



Adversarial Soft Advantage Fitting: Imitation Learning without Policy Optimization

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Preliminaries I

- Consider a T -horizon γ -discounted MDP $\mathcal{M} = \langle \mathcal{S}, \mathcal{A}, \mathcal{P}, \mathcal{P}_0, \gamma, r, T \rangle$, where
 - \mathcal{S} is the state space;
 - \mathcal{A} is the action space;
 - $\mathcal{P}(s'|s, a) \in [0, 1]$ is the transition dynamics;
 - $\mathcal{P}_0(s_0)$ is the initial state distribution;
 - $\gamma \in [0, 1]$ is the discount factor;
 - $r(s, a) \in \mathbb{R}$ with r being bounded is the reward function;
 - $T \in \mathbb{N} \cup \{\infty\}$ is the horizon length.
- We suppose that \mathcal{S} and \mathcal{A} are both finite, and $T < \infty$ for $\gamma = 1$.
- For any trajectory $\tau = (s_0, a_0, s_1, a_1, \dots, s_{T-1}, a_{T-1}, s_T)$, define its probability $P_\pi(\tau)$ of being sampled on \mathcal{M} as

$$P_\pi(\tau) \triangleq \mathcal{P}_0(s_0) \prod_{t=0}^{T-1} \pi(a_t|s_t) \mathcal{P}(s_{t+1}|s_t, a_t).$$



Preliminaries II

- For any policy π , we define its occupancy measure $\rho^\pi : \mathcal{S} \times \mathcal{A} \rightarrow [0, 1]$ as

$$\rho^\pi(s, a) = \frac{1}{Z(\gamma, T)} \sum_{t=0}^{T-1} \gamma^t \left(\sum_{\tau: (s_t, a_t) = (s, a)} P_\pi(\tau) \right) = \frac{1}{Z(\gamma, T)} \sum_{t=0}^{T-1} \gamma^t \Pr(s_t = s) \pi(a|s),$$

where $Z(\gamma, T) = \sum_t^{T-1} \gamma^t$.

- The expected sum of discounted rewards can be expressed in term of the occupancy measure as

$$J_\pi[r(s, a)] \triangleq \mathbb{E}_{\tau \sim P_\pi} \left[\sum_{t=0}^{T-1} \gamma^t r(s_t, a_t) \right] = Z(\gamma, T) \mathbb{E}_{(s, a) \sim \rho^\pi} [r(s, a)].$$



Preliminaries III

- By properly regularizing the learned reward function r , (Ho & Ermon, 2016) associated the maximum entropy IRL problem with GAN, thus getting GAIL's objective:

$$\min_{\pi} \max_D \mathbb{E}_{(s,a) \sim \rho^{\pi_E}} [\log(D(s,a))] + \mathbb{E}_{(s,a) \sim \rho^\pi} [\log(1 - D(s,a))],$$

which is equivalent to the following Jensen-Shannon divergence minimization problem,

$$\min_{\pi} D_{JS}(\rho_\pi, \rho_{\pi_E}).$$



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Motivation

- GAIL performs not well in practice.
 - ① The min-max optimization procedure of GAIL is brittle and unstable;
 - ② The RL process is sample-inefficient and tricky.
- Can we instead imitate the expert without adversarial training and RL policy optimization?

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Method I

Consider the following new objective

$$\min_{\pi_G} \max_{\tilde{\pi}} L(\tilde{\pi}, \pi_G) := \mathbb{E}_{\tau \sim P_{\pi_E}} [\log D_{\tilde{\pi}, \pi_G}(\tau)] + \mathbb{E}_{\tau \sim P_{\pi_G}} [\log(1 - D_{\tilde{\pi}, \pi_G}(\tau))], \quad (1)$$

with the *structured discriminator*:

$$D_{\tilde{\pi}, \pi_G}(x) = \frac{P_{\tilde{\pi}}(\tau)}{P_{\tilde{\pi}}(\tau) + P_{\pi_G}(\tau)} = \frac{q_{\tilde{\pi}}(\tau)}{q_{\tilde{\pi}}(\tau) + q_{\pi_G}(\tau)}.$$

Here $q_{\pi}(\tau) = \prod_{t=0}^{T-1} \pi(a_t | s_t)$.

Lemma 1.

For any stationary policy π , there is an one-to-one correspondence between π and q_{π} on \mathcal{M} .



Method II

Proof: For any trajectory $\tau = (s_0, a_0, s_1, a_1, \dots, s_{T-1}, a_{T-1}, s_T)$, we have that $P_\pi(\tau) = q_\pi \times \xi(\tau)$, with

$$\xi(\tau) := \mathcal{P}_0(s_0) \prod_{t=0}^{T-1} \mathcal{P}(s_{t+1}|s_t, a_t).$$

Since $\xi(\tau)$ is solely determined by the MDP \mathcal{M} , there is an one-to-one correspondence between q_π and P_π . And from the definition of ρ^π , we know that ρ^π can be computed directly from P_π . From Theorem 2 of (Syed et al., 2008), we know that ρ^π and π is one-to-one corresponded. Thus concluding the proof. □



Method III

Theorem 1.

The optimal $\tilde{\pi}^* = \arg \max_{\tilde{\pi}} L(\tilde{\pi}, \pi_G)$ for any π_G in Eq. (1) is such that $q_{\tilde{\pi}^*} = q_{\pi_E}$, and using $\tilde{\pi}^*$ as the generator policy $\tilde{\pi}^*$ minimizes $L(\tilde{\pi}^*, \pi_G)$, i.e,

$$\tilde{\pi}^* \in \arg \min_{\pi_G} \max_{\tilde{\pi}} L(\tilde{\pi}, \pi_G) = \arg \min_{\pi_G} L(\tilde{\pi}^*, \pi_G).$$

Proof: Theorem 1 states that given $L(\tilde{\pi}, \pi_G)$ defined in Eq. (1):

- a $\tilde{\pi}^* = \arg \max_{\tilde{\pi}} L(\tilde{\pi}, \pi_G)$ satisfies $q_{\tilde{\pi}^*} = q_{\pi_E}$;
- b $\pi_G^* = \tilde{\pi}^* \in \arg \min_{\pi_G} L(\tilde{\pi}^*, \pi_G)$.

We will give the corresponding proofs of (a) and (b) below.



Method IV

a By expanding Eq. (1), we have that

$$\begin{aligned}\arg \max_{\tilde{\pi}} L(\tilde{\pi}, \pi_G) &= \arg \max_{\tilde{\pi}} \sum_{\tau_i} P_{\pi_E}(\tau_i) \log D_{\tilde{\pi}, \pi_G}(\tau_i) + P_{\pi_G}(\tau_i) \log(1 - D_{\tilde{\pi}, \pi_G}(\tau_i)) \\ &= \arg \max_{\tilde{\pi}} \sum_{\tau_i} \xi(\tau_i) (q_{\pi_E}(\tau_i) \log D_{\tilde{\pi}, \pi_G}(\tau_i) + q_{\pi_G}(\tau_i) \log(1 - D_{\tilde{\pi}, \pi_G}(\tau_i))) \\ &= \arg \max_{\tilde{\pi}} \sum_{\tau_i} L_i(\tau_i).\end{aligned}$$

From Proposition 1 of (Goodfellow et al., 2014), we get

$$D_{\tilde{\pi}, \pi_G}^* = \arg \max_{D_{\tilde{\pi}, \pi_G}} L_i(\tau_i) = \frac{q_{\pi_E}(\tau_i)}{q_{\pi_E}(\tau_i) + q_{\pi_G}(\tau_i)}.$$

Thus from the definition and monotonicity of $D_{\tilde{\pi}, \pi_G}^*$, we get $q_{\tilde{\pi}^*} = q_{\pi_E}$. Then by using Lemma 1, we conclude that $\tilde{\pi}^* = \pi_E$.



Method V

⑥ we use the conclusion from (a), and get

$$\begin{aligned}\pi_G^* &= \arg \min_{\pi_G} L(\tilde{\pi}^*, \pi_G) \\&= \arg \min_{\pi_G} \mathbb{E}_{\tau \sim P_{\pi_E}} \left[\log \frac{P_{\pi_E}(\tau)}{P_{\pi_E}(\tau) + P_{\pi_G}(\tau)} \right] + \mathbb{E}_{\tau \sim P_{\pi_G}} \left[\log \frac{P_{\pi_G}(\tau)}{P_{\pi_E}(\tau) + P_{\pi_G}(\tau)} \right] \\&= \arg \min_{\pi_G} -\log 4 + 2D_{\text{JS}}(P_{\pi_E} \| P_{\pi_G}) \\&= \pi_E.\end{aligned}$$

Conclude the proof.

Method VI



From Theorem 1, we find that optimizing the inner $\tilde{\pi}$ will give us the optimal outer π_G . We thus get ASAF, a new imitation learning algorithm with pseudocode shown in Algorithm 1.

Algorithm 1 ASAF

Require: expert trajectories $\mathcal{D}_E = \{\tau_i^{(E)}\}_{i=1}^{N_E}$

randomly initialize $\tilde{\pi}$ and set $\pi_G \leftarrow \tilde{\pi}$

for steps $m = 0$ to M **do**

 Collect trajectories $\mathcal{D}_G = \{\tau_i^{(G)}\}_{i=1}^{N_G}$ using π_G

 Update $\tilde{\pi}$ by minimizing Eq. (2)

$\pi_G \leftarrow \tilde{\pi}$

end for



Method VII

$$\mathcal{L}_{BCE}(\mathcal{D}_E, \mathcal{D}_G, \tilde{\pi}) \approx -\frac{1}{n_E} \sum_{i=1}^{n_E} \log D_{\tilde{\pi}, \pi_G}(\tau_i^{(E)}) - \frac{1}{n_G} \sum_{i=1}^{n_G} \log (1 - D_{\tilde{\pi}, \pi_G}(\tau_i^{(G)})), \quad (2)$$

where $\tau_i^{(E)} \sim \mathcal{D}_E$, $\tau_i^{(G)} \sim \mathcal{D}_G$ and

$$D_{\tilde{\pi}, \pi_G}(\tau) = \frac{\prod_{i=1}^{T-1} \tilde{\pi}(a_t | s_t)}{\prod_{i=1}^{T-1} \tilde{\pi}(a_t | s_t) + \prod_{i=1}^{T-1} \pi_G(a_t | s_t)}. \quad (3)$$

Remark: ASAFAF uses the full-length trajectory, which may be sample-inefficient. The authors also considered using a window size of w or even transition-wise variants, and named them ASAFAF- w and ASAFAF-1, respectively.

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Experiments I

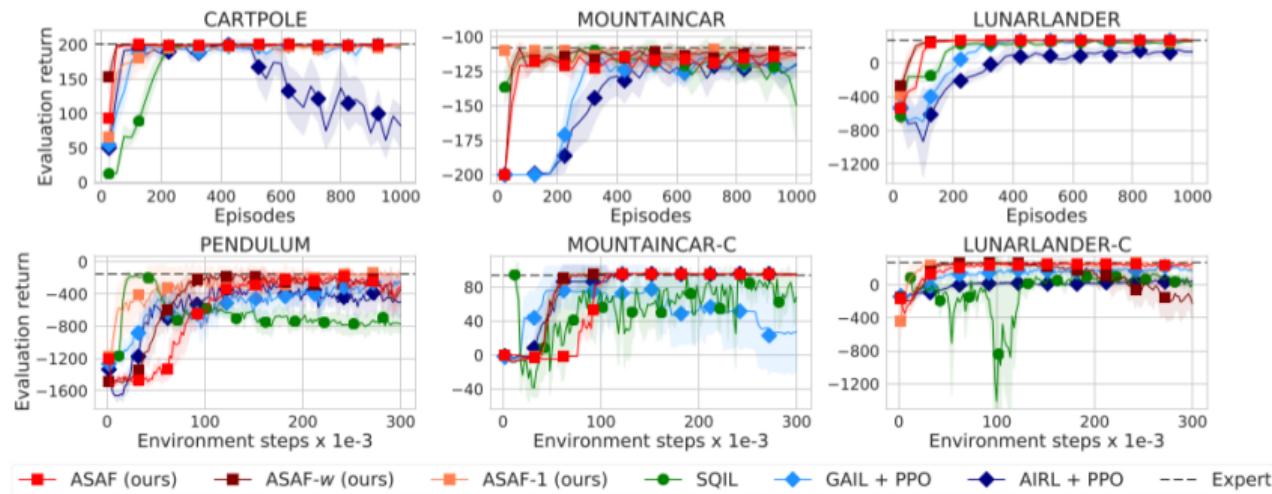


Figure 1: Results on classic control and Box2D tasks for 10 expert demonstrations. First row contains discrete actions environments, second row corresponds to continuous control.

Experiments II

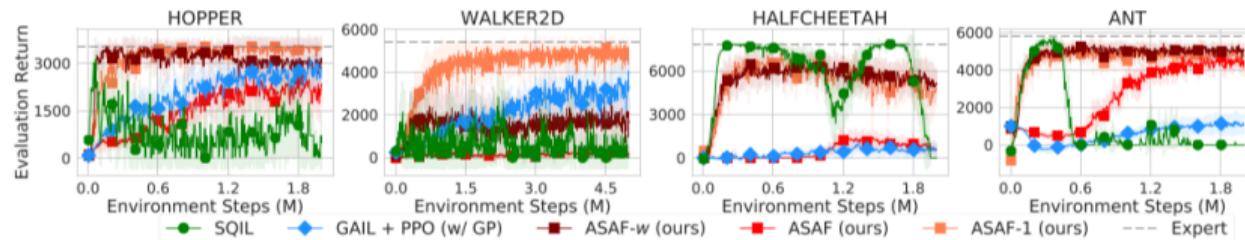


Figure 2: Results on MuJoCo tasks for 25 expert demonstrations.

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- Model learning

$$D_{\tilde{\mathcal{P}}, \mathcal{P}_G}(\tau) = \frac{\tilde{\mathcal{P}}(s_0) \prod_{i=1}^{T-1} \tilde{\mathcal{P}}(a_t|s_t)}{\prod_{i=1}^{T-1} \tilde{\mathcal{P}}(a_t|s_t) + \prod_{i=1}^{T-1} \mathcal{P}_G(a_t|s_t)}.$$

- Reduction to transition-wise scenario: The author also discussed a novel transition-wise objective (connected to (Fu et al., 2017)), which is only suit for discrete action space.
- We can use any policy to sample fake trajectories.

The End

Thanks!
Q & A



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