A Unified View of Entropy-Regularized Markov Decision Processes

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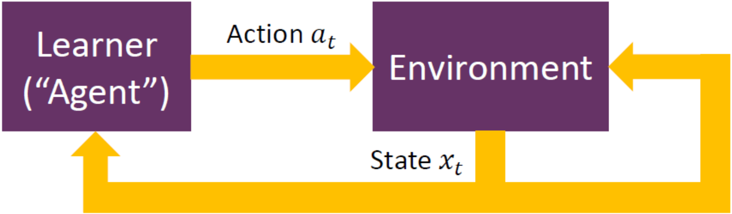
Based on joint work with Anders Jonsson and Vicenç Gómez

Outline

1. MDP basics in 5 minutes
2. Exploration and regularization in RL
3. Entropy-regularized RL
   - Recent trends
   - A unifying theory
   - An algorithmic framework
   - Some results

Markov decision processes



Repeat for $t = 1, 2, \ldots$:

- Learner
  - observes state x_t and plays action a_t
  - obtains reward $r(x_t, a_t)$,
- Environment generates next state $x_{t+1} \sim P(\cdot|x_t, a_t)$.

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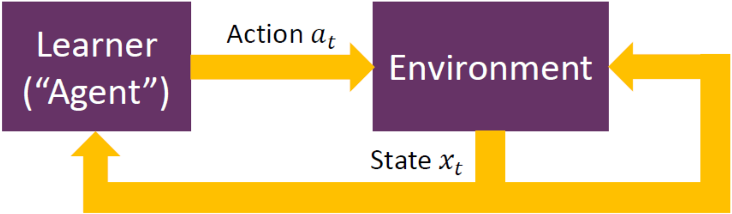


Repeat for $t = 1, 2, \ldots$:

- LEARNER
  - observes state x_t and plays action a_t
  - obtains reward $r(x_t, a_t)$,
- ENVIRONMENT generates next state $x_{t+1} \sim P(\cdot|x_t, a_t)$.

GOAL: gather as much reward as possible

Optimal control in MDPs

A 5-minute summary

- Average-reward criterion:

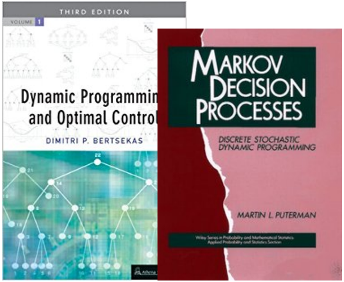
$$\liminf_{T \to \infty} \mathbb{E}\left[\frac{1}{T} \sum_{t=1}^{T} r(x_t, a_t) \right].$$

- Basic fact: enough to consider *stationary policies*

$$\pi(a|x) = \mathbb{P}\left[a_t = a \middle| x_t = x \right].$$

- Under mild assumptions, every π induces stationary distribution μ_π:

$$\mu_\pi(x, a) = \lim_{t \to \infty} \mathbb{P}\left[x_t = x, a_t = a \right].$$



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Notice: average reward of π is linear in μ_π:

$$\lim_{T\to\infty} \mathbb{E}\left[\frac{1}{T}\sum_{t=1}^{T} r(x_t, a_t)\right] = \sum_{x,a} \mu_\pi(x,a) r(x,a) = \langle \mu_\pi, r \rangle$$

Optimal control in MDPs

The LP formulation

Primal LP

$$\rho^* = \max_{\mu \in \Delta} \langle \mu, r \rangle$$

$$\Delta = \left\{ \text{distribution } \mu : \sum_b \mu(y, b) = \sum_{x,a} P(y|x, a)\mu(x, a) \quad (\forall y) \right\}$$

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Dual LP

$$\rho^* = \min_{\rho \in \mathbb{R}} \rho$$

$$\text{s.t.} \quad V(x) \geq r(x, a) - \rho + \sum_y P(y|x, a) V(y) \quad (\forall x, a)$$

Optimal control in MDPs

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Dual "LP" ≡ The Bellman equations

$$V^*(x) = \max_a \left(r(x, a) - \rho^* + \sum_y P(y|x, a) V^*(y) \right) \quad (\forall x)$$

Reinforcement Learning in MDPs

Reinforcement Learning

$\approx$

learning optimal policies in unknown MDPs

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Exactly solving imperfectly known MDPs is a bad idea!

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SOLUTION:
Regularization!

A recent trend: (Entropy-)Regularized RL

Two popular approaches

Idea 1: Soften the max in the Bellman optimality equations!

$$V^*(x) = \max_a \left(r(x,a) - \rho^* + \sum_y P(y|x,a) V^*(y) \right)$$

A recent trend: (Entropy-)Regularized RL

Two popular approaches

Idea 1: Soften the max in the Bellman optimality equations!

$$V_\eta^*(x) = \frac{1}{\eta} \log \sum_a \exp\left(\eta\left(r(x,a) - \rho_\eta^* + \sum_y P(y|x,a)\, V_\eta^*(y)\right)\right)$$

[Marcus et al., 1997, Ruszczyński, 2010, Ziebart et al., 2010, Ziebart, 2010, Braun et al., 2011, Azar et al., 2012, Rawlik et al., 2012, Fox et al., 2016, Asadi and Littman, 2017, Haarnoja et al., 2017, Schulman et al., 2017, Nachum et al., 2017] ...

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Idea 2: Maximize a regularized objective!

$$\rho(\mu) = \langle \mu, r \rangle$$

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Idea 2: Maximize a regularized objective!

$$\rho_\eta(\mu) = \langle \mu, r \rangle - \frac{1}{\eta} R(\mu)$$

[Peters et al., 2010, Montgomery and Levine, 2016, Schulman et al., 2015, Mnih et al., 2016, O'Donoghue et al., 2017]

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$$V^*_\eta(x) = \frac{1}{\cdot}\log\sum \exp\left(\eta\left(r(x,a) - \rho^* + \sum P(y|x,a)\,V^*(y)\right)\right)$$

[Marcus … , Azar et al., 20… 017, Schulma…

Idea …

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Numerous open questions:

- are these approaches connected?
- do the derived algorithms converge anywhere?
- does a solution even exist?

A unified framework for entropy-regularized MDPs

N, Jonsson and Gómez (2017)

Primal LP

$$\rho^* = \max_{\mu \in \Delta} \langle \mu, r \rangle$$

Dual "LP"

$$V^*(x) = \max_a \left(r(x,a) - \rho^* + \sum_y P(y|x,a) V^*(y) \right) \quad (\forall x)$$

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Primal convex program

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Dual "convex program"

$$V_\eta^*(x) = \frac{1}{\eta} \log \sum_a \exp\left(\eta \left(r(x,a) - \rho_\eta^* + \sum_y P(y|x,a) V_\eta^*(y) \right) \right)$$

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$R(\mu) = ???$

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Conditional entropy regularization

N, Jonsson and Gómez (2017)

Theorem

The two convex programs are connected by Lagrangian duality with the choice

$$R(\mu) = \sum_{x,a} \mu(x,a) \log \frac{\mu(x,a)}{\sum_b \mu(x,b)}$$
$$= \sum_{x,a} \mu(x,a) \log \pi_\mu(a|x)$$

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Lemma

The conditional entropy $R(\mu)$ is convex in μ and the associated Bregman divergence is

$$D\left(\mu \| \mu'\right) = \sum_{x,a} \mu(x,a) \log \frac{\pi_\mu(a|x)}{\pi_{\mu'}(a|x)} \geq 0.$$

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N, Jonsson and Gómez (2017)

Primal convex program

Immediate consequences:

- existence & uniqueness results
- well-defined contractive DP operators
- policy gradient theorems...

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A unified algorithmic framework

N, Jonsson and Gómez (2017)

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Every algorithm is either Mirror Descent or Dual Averaging / FTRL!

A unified algorithmic framework

N, Jonsson and Gómez (2017)

Every algorithm is either Mirror Descent or Dual Averaging / FTRL!

- provides a common analytic framework
- ensures convergence
- explains numerous recent algorithms

Mirror Descent

N, Jonsson and Gómez (2017)

Mirror descent

$$\mu_{t+1} = \arg\max_{\mu \in \Delta} \left(\langle \mu, r \rangle - \frac{1}{\eta} D\left(\mu \| \mu_t\right) \right)$$

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N, Jonsson and Gómez (2017)

Mirror descent

$$\mu_{t+1} = \arg\max_{\mu \in \Delta} \left(\langle \mu, r \rangle - \frac{1}{\eta} D\left(\mu \| \mu_t\right) \right)$$

Closed-form policy update:

$$\pi_{t+1}(a|x) = \pi_t(a|x) e^{\eta\left(r(x,a) + \sum_{x'} P(x'|x,a) V_t(x') - V_t(x)\right)}$$

$$V_t(x) = \text{softmax}_a^{\eta} \left(r(x,a) - \rho_t + \sum_y P(y|x,a) V_t(y) \right)$$

Example:

Trust-region policy optimization ≈ Mirror Descent

N, Jonsson and Gómez (2017)

Trust-Region Policy Optimization [Schulman et al., 2015]:

$$D_{\mathrm{TRPO}}\left(\mu \| \mu_{\mathrm{old}}\right) = \sum_{x,a} \nu_{\mathrm{old}}(x) \pi_{\mu}(a|x) \log \frac{\pi_{\mu}(a|x)}{\pi_{\mathrm{old}}(a|x)}$$

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Still has closed-form policy update

$$\pi_{t+1}(a|x) \propto \pi_t(a|x) e^{\eta\left(r(x,a) + \sum_{x'} P(x'|x,a) \widetilde{V}_t(x')\right)}$$

$$\widetilde{V}_t(x) = \sum_a \pi_t(a|x) \left(r(x,a) - \rho_t + \sum_y P(y|x,a) \widetilde{V}_t(y) \right)$$

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Observation

TRPO is equivalent to the MDP-E algorithm by Even-Dar, Kakade, and Mansour [2004, 2009]

$\Rightarrow$ TRPO converges to the optimal policy!

(can be also shown by constructing an appropriate mirror space)

Dual Averaging / Follow-the-Regularized-Leader

N, Jonsson and Gómez (2017)

Dual Averaging / FTRL

$$\mu_{t+1} = \underset{\mu \in \Delta}{\arg\max} \left(\langle \mu, r \rangle - \frac{1}{\eta_t} R(\mu) \right)$$

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Example:

A3C $\approx$ Dual Averaging

N, Jonsson and Gómez (2017)

"A3C" [Mnih et al., 2016, O'Donoghue et al., 2017]:

$$R_{\mathrm{A3C}}(\mu) = \sum_{x,a} \nu_{\mathrm{old}}(x)\pi_\mu(a|x)\log\pi_\mu(a|x)$$

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Divergence alert!!!

closed-form updates equivalent to softmax policy iteration

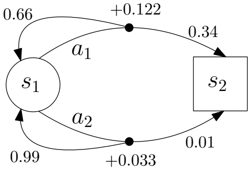
which is known to be divergent

(convex-optimization hint: A3C optimizes a non-stationary and non-convex objective with no mirror space!)

Experiment:

does A3C converge anywhere?

N, Jonsson and Gómez (2017), example inspired by Asadi and Littman [2017]



$$\pi(a_1|s_1) = \frac{\exp(\theta_1)}{\exp(\theta_1)+\exp(\theta_2)}$$

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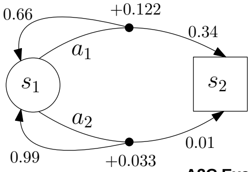

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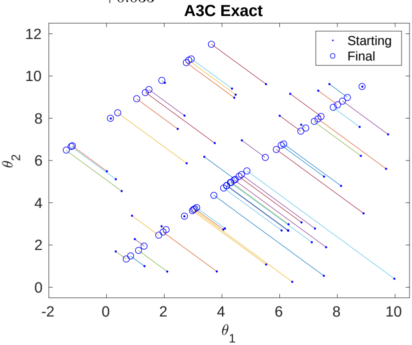

Patching A3C

N, Jonsson and Gómez (2017)

Perform gradient descent on the objective regularized with

$$R(\mu) = \sum_{x,a} \nu_\mu(x)\pi_\mu(a|x) \log \frac{\pi_\mu(a|x)}{\pi_{\text{old}}(a|x)}.$$

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Regularized Policy Gradient Theorem

$$\nabla_\theta \left(\langle \mu_\theta, r \rangle - \frac{1}{\eta} R(\mu_\theta) \right) = \mathbb{E}_{(x,a)\sim\mu_\theta} \left[\nabla_\theta \log \pi_\theta(a|x) A_\eta^\pi(x,a) \right],$$

where A_η^π is the regularized advantage function satisfying

$$A_\eta^\pi(x,a) = r(x,a) - \frac{1}{\eta} \log \pi(a|x) + \sum_y P(y|x,a) V_\eta^\pi(y) - V_\eta^\pi(x)$$

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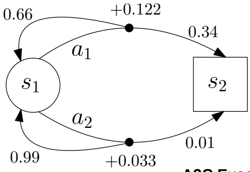

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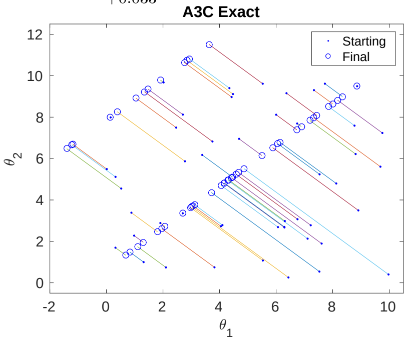

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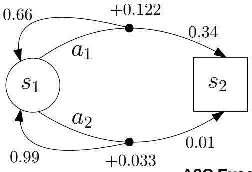

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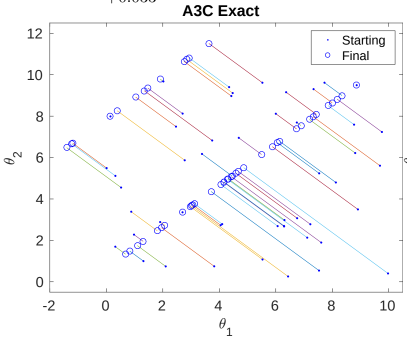

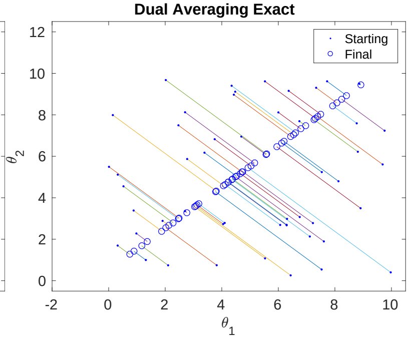

Other algorithms in our framework

N, Jonsson and Gómez (2017)

Mirror Descent:

- Dynamic Policy Programming [Azar et al., 2012], Ψ-learning [Rawlik et al., 2012]
- Relative Entropy Policy Search [Peters et al., 2010, Zimin and Neu, 2013, Montgomery and Levine, 2016]

Dual Averaging:

- "MellowMax" RL algorithms of [Asadi and Littman, 2017], G-learning [Fox et al., 2016]
- "Energy-based policy search" [Haarnoja et al., 2017]
- "Path consistency learning" [Nachum et al., 2017]

Experiments

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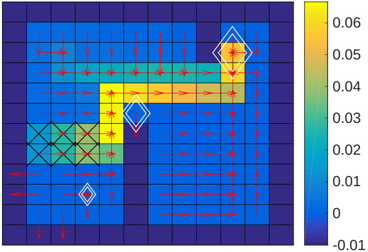
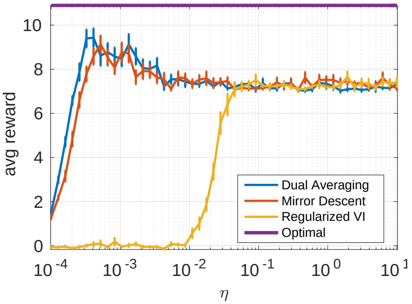


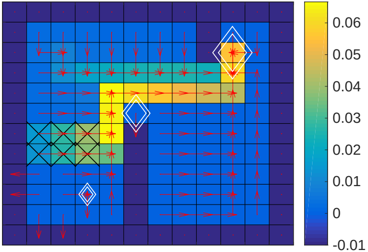


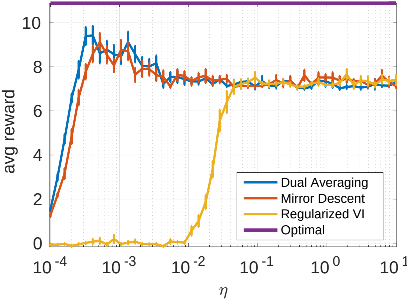
"Regularization curve":

- η too large: convergence to suboptimal goal $\leftrightarrow$ overfitting
- η too small: policy too close to uniform $\leftrightarrow$ underfitting

Experiments

N, Jonsson and Gómez (2017)





"Regularization curve":

- η too large: convergence to suboptimal goal ↔ overfitting
- η too small: policy too close to uniform ↔ underfitting

Dual Averaging perspective seems essential!

- DA theory suggests $\eta_t = t \cdot \eta_0$
- Regularized Value Iteration with constant η is bad

Outlook

Can regularization provide a useful perspective on exploration?

- "Exploration" integrated in the foundations: regularized Bellman equations
- convex optimization framework provides analysis tools and algorithmic templates

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The way towards more effective algorithms?

Thanks!!

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