Planning in MDPs

Sham Kakade and Kianté Brantley

CS 2824: Foundations of Reinforcement Learning

Announcements

- The first **reading assignmen**t is out, and it is due on Feb 4th at 23:59

- **Office Hours:**
  - Tuesday 3-4 PM (Lukas)
  - Wednesday 1-2 PM (Jay)
  - Thursday 2:15-3:15 PM (Alex)

Recap: Value iteration

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Q: when will π^t be the optimal policy?

Outline

1. Policy Iteration

2. Computation complexity of VI and PI

3. Linear Programming formulation

Policy Iteration Algorithm:

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Policy Iteration Algorithm:

Closed-form for PE
(see 1.1.3 in Monograph)

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Analysis of Policy Iteration

Recall: Policy Improvement $\pi^{t+1}(s) = \arg\max_a Q^{\pi^t}(s,a), \forall s$

Lemma: Monotonic improvement $Q^{\pi^{t+1}}(s,a) \geq Q^{\pi^t}(s,a), \forall s, a$

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$$V^{\pi^{t+1}}(s) \geq V^{\pi^t}(s), \forall s$$

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$$\leq \gamma \|V^\star - V^{\pi^t}\|_\infty$$

Analysis of Policy Iteration

Q: what happens when π^{t+1} and π^t are exactly the same?

Show that π^t is an optimal policy $\pi^\star$

Q: does this imply that the algorithm will terminate?

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3. Linear Programming formulation

Computation complexity of VI and PI

Given an MDP $\mathscr{M} = (S, A, P, r, \gamma)$ can we exactly compute $Q^\star$ (or find $\pi^\star$) in time polynomial wrt $S, A, 1/(1-\gamma)$?

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What about poly(S, A) algs?

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The primal linear programming

Recall the Bellman consistency:

$$V(s) = \max_a \left\{ r(s,a) + \gamma \mathbb{E}_{s' \sim P(\cdot|s,a)} \left[V(s) \right] \right\}, \forall s$$

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s.t. $V(s) \geq \max_a \left[r(s,a) + \gamma \mathbb{E}_{s' \sim P(\cdot|s,a)} V(s') \right] \quad \forall s \in S$

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$$\leq \mathbb{E} \left[r(s, \widehat{\pi}(s)) + \gamma r(s', \widehat{\pi}(s')) + \ldots \right] = V^{\widehat{\pi}}(s)$$

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Convert the constriant to linear

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LP Runtime

[Ye, '05]: there is an interior point algorithm (CIPA)
which is ("nearly") strongly polynomial, i.e., no poly dependence on $1/(1-\gamma)$

$$S^4 A^4 \ln\left(\frac{S}{1-\gamma}\right)$$

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- Let us start by understanding the dual variables

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$\mathbb{P}_h(s, a; s_0, \pi)$: probability of π visiting (s, a) at time step $h \in \mathbb{N}$, starting at s_0

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$$d_{s_0}^{\pi}(s, a) = (1 - \gamma) \sum_{h=0}^{\infty} \gamma^h \mathbb{P}_h(s, a; s_0, \pi)$$

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$$V^{\pi}(s_0) = \frac{1}{1-\gamma} \sum_{s,a} d^{\pi}_{s_0}(s, a) r(s, a)$$

A Bellman equation like property for $d^{\pi}_{s_0}(s, a)$

$$\sum_{a} d^{\pi}_{\mu}(s, a) = (1 - \gamma)\mu(s) + \gamma \sum_{\bar{s}, \bar{a}} P(s \mid \bar{s}, \bar{a}) d^{\pi}_{\mu}(\bar{s}, \bar{a})$$

Proof:

A Bellman equation like property for $d_{s_0}^{\pi}(s)$

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$$d^\pi_{\mu}(s) = (1-\gamma)\mu(s) + \gamma(1-\gamma)\sum_{h\geq 0}\gamma^h \mathbb{P}_{h+1}(s; s_0, \pi)$$

$$d^\pi_{\mu}(s) = (1-\gamma)\mu(s) + \gamma\sum_{s'} P(s \mid s') d^\pi_{\mu}(s')$$

The "State-Action" Polytope

- Let us define the state-action polytope K as follows:

$$K_\mu := \left\{ d \,|\, d \geq 0 \ \text{ and } \ \sum_a d(s,a) = (1-\gamma)\mu(s) + \gamma \sum_{s',a'} P(s\,|\,s',a') d(s',a') \right\}$$

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- This set precisely characterizes all state-action visitation distributions:

Lemma: $d \in K_\mu$ if and only if there exists a (possibly randomized) policy π s.t. $d_\mu^\pi = d$

The Dual LP

$$\max \sum_{s,a} d(s,a) r(s,a)$$

$$\text{s.t.} \quad d \in K_\mu$$

- One can verify that this is the dual of the primal LP.

Summary

Notations: Value / Q functions, state-action occupant measures, Bellman equation / optimality

Planning algorithms: VI, PI, LP (primal and dual)