

Batch / Offline RL Policy Evaluation

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CS234
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Thanks to Phil Thomas for some figures

Refresh Your Understanding: Fast RL

Select all that are true:

- In Thompson sampling for MDPs, the posterior over the dynamics can be updated after each transition
- When using a Beta prior for a Bernoulli reward parameter for an (s,a) pair, the posterior after N samples of that pair time steps can be the same as after $N+2$ samples
- The optimism bonuses discussed for MBIE-EB depend on the maximum reward but not on the maximum value function
- In class we discussed adding a bonus term to an update for a (s,a,r,s') tuple using Q-learning with function approximation. Adding this bonus term will ensure all Q estimates used to make decisions online using DQN are optimistic with respect to Q^*
- Not sure

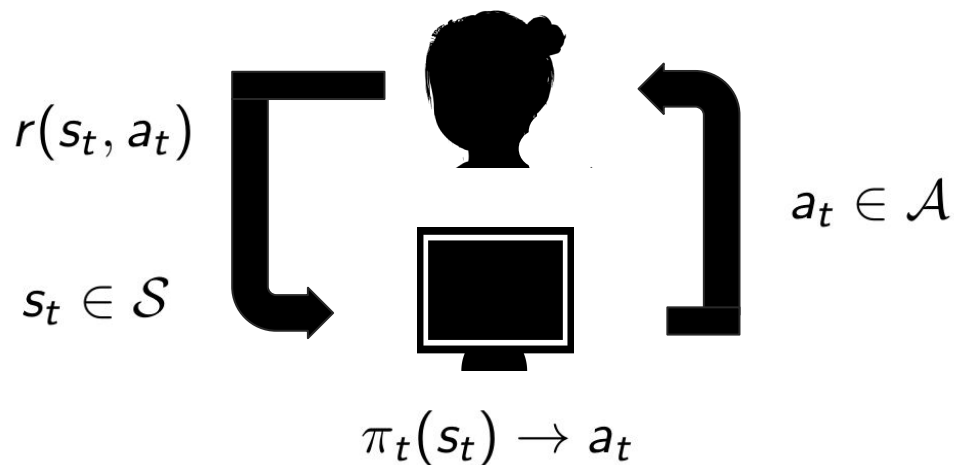
Outline for Today

1. Introduction and Setting
2. Offline batch evaluation using models
3. Offline batch evaluation using Q functions
4. Offline batch evaluation using importance sampling

Where We Are

- Fast reinforcement learning
- **Learning from offline data**
 - Overview and Policy evaluation
 - Imitation Learning
 - Policy optimization
 - Guest lecture with Dr. Lihong Li

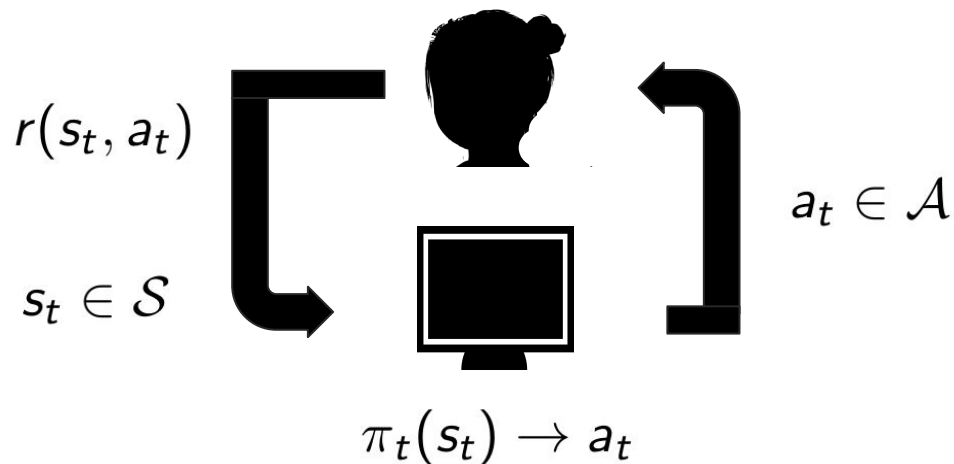
Reinforcement Learning



$$\underbrace{V^\pi(s)}_{\text{Value func.}} = \underbrace{r(s, \pi(s))}_{\text{Reward}} + \gamma \sum_{s'} \underbrace{p(s'|s, a)}_{\text{Dynamics}} V^\pi(s')$$

Only observed through samples (experience)

New Topic: Counterfactual / Batch RL



$\mathcal{D}$: Dataset of n traj.s τ , $\tau \sim \pi_b$

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Patient group 1 →   → Outcome: 92

Patient group 2 →   → Outcome: 91

Patient group 1 →   → Outcome: 92

Patient group 2 →   → Outcome: 91

 → ?

“What If?” Reasoning Given Past Data

Patient group 1 →   → Outcome: 92

Patient group 2 →   → Outcome: 91



?

What information would you want to know in order to decide, given the above evidence, how best to treat new patient?

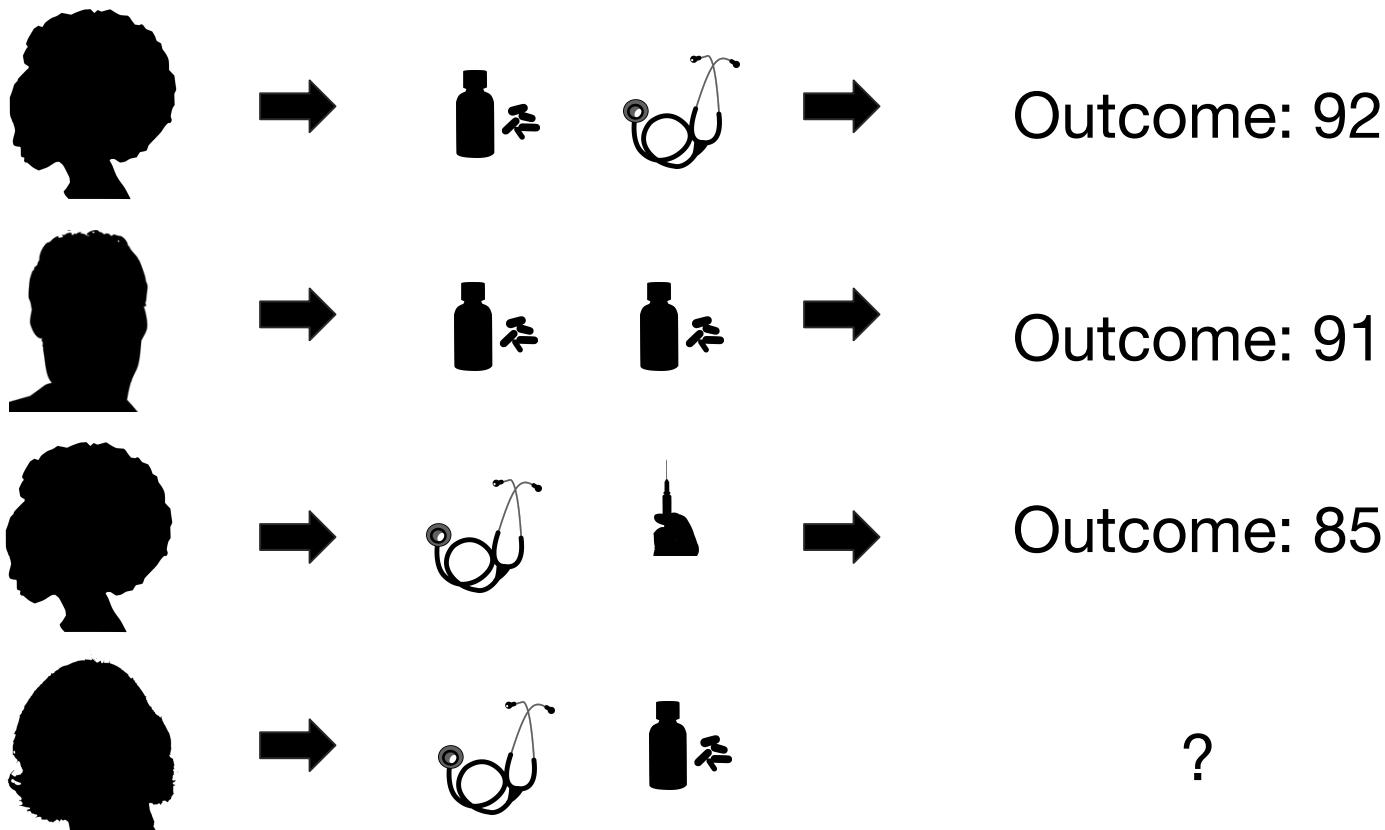
Data Is Censored in that Only Observe Outcomes for Decisions Made

Patient group 1 →   → Outcome: 92

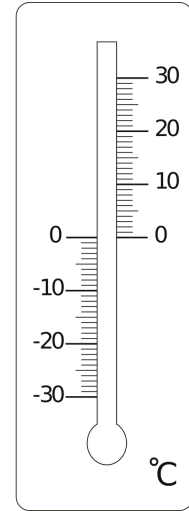
Patient group 2 →   → Outcome: 91

 → ?

Need for Generalization



Potential Applications



Off Policy Reinforcement Learning

Watkins 1989

Watkins and Dayan 1992

Precup et al. 2000

Lagoudakis and Parr 2002

Murphy 2005

Sutton, Szepesvari and Maei 2009

Shortreed, Laber, Lizotte, Stroup, Pineau, & Murphy 2011

Degirs, White, and Sutton 2012

Mnih et al. 2015

Mahmood et al. 2014

Jiang & Li 2016

Hallak, Tamar and Mannor 2015

Munos, Stepleton, Harutyunyan and Bellemare 2016

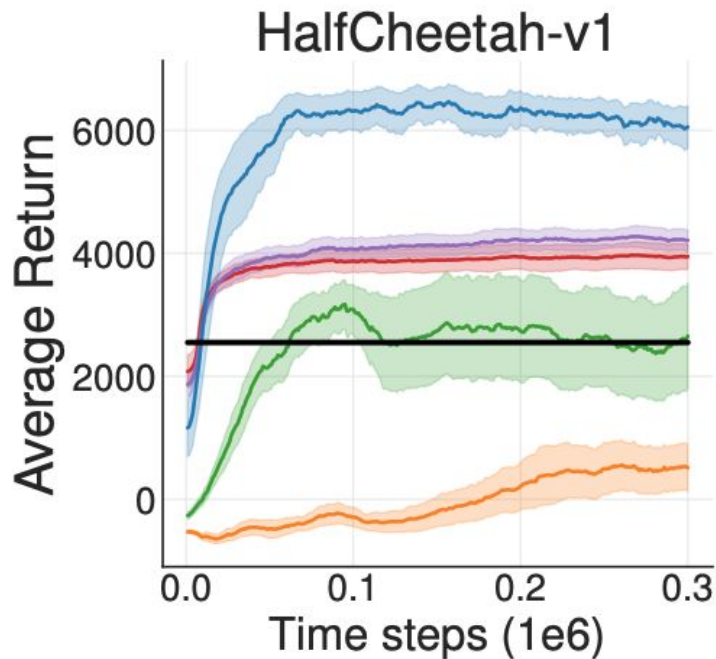
Sutton, Mahmood and White 2016

Du, Chen, Li, Ziao, and Zhou 2016 ...

Why Can't We Just Use Q-Learning?

- Q-learning is an off policy RL algorithm
 - Can be used with data different than the state--action pairs would visit under the optimal Q state action values
- But deadly triad of bootstrapping, function approximation and off policy, and can fail

Important in Practice



BCQ figure from Fujimoto,
Meger, Precup ICML 2019

BCQ

DDPG

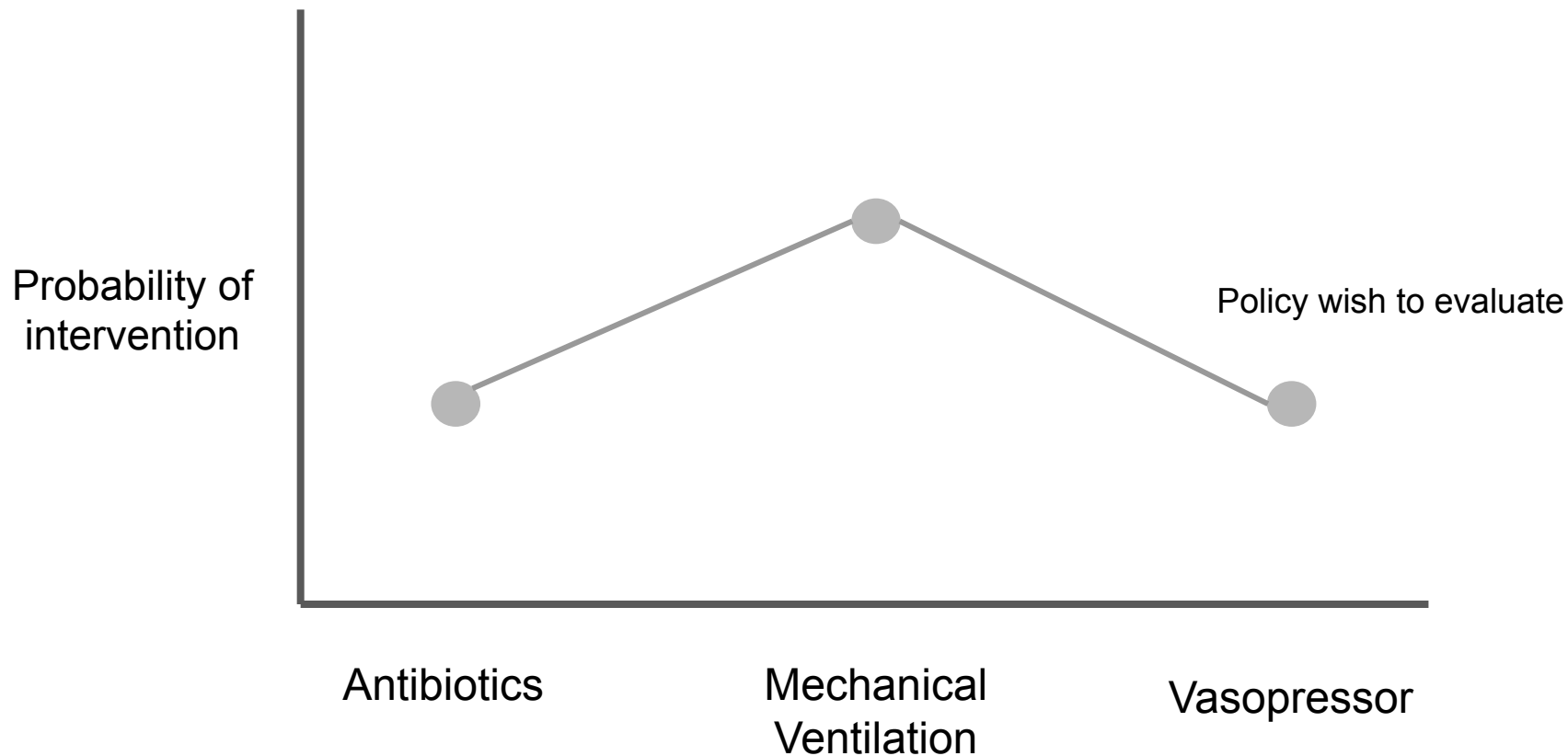
DQN

BC

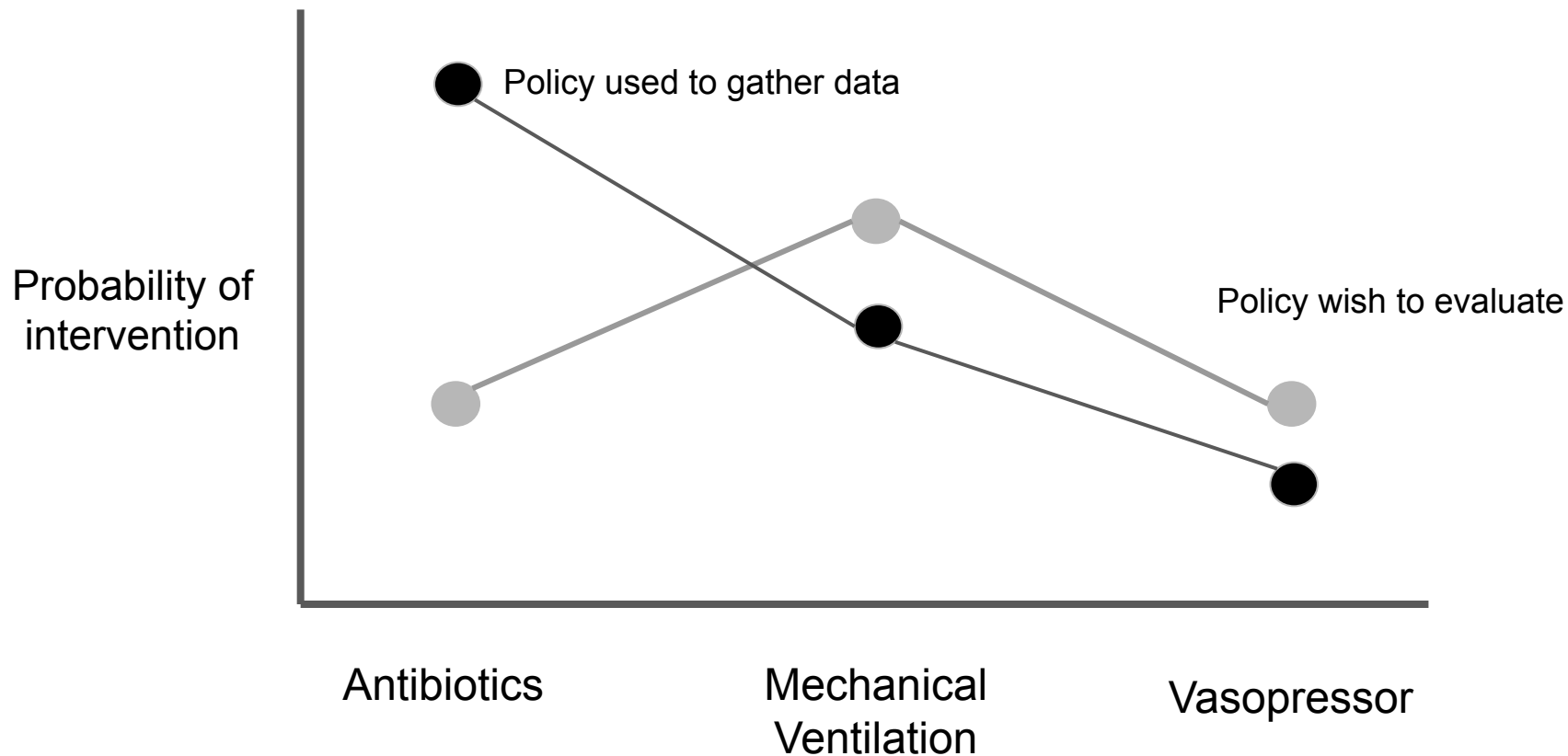
VAE-BC

Behavioral₁₇

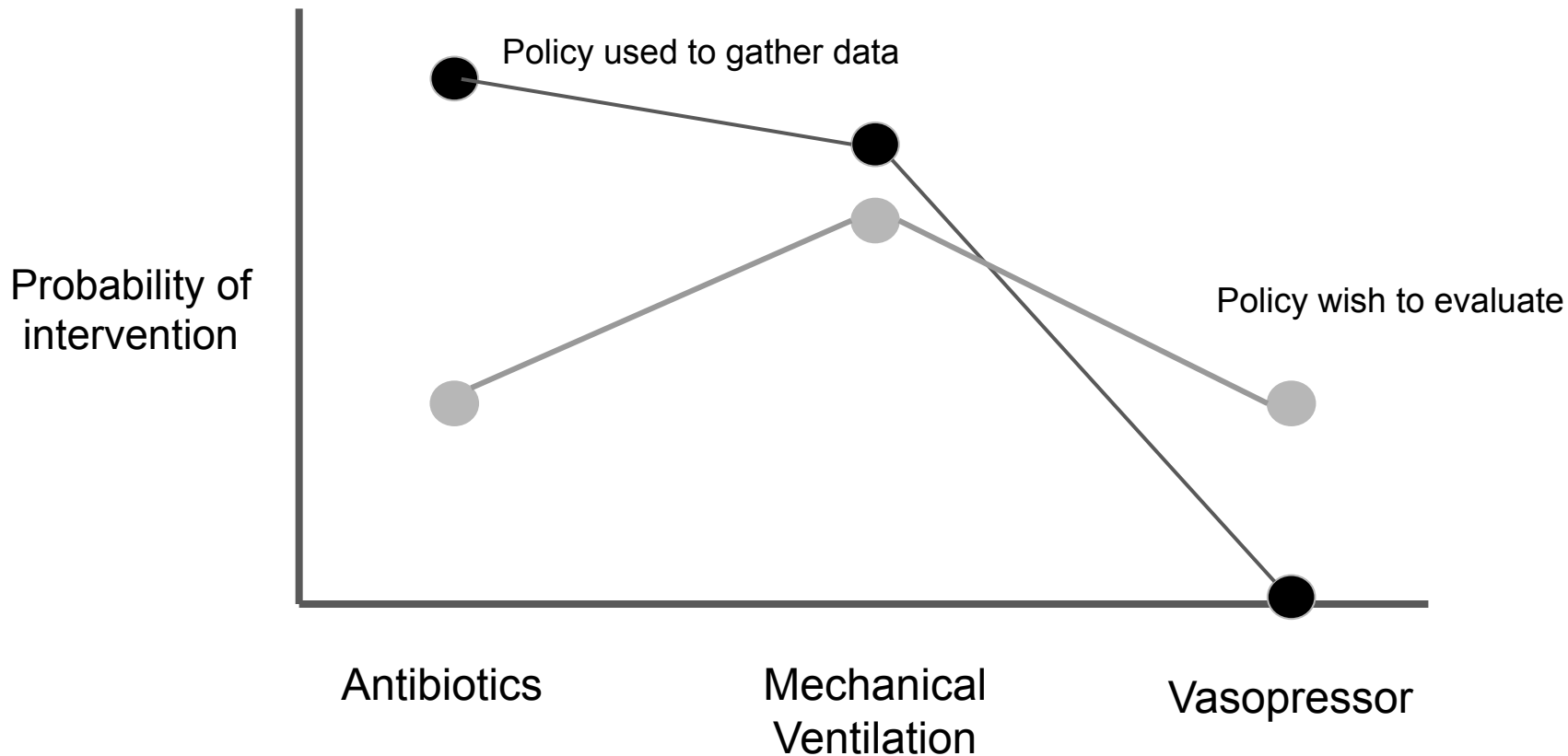
Challenge: Overlap Requirement



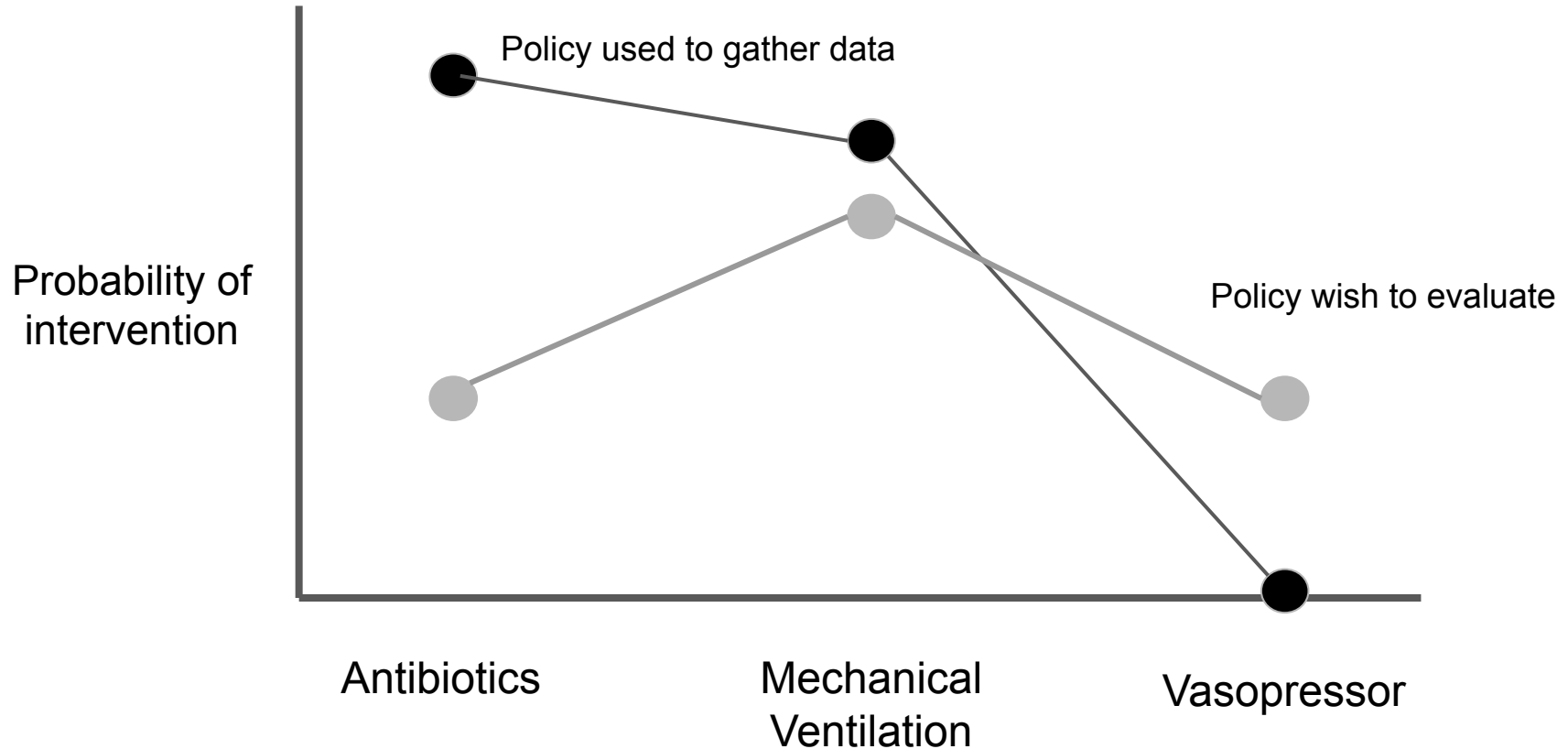
Overlap Requirement: Data Must Support Policy Wish to Evaluate



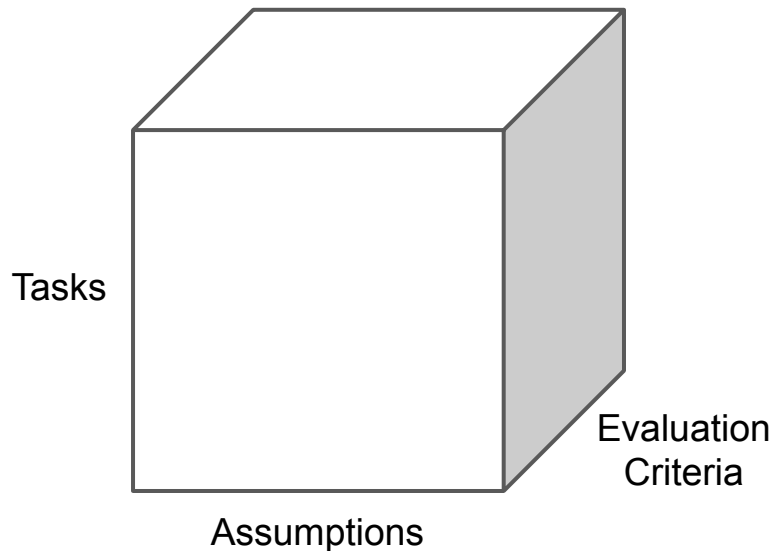
No Overlap for Vasopressor $\Rightarrow$ Can't Do Off Policy Estimation for Desired Policy



How to Evaluate Sufficient Overlap in Real Data?



Offline / Batch Reinforcement Learning



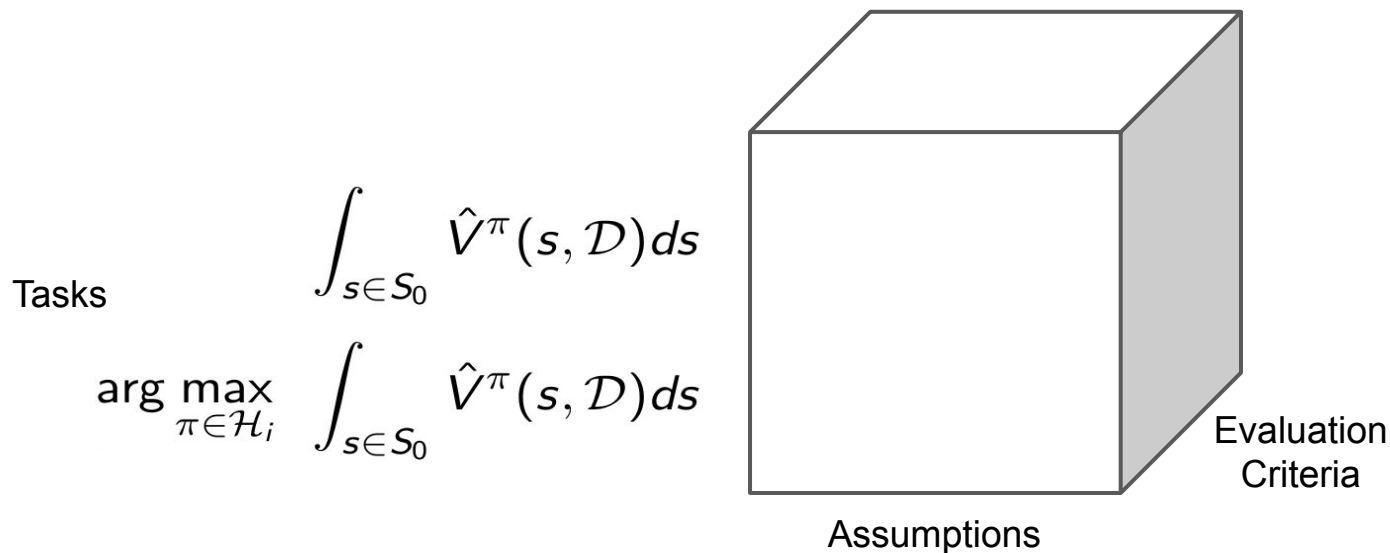
$\mathcal{D}$: Dataset of n traj.s τ , $\tau \sim \pi_b$

π : Policy mapping $s \rightarrow a$

S_0 : Set of initial states

$\hat{V}^\pi(s, \mathcal{D})$: Estimate $V(s)$ w/dataset $\mathcal{D}$

Common Tasks: Off Policy Evaluation & Optimization



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Common Assumptions

- Stationary process: Policy will be evaluated in or deployed in the same stationary decision process as the behavior policy operated in to gather data
- **Markov**
- Sequential ignorability (no confounding)

$$\{Y(A_{1:(t-1)}, a_{t:T}), S_{t'}(A_{1:(t-1)}, a_{t:(t'-1)})\}_{t'=t+1}^T \perp\!\!\!\perp A_t \mid \mathcal{F}_t$$

- Overlap

$$\forall(s, a) \mu_e(s, a) > 0 \rightarrow \mu_b(s, a) > 0$$

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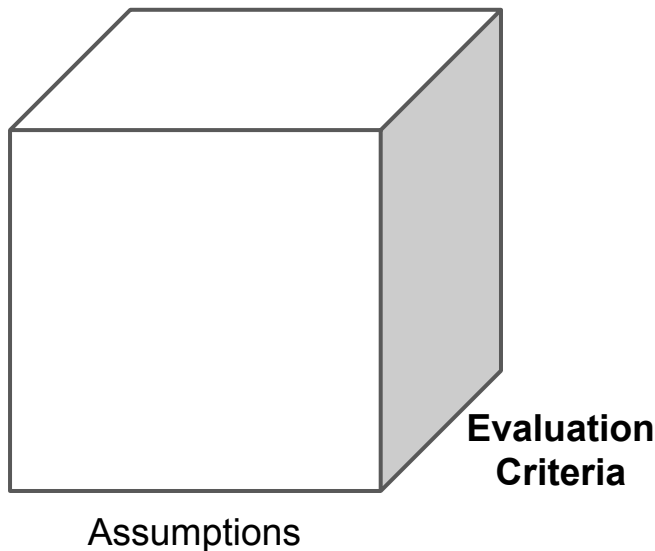
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$\hat{V}^\pi(s, \mathcal{D})$: Estimate $V(s)$ w/dataset $\mathcal{D}$

Common Tasks: Off Policy Evaluation & Optimization

Tasks

$$\int_{s \in S_0} \hat{V}^{\pi}(s, \mathcal{D}) ds$$
$$\arg \max_{\pi \in \mathcal{H}_i} \int_{s \in S_0} \hat{V}^{\pi}(s, \mathcal{D}) ds$$



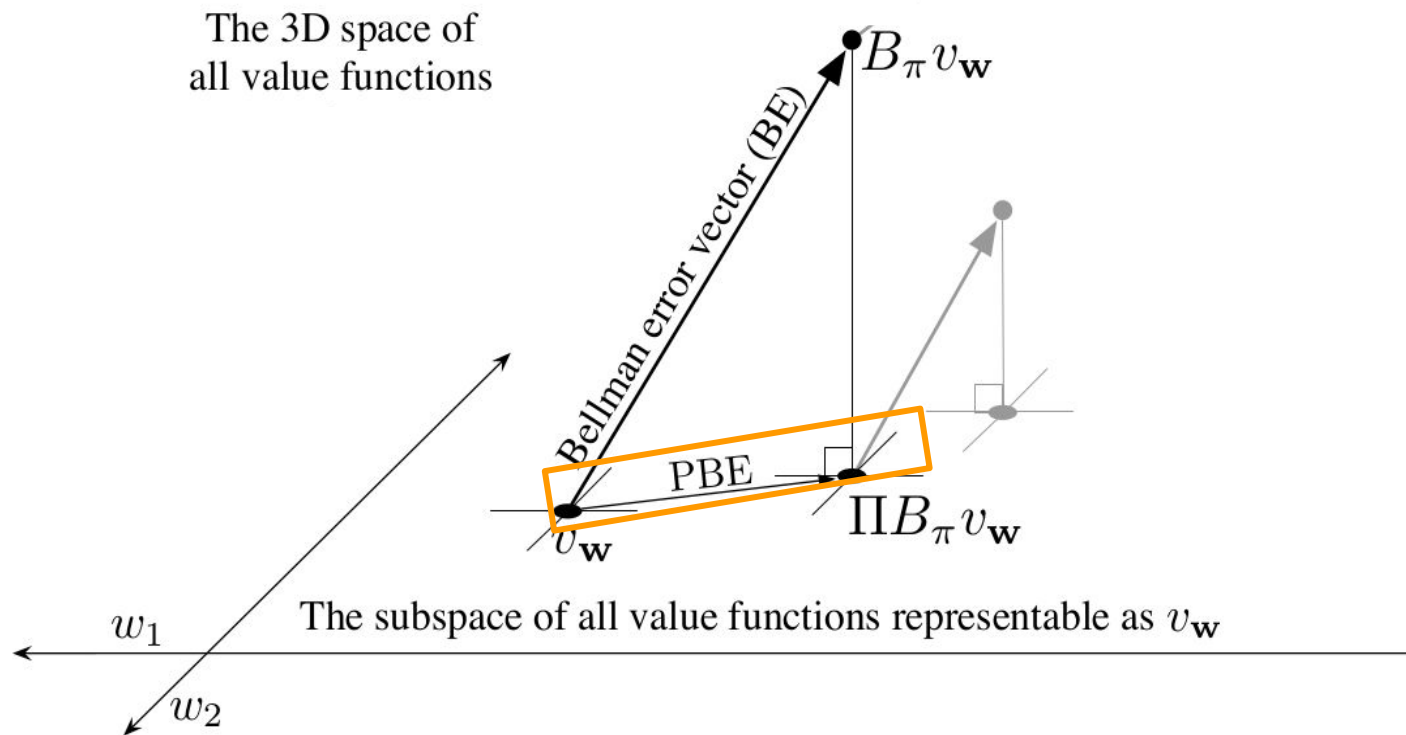
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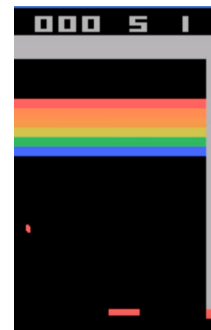
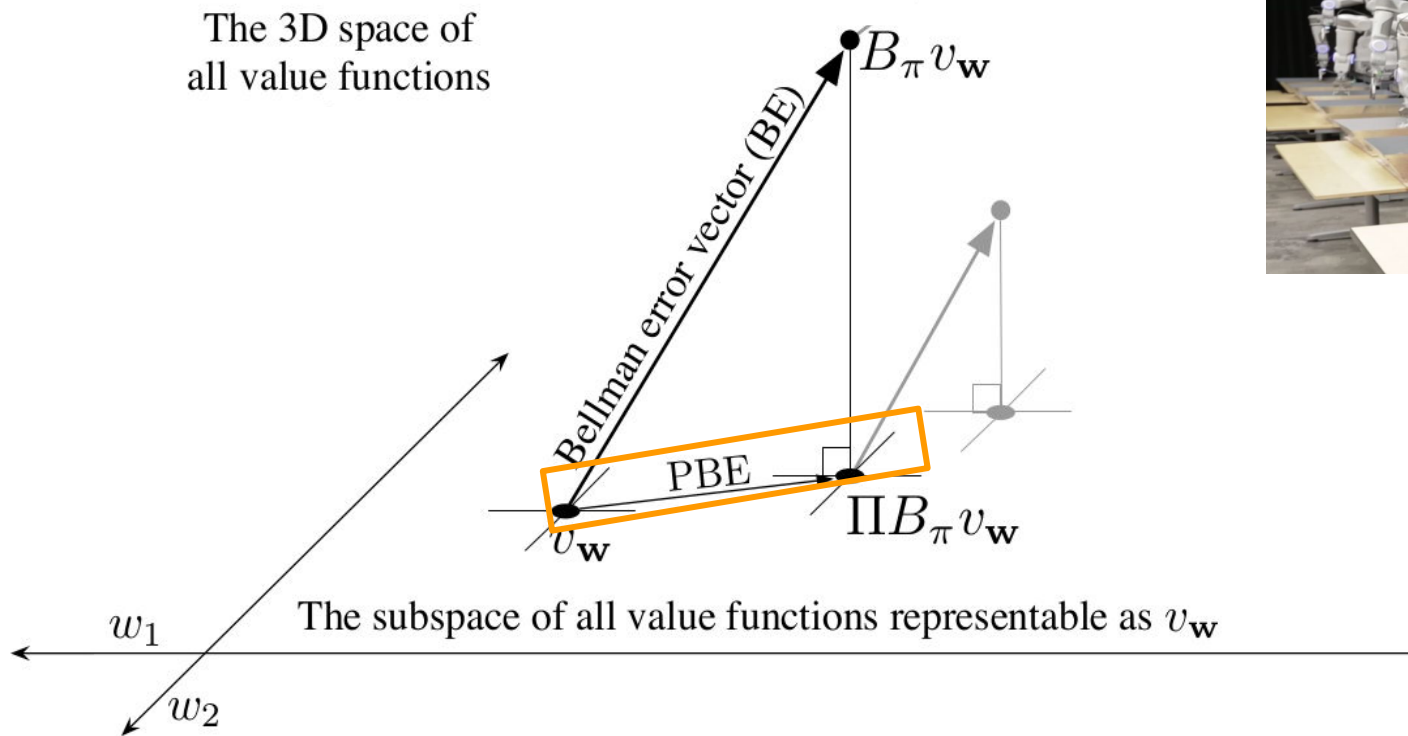
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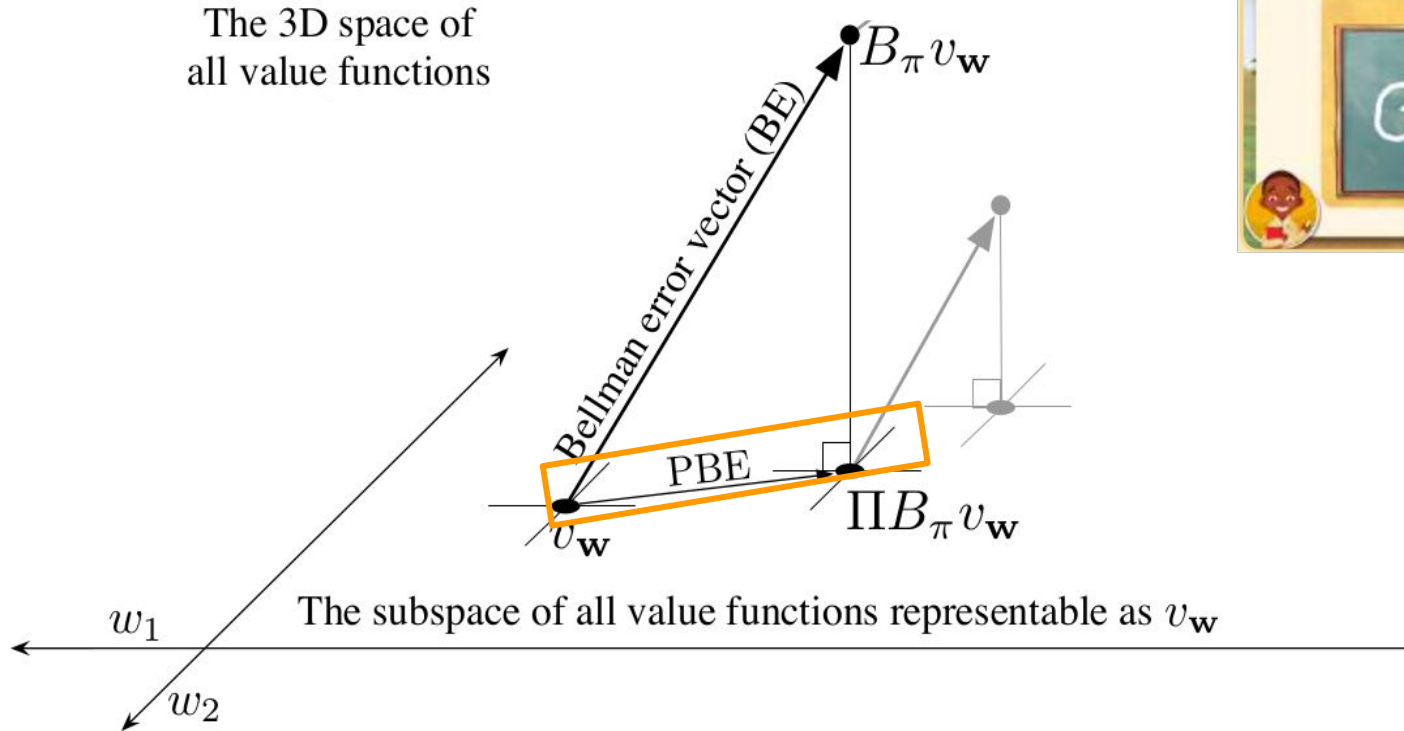
Off Policy Reinforcement Learning



Off Policy Reinforcement Learning



Batch Off Policy Reinforcement Learning



Batch Off Policy Reinforcement Learning

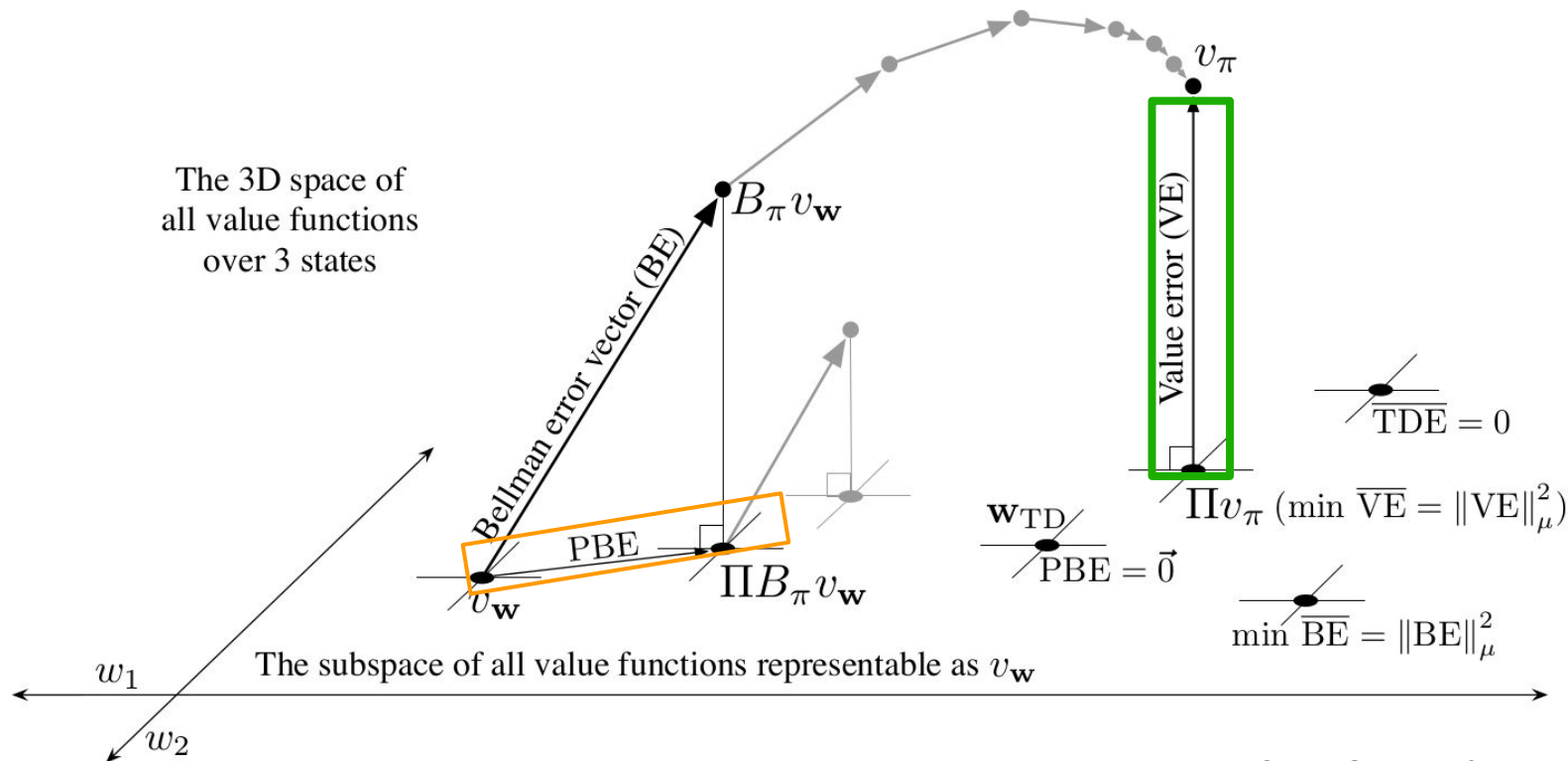


Figure from Sutton & Barto 2018

Common Evaluation Criteria for Off Policy Evaluation

- Computational efficiency
- Performance accuracy

$$\forall \mathcal{D}_i \in \{\mathcal{D}_1 \sim \mathcal{M}_1, \mathcal{D}_2 \sim \mathcal{M}_2, \dots, \mathcal{D}_K \sim \mathcal{M}_K\} \quad \frac{1}{|\rho|} \sum_{s_0 \in \rho} (\hat{V}_{\mathcal{M}_i}^{\pi}(s_0, \mathcal{D}_i) - V_{\mathcal{M}_i}^{\pi}(s_0))^2$$

$$\lim_{|\mathcal{D}| \rightarrow \infty} \frac{1}{|\rho|} \sum_{s_0 \in \rho} \hat{V}^{\pi}(s_0, \mathcal{D}) \rightarrow \frac{1}{|\rho|} \sum_{s_0 \in \rho} V^{\pi}(s_0)$$

$$\frac{1}{|\rho|} \sum_{s_0 \in \rho} \hat{V}^{\pi}(s_0, \mathcal{D}) \leq \frac{1}{|\rho|} \sum_{s_0 \in \rho} V^{\pi}(s_0) - f(n, \dots)$$

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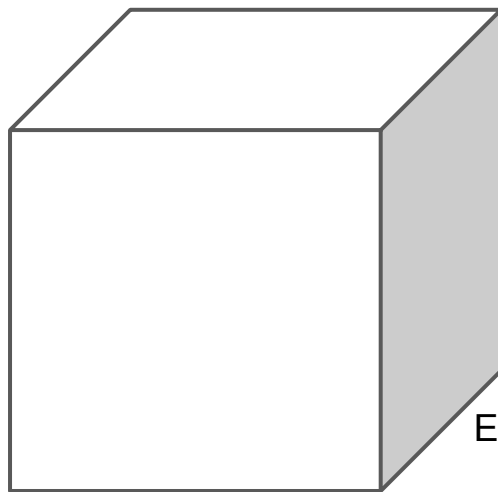
S_0 : Set of initial states

$\hat{V}^{\pi}(s, \mathcal{D})$: Estimate $V(s)$ w/dataset $\mathcal{D}$

Offline / Batch Reinforcement Learning

Tasks

$$\arg \max_{\pi \in \mathcal{H}_i} \int_{s \in S_0} \hat{V}^{\pi}(s, \mathcal{D}) ds$$



Assumptions

Evaluation
Criteria

- Empirical accuracy
- Consistency
- Robustness
- Asymptotic efficiency
- Finite sample bounds
- Computational cost

- Markov?
- Overlap?
- Sequential ignorability?

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Batch Policy Optimization: Find a Good Policy That Will Perform Well in the Future

$$\underbrace{\arg \max_{\pi \in \mathcal{H}_i} \max_{\mathcal{H}_i \in \{\mathcal{H}_1, \mathcal{H}_2, \dots\}}}_{\text{Policy Optimization}} \underbrace{\int_{s \in S_0} \hat{V}^\pi(s, \mathcal{D}) ds}_{\text{Policy Evaluation}}$$

$$\mathcal{H} = \mathcal{M}, \mathcal{V}, \Pi ?$$

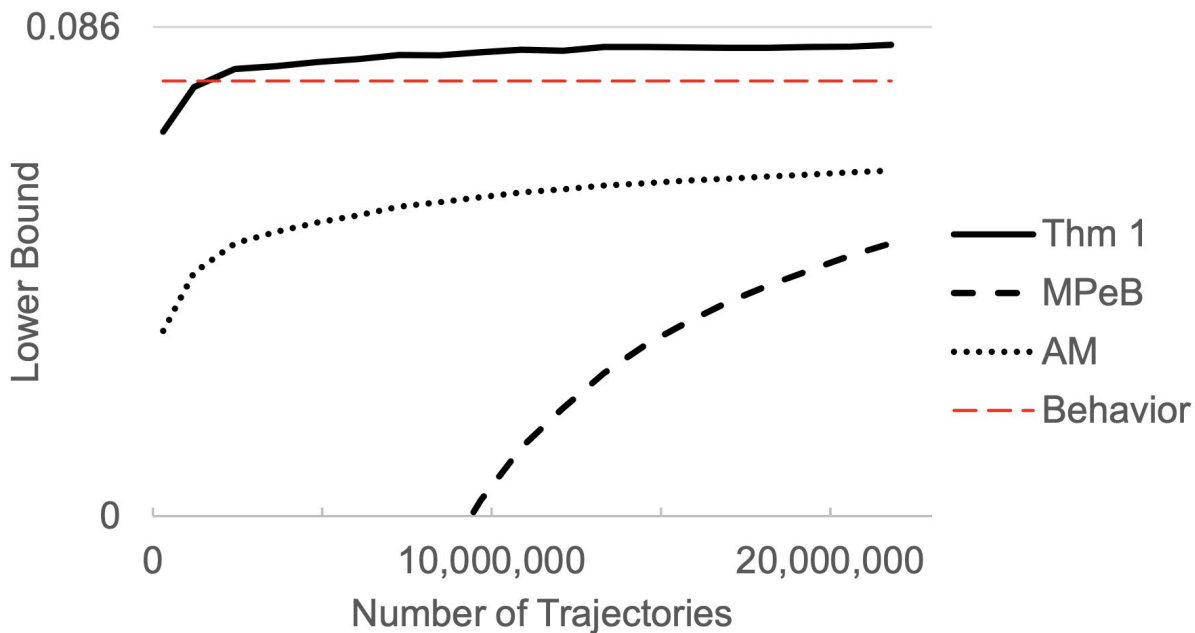
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Batch Policy Evaluation: Estimate the Performance of a Particular Decision Policy

$$\underbrace{\arg \max_{\pi \in \mathcal{H}_i} \max_{\mathcal{H}_i \in \{\mathcal{H}_1, \mathcal{H}_2, \dots\}}}_{\text{Policy Optimization}} \underbrace{\int_{s \in S_0} \hat{V}^\pi(s, \mathcal{D}) ds}_{\text{Policy Evaluation}}$$

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Policy Evaluation



Outline

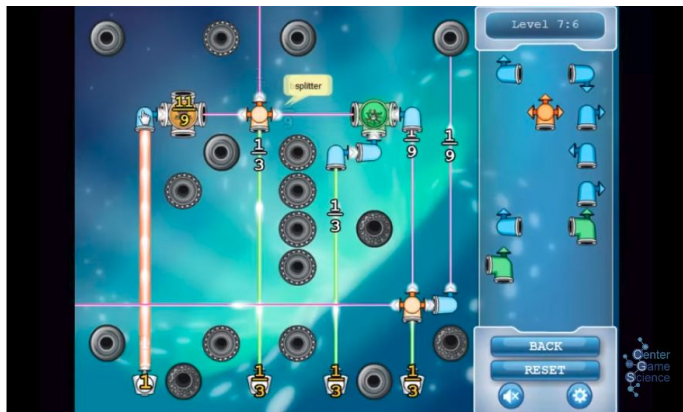
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5. Safe batch RL

Level 1:8
Fork

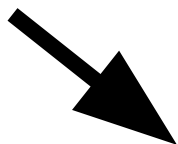
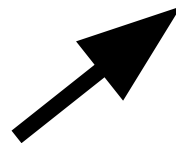


MENU

OPTIONS



Took > 30s



Took <= 30s



Given ~11k Learners' Trajectories
With Random Action (Levels)

Goal: Learn a New Policy to
Maximize Student Persistence

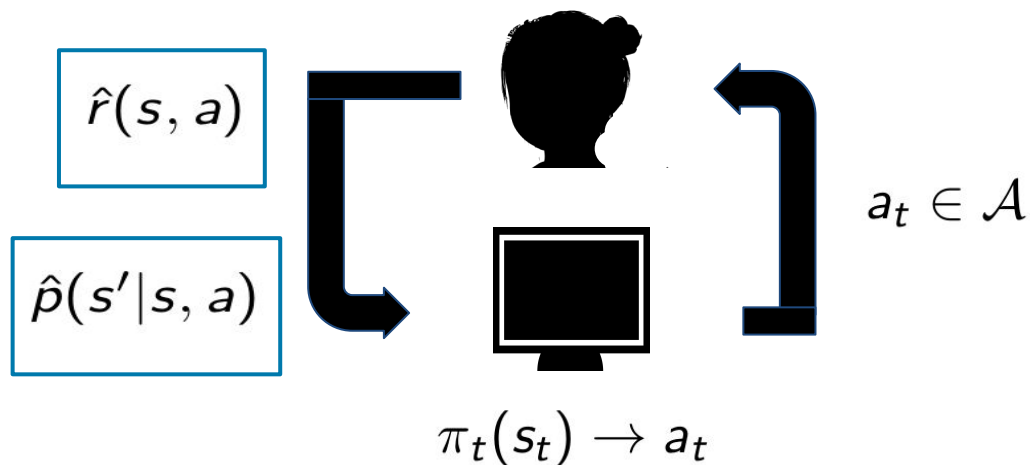
Level 1:8
Fork



MENU

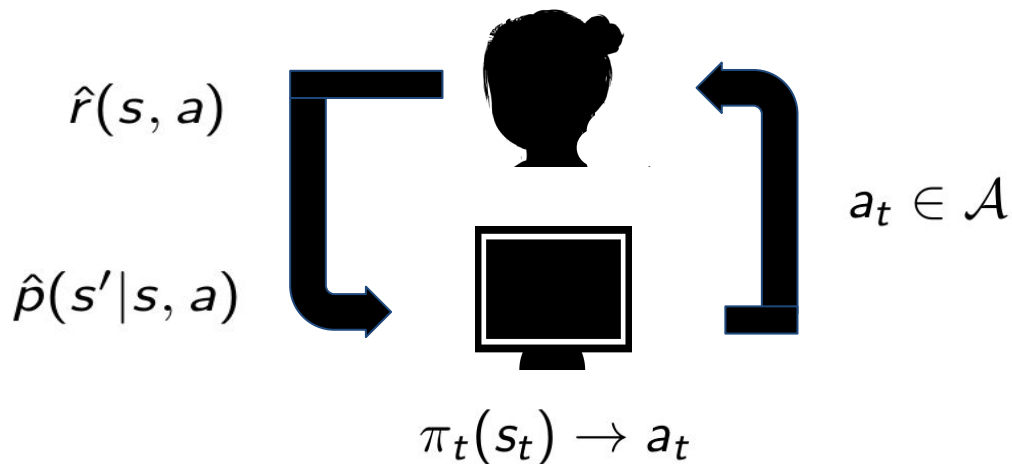
OPTIONS

Learn Dynamics and Reward Models from Data



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Learn Dynamics and Reward Models from Data, Evaluate Policy



$$V^\pi \approx (I - \gamma \hat{P}^\pi)^{-1} \hat{R}^\pi$$

$$P^\pi(s'|s) = p(s'|s, \pi(s))$$

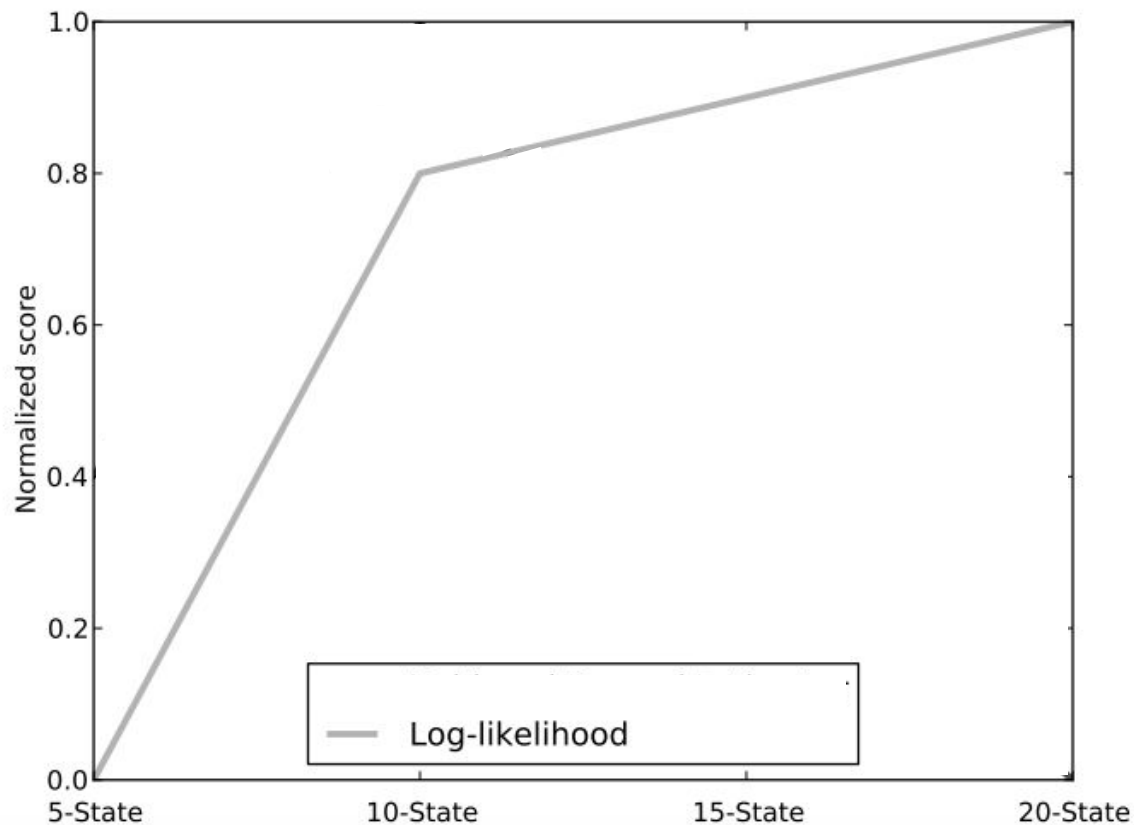
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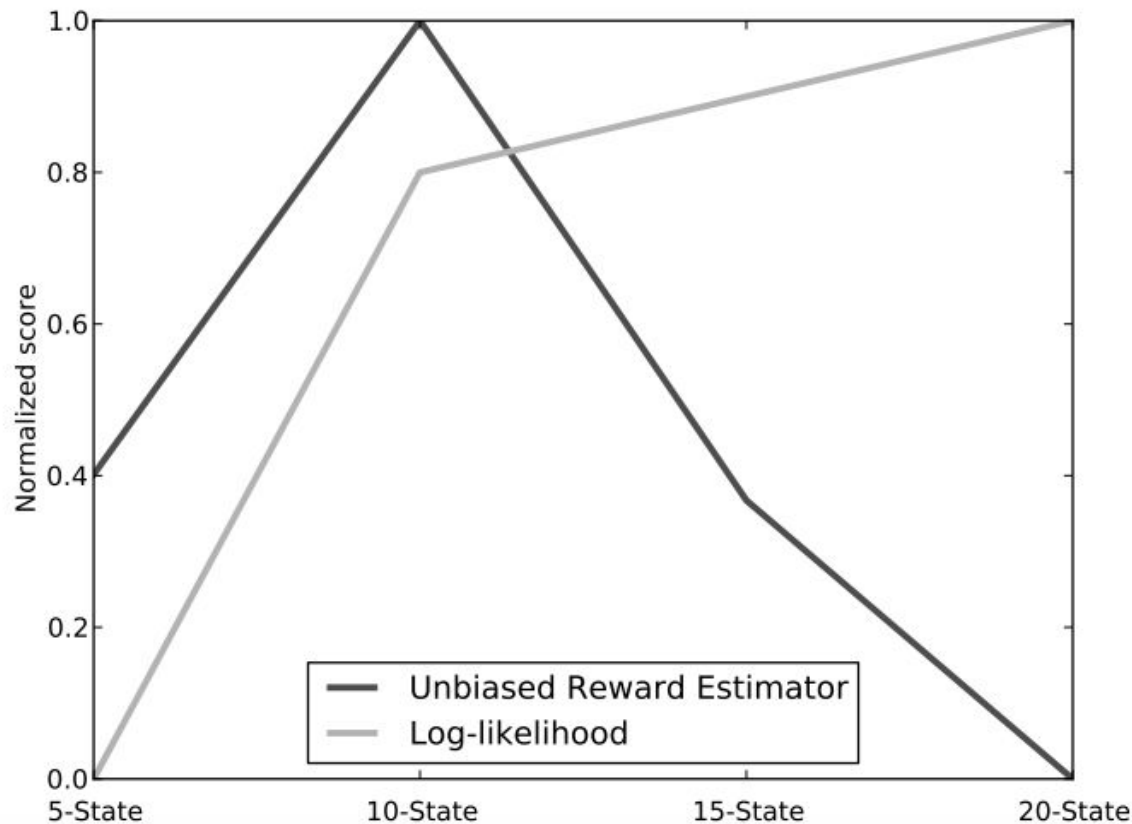
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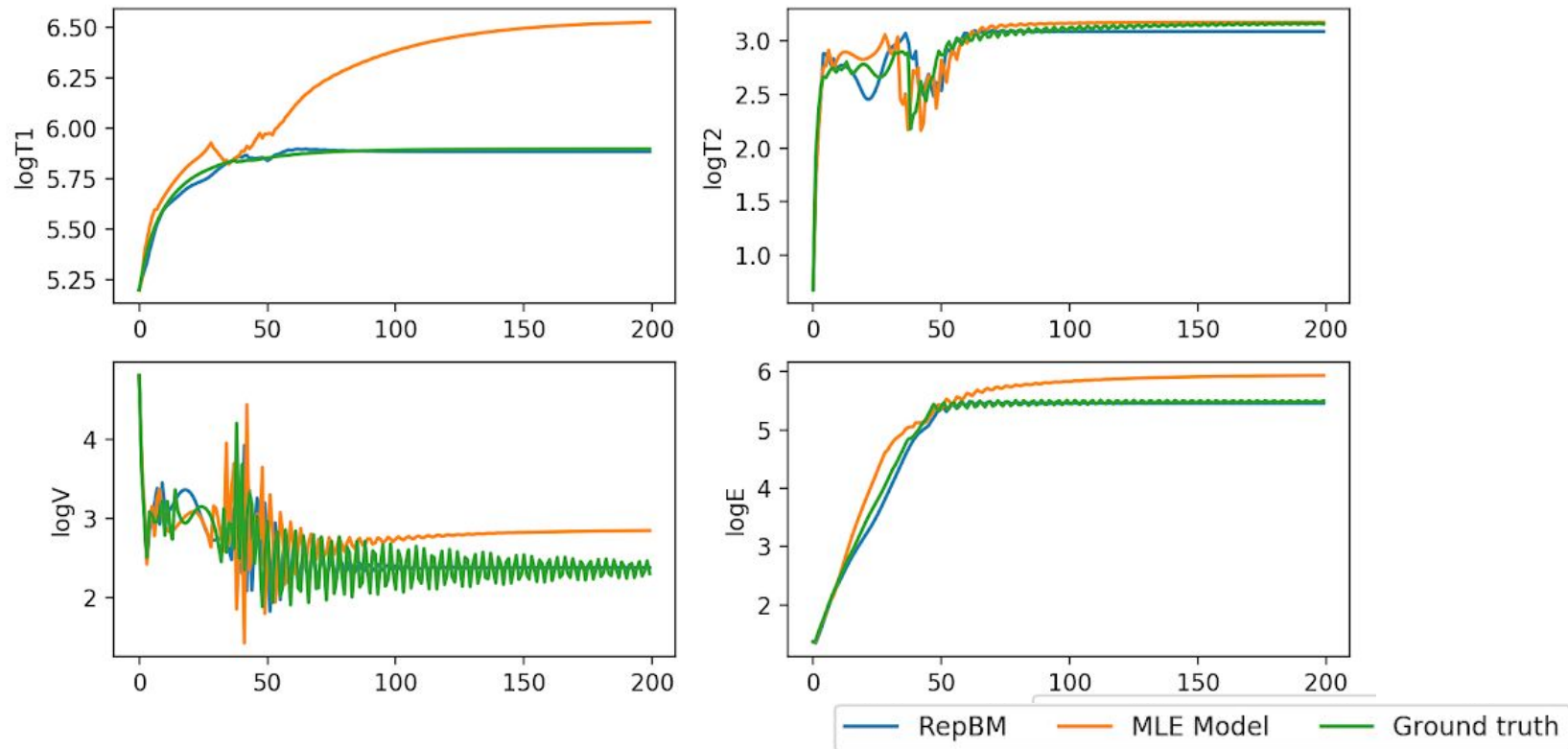
Better Dynamics/Reward Models for Existing Data (Improve likelihood)



Better Dynamics/Reward Models for Existing Data, May **Not** Lead to Better Policies for Future Use → Bias due to Model **Misspecification**



Models Fit for Off Policy Evaluation Can Result in Better Estimates When Trained Under a **Different Loss Function**



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Model Free Value Function Approximation: Fitted Q Evaluation

$$\mathcal{D} = (s_i, a_i, r_i, s_{i+1}) \forall i$$

$$\tilde{Q}^{\pi}(s_i, a_i) = r_i + \gamma V_{\theta}^{\pi}(s_{i+1})$$

$$\arg \min_{\theta} \sum_i (Q_{\theta}^{\pi}(s_i, a_i) - \tilde{Q}^{\pi}(s_i, a_i))^2$$

- Fitted Q evaluation, LSTD, ...

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Algorithm 3 Fitted Q Evaluation: $\text{FQE}(\pi, c)$

Input: Dataset $D = \{x_i, a_i, x'_i, c_i\}_{i=1}^n \sim \pi_D$. Function class F .

Policy π to be evaluated

- 1: Initialize $Q_0 \in F$ randomly
- 2: **for** $k = 1, 2, \dots, K$ **do**
- 3: Compute target $y_i = c_i + \gamma Q_{k-1}(x'_i, \pi(x'_i)) \quad \forall i$
- 4: Build training set $\tilde{D}_k = \{(x_i, a_i), y_i\}_{i=1}^n$
- 5: Solve a supervised learning problem:

$$Q_k = \arg \min_{f \in F} \frac{1}{n} \sum_{i=1}^n (f(x_i, a_i) - y_i)^2$$

6: **end for**

Output: $\hat{C}^\pi(x) = Q_K(x, \pi(x)) \quad \forall x$

Let's assume
we use a DNN
for F .

What is
different vs
DQN?

Example Fitted Q Evaluation Guarantees

$$d_F^\pi = \sup_{g \in F} \inf_{f \in F} \|f - B^\pi g\|_\pi$$

Theorem 4.2 (Generalization error of FQE). *Under Assumption 1, for $\epsilon > 0$ & $\delta \in (0, 1)$, after K iterations of Fitted Q Evaluation (Algorithm 3), for $n = O\left(\frac{\bar{C}^4}{\epsilon^2} \left(\log \frac{K}{\delta} + \dim_F \log \frac{\bar{C}^2}{\epsilon^2} + \log \dim_F\right)\right)$, we have with probability $1 - \delta$:*

$$\left| \int_{s_0 \in \rho} \hat{V}^\pi(s_0) - V^\pi(s_0) \right| \leq \frac{\gamma^{.5}}{(1 - \gamma)^{1.5}} \left(\sqrt{\beta_u} (2d_F^\pi + \epsilon) + \frac{2\gamma^{K/2} \bar{C}}{(1 - \gamma)^{.5}} \right)$$

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Model Free Policy Evaluation

- Challenge: still relies on Markov assumption
- Challenge: still relies on models being well specified or have no computable guarantees if there is misspecification

$$d_F^\pi = \sup_{g \in F} \inf_{f \in F} \|f - B^\pi g\|_\pi$$

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Off Policy Evaluation With Minimal Assumptions

- Would like a method that doesn't rely on models being correct or Markov assumption
- Monte Carlo methods did this for online policy evaluation
- We would like to do something similar
- Challenge: data distribution mismatch

Computing Expected Return Under a Distribution

$$\mathbb{E}_p[r] = \sum_x p(x)r(x)$$

Computing Expected Return Under a Alternate Distribution: Simple Idea

$$\mathbb{E}_p[r] = \sum_x p(x)r(x)$$

Computing Expected Return Under a Alternate Distribution: Simple Idea, Worked Example

$$\mathbb{E}_p[r] = \sum_x p(x)r(x)$$

	Arm 1	Arm 2	Arm 3	Arm 4
Gaussian mean	10	1	0	0.5
Behavior policy q	0.2	0.5	0.15	0.15
Evaluation policy p	0.8	0.2	0	0
Num samples from behavior q	20	50	15	15

Why Did This Fail?

$$\mathbb{E}_p[r] = \sum_x p(x)r(x)$$

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Importance Sampling*

$$\mathbb{E}_p[r] = \sum_x p(x)r(x)$$

*Former CS234 student said this was his favorite idea of the class!

Importance Sampling: Can Compute Expected Value Under An Alternate Distribution!

$$\begin{aligned}\mathbb{E}_p[r] &= \sum_x p(x)r(x) \\ &= \sum_x \frac{p(x)q(x)}{q(x)} r(x) \\ &\approx \frac{1}{N} \sum_{i=1, x \sim q}^N \frac{p(x_i)}{q(x_i)} r(x_i)\end{aligned}$$

Importance Sampling is an Unbiased Estimator of True Expectation Under Desired Distribution If

$$\begin{aligned}\mathbb{E}_p[r] &= \sum_x p(x)r(x) \\ &= \sum_x \frac{p(x)q(x)}{q(x)} r(x) \\ &\approx \frac{1}{N} \sum_{i=1, x \sim q}^N \frac{p(x_i)}{q(x_i)} r(x_i)\end{aligned}$$

- The sampling distribution $q(x) > 0$ for all x s.t. $p(x) > 0$ (Coverage / overlap)
- No hidden confounding

Importance Sampling (IS) Example

$$\begin{aligned}\mathbb{E}_p[r] &= \sum_x p(x)r(x) \\ &= \sum_x \frac{p(x)q(x)}{q(x)} r(x) \\ &\approx \frac{1}{N} \sum_{i=1, x \sim q}^N \frac{p(x_i)}{q(x_i)} r(x_i)\end{aligned}$$

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X = arms

Expected reward for following behavior policy? $0.2*10 + 0.5*1 + 0*0.15 + 0.15*.5$

Expected reward for target policy p? $0.8*10 + 0.2*1 = 8.2$

Computing expected reward for p using IS: $(20/100) * (.8/.2) * 10 + (50/100)*(.2/.5)*1 = 8.2$ ₅₉

Check Your Understanding: Importance Sampling

We can use importance sampling to do batch bandit policy evaluation. Consider we have a dataset for pulls from 3 arms. Consider that arm 1 is a Bernoulli where with probability .98 we get 0 and with probability 0.02 we get 100. Arm 2 is a Bernoulli where with probability 0.55 the reward is 2 else the reward is 0. Arm 3 has a probability of yielding a reward of 1 with probability 0.5 else it gets 0. Select all that are true.

- Data is sampled from π_1 where with probability 0.8 it pulls arm 3 else it pulls arm 2. The policy we wish to evaluate, π_2 , pulls arm 2 with probability 0.5 else it pulls arm 1. π_2 has higher true reward than π_1 .
- We cannot use π_1 to get an unbiased estimate of the average reward π_2 using importance sampling.
- If rewards can be positive or negative, we can still get a lower bound on π_2 using data from π_1 using importance sampling
- Now assume π_1 selects arm1 with probability 0.2 and arm2 with probability 0.8. We can use importance sampling to get an unbiased estimate of π_2 using data from π_1 .
- Still with the same π_1 , it is likely with $N=20$ pulls that the estimate using IS for π_2 will be higher than the empirical value of π_1 .
- Not Sure

Importance Sampling for RL Policy Evaluation

$$V^{\pi}(s) = \sum_{\tau} p(\tau|\pi, s) R(\tau)$$

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Importance Sampling for RL Policy Evaluation

$$\begin{aligned} V^\pi(s) &= \sum_{\tau} p(\tau|\pi, s) R(\tau) \\ &= \sum_{\tau} p(\tau|\pi_b, s) \frac{p(\tau|\pi, s)}{p(\tau|\pi_b, s)} R_{\tau} \\ &\approx \sum_{i=1, \tau_i \sim \pi_b}^N \frac{p(\tau_i|\pi, s)}{p(\tau_i|\pi_b, s)} R_{\tau_i} \end{aligned}$$

$\mathcal{D}$: Dataset of n traj.s τ , $\tau \sim \pi_b$

π : Policy mapping $s \rightarrow a$

S_0 : Set of initial states

$\hat{V}^\pi(s, \mathcal{D})$: Estimate $V(s)$ w/dataset $\mathcal{D}$

Importance Sampling for RL Policy Evaluation

$$\begin{aligned} V^\pi(s) &= \sum_{\tau} p(\tau|\pi, s) R(\tau) \\ &= \sum_{\tau} p(\tau|\pi_b, s) \frac{p(\tau|\pi, s)}{p(\tau|\pi_b, s)} R_{\tau} \\ &\approx \sum_{i=1, \tau_i \sim \pi_b}^N \frac{p(\tau_i|\pi, s)}{p(\tau_i|\pi_b, s)} R_{\tau_i} \\ &= \sum_{i=1, \tau_i \sim \pi_b}^N R_{\tau_i} \prod_{t=1}^{H_i} \frac{p(s_{i,t+1}|s_{it}, a_{it}) p(a_{it}|\pi, s_{it})}{p(s_{i,t+1}|s_{it}, a_{it}) p(a_{it}|\pi_b, s_{it})} \\ &= \sum_{i=1, \tau_i \sim \pi_b}^N R_{\tau_i} \prod_{t=1}^{H_i} \frac{p(a_{it}|\pi, s_{it})}{p(a_{it}|\pi_b, s_{it})} \end{aligned}$$

$\mathcal{D}$: Dataset of n traj.s τ , $\tau \sim \pi_b$

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$\hat{V}^\pi(s, \mathcal{D})$: Estimate $V(s)$ w/dataset $\mathcal{D}$

Importance Sampling for RL Policy Evaluation: Don't Need to Know Dynamics Model!

$$\begin{aligned} V^\pi(s) &= \sum_{\tau} p(\tau|\pi, s) R(\tau) \\ &= \sum_{\tau} p(\tau|\pi_b, s) \frac{p(\tau|\pi, s)}{p(\tau|\pi_b, s)} R_{\tau} \\ &\approx \sum_{i=1, \tau_i \sim \pi_b}^N \frac{p(\tau_i|\pi, s)}{p(\tau_i|\pi_b, s)} R_{\tau_i} \\ &= \sum_{i=1, \tau_i \sim \pi_b}^N R_{\tau_i} \prod_{t=1}^{H_i} \frac{p(s_{i,t+1}|s_{it}, a_{it}) p(a_{it}|\pi, s_{it})}{p(s_{i,t+1}|s_{it}, a_{it}) p(a_{it}|\pi_b, s_{it})} \\ &= \sum_{i=1, \tau_i \sim \pi_b}^N R_{\tau_i} \prod_{t=1}^{H_i} \frac{p(a_{it}|\pi, s_{it})}{p(a_{it}|\pi_b, s_{it})} \end{aligned}$$

$\mathcal{D}$: Dataset of n traj.s τ , $\tau \sim \pi_b$

π : Policy mapping $s \rightarrow a$

S_0 : Set of initial states

$\hat{V}^\pi(s, \mathcal{D})$: Estimate $V(s)$ w/dataset $\mathcal{D}$

- First used for RL by Precup, Sutton & Singh 2000. Recent work includes: Thomas, Theodorou, Ghavamzadeh 2015; Thomas and Brunskill 2016; Guo, Thomas, Brunskill 2017; Hanna, Niekum, Stone 2019

Importance Sampling

- Does not rely on Markov assumption
- Requires minimal assumptions
- Provides unbiased estimator
- Similar to Monte Carlo estimator but corrects for distribution mismatch

Check Your Understanding: Importance Sampling 2

Select all that you'd guess might be true about importance sampling

- It requires the behavior policy to visit all the state--action pairs that would be visited under the evaluation policy in order to get an unbiased estimator
- It is likely to be high variance
- Not Sure

Per Decision Importance Sampling (PDIS)

- Leverage temporal structure of the domain (**similar to policy gradient**)

$$IS(D) = \frac{1}{n} \sum_{i=1}^n \left(\prod_{t=1}^L \frac{\pi_e(a_t | s_t)}{\pi_b(a_t | s_t)} \right) \left(\sum_{t=1}^L \gamma^t R_t^i \right)$$

$$PSID(D) = \sum_{t=1}^L \gamma^t \frac{1}{n} \sum_{i=1}^n \left(\prod_{\tau=1}^t \frac{\pi_e(a_\tau | s_\tau)}{\pi_b(a_\tau | s_\tau)} \right) R_t^i$$

Importance Sampling Variance

- Importance sampling, like Monte Carlo estimation, is generally high variance
- Importance sampling is particularly high variance for estimating the return of a policy in a sequential decision process

$$= \sum_{i=1, \tau_i \sim \pi_b}^N R_{\tau_i} \prod_{t=1}^{H_i} \frac{p(a_{it} | \pi, s_{it})}{p(a_{it} | \pi_b, s_{it})}$$

- Variance can generally scale exponentially with the horizon
 - a. Concentration inequalities like Hoeffding scale with the largest range of the variable
 - b. The largest range of the variable depends on the product of importance weights
 - c. **Check your understanding: for a H step horizon with a maximum reward in a single trajectory of 1, and if $p(a|s, \pi_b) = .1$ and $p(a|s, \pi) = 1$ for each time step, what is the maximum importance-weighted return for a single trajectory?**

$$R_{\tau_i} \prod_{t=1}^{H_i} \frac{p(a_{it} | \pi, s_{it})}{p(a_{it} | \pi_b, s_{it})}$$

Outline

1. Introduction and Setting
2. Offline batch evaluation using models
3. Offline batch evaluation using Q functions
4. Offline batch evaluation using importance sampling

What You Should Know

- Be able to define and apply importance sampling for off policy policy evaluation
- Define some limitations of IS (variance)
- Define why we might want to do batch offline RL and potential applications
- Be aware of the main potential limitations of model and model free methods

Class Organization

- Fast reinforcement learning
- **Learning from offline data**
 - Overview and Policy evaluation
 - **Next time: Imitation Learning**
 - Policy optimization
 - Guest lecture with Dr. Lihong Li