac{1-\gamma}{8\sqrt{T}}$, and taking expectation w.r.t the randomness in iterations 0 to $T - 1$,

$$\begin{aligned} (1 - \gamma) \mathbb{E} \|\nu_{\theta_t} - \nu_{\theta^*}\|_D^2 &\leq \mathbb{E} \left[\frac{\|\theta_t - \theta^*\|^2 - \|\theta_{t+1} - \theta^*\|^2}{\alpha_t} \right] + 2\alpha_t \sigma^2 \\ &\leq \frac{8\sqrt{T}}{1 - \gamma} \mathbb{E} [\|\theta_t - \theta^*\|^2 - \|\theta_{t+1} - \theta^*\|^2] + \frac{\sigma^2 (1 - \gamma)}{4\sqrt{T}} \end{aligned}$$

Linear TD(0) Analysis – IID

Recall $(1 - \gamma) \mathbb{E} \|v_{\theta_t} - v_{\theta^*}\|_D^2 \leq \frac{8\sqrt{T}}{1-\gamma} \mathbb{E} [\|\theta_t - \theta^*\|^2 - \|\theta_{t+1} - \theta^*\|^2] + \frac{\sigma^2(1-\gamma)}{4\sqrt{T}}$. Summing from $t = 0$ to $T - 1$,

$$\begin{aligned} (1 - \gamma) \sum_{t=0}^{T-1} \mathbb{E} \|v_{\theta_t} - v_{\theta^*}\|_D^2 &\leq \frac{8\sqrt{T}}{1 - \gamma} \|\theta_0 - \theta^*\|^2 + \frac{\sigma^2(1 - \gamma) \sqrt{T}}{4} \\ \implies \frac{\sum_{t=0}^{T-1} \mathbb{E} \|v_{\theta_t} - v_{\theta^*}\|_D^2}{T} &\leq \frac{8 \|\theta_0 - \theta^*\|^2}{(1 - \gamma)^2 \sqrt{T}} + \frac{\sigma^2}{4\sqrt{T}} \quad (\text{Dividing by } (1 - \gamma) T) \end{aligned}$$

Using Jensen's inequality,

$$\mathbb{E} \|v_{\bar{\theta}_T} - v_{\theta^*}\|_D^2 \leq \frac{8 \|\theta_0 - \theta^*\|^2}{(1 - \gamma)^2 \sqrt{T}} + \frac{\sigma^2}{4\sqrt{T}} \quad \square$$

By using more complicated step-size sequences, we can also show convergence for the last-iterate θ_T (similar to the previous proofs).

Linear TD(0) Analysis – Markovian

The previous analysis assumes that (s_t, s_{t+1}) are sampled i.i.d from the stationary distribution. However, (s_t, s_{t+1}) are gathered from a single trajectory of the Markov chain induced by policy π . Hence, the samples are correlated and assuming that they are i.i.d is not valid. However, under certain standard assumptions, we can adapt the previous proof.

Assumption: The underlying Markov chain is “fast-mixing” i.e. for constants $m > 0$ and $\rho \in (0, 1)$, and all t , if $\text{TV}(P, Q)$ is the total variation distance between distributions P, Q , then,

$$\sup_s \text{TV}(\text{Pr}^\pi[s_t | s_0 = s], \omega) \leq m \rho^t$$

i.e. the distribution over states approaches the stationary distribution exponentially fast.

Define $\tau_{\text{mix}}(\epsilon) = \min\{t | \rho^t \leq \epsilon\}$ as the mixing time of the Markov chain.



Linear TD(0) Analysis – Markovian

Projected linear TD(0) update: $\theta_{t+1} = \text{Proj} [\theta_{t+1} + \alpha_t g_t(\theta)]$. The projection is onto the ball $\mathcal{B} = \{\theta \mid \|\theta\| \leq R\}$ where R is an upper-bound on $\|\theta^*\|$.

Claim: Assuming fast-mixing of the underlying Markov chain, Projected linear TD(0) with $\alpha_t = \frac{1}{\sqrt{t}}$ has the following convergence:

$$\mathbb{E} \|\nu_{\bar{\theta}_T} - \nu_{\theta^*}\|_D^2 \leq O \left(\frac{\|\theta_0 - \theta^*\|^2}{\sqrt{T}} + \frac{(1 + 2R)^2 (1 + \tau_{\text{mix}}(1/\sqrt{T}))}{\sqrt{T}} \right).$$

- Intuitively, every cycle of $\tau_{\text{mix}}(\cdot)$ samples provides as much information as a single independent sample from the stationary distribution.
- If (s_t, s_{t+1}) were sampled i.i.d. from ω , $\tau_{\text{mix}}(\cdot) = 0$ and we would obtain the IID result.
- The proof is similar to the i.i.d case except that it needs to carefully handle correlations and bound $\mathbb{E} [\langle g_t(\theta_t) - \bar{g}(\theta_t), \theta_t - \theta^* \rangle] \neq 0$.
- For more details, refer to [BRS18, Section 8].

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