Offline Reinforcement Learning

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The story thus far ...

- ✅ Decision-making
- ✅ Perception
- ✅ Models of humans
- ☐ Practical Robot Learning
  - Today-> ☐ Offline RL
  - ☐ Sim-to-Real

Today's class

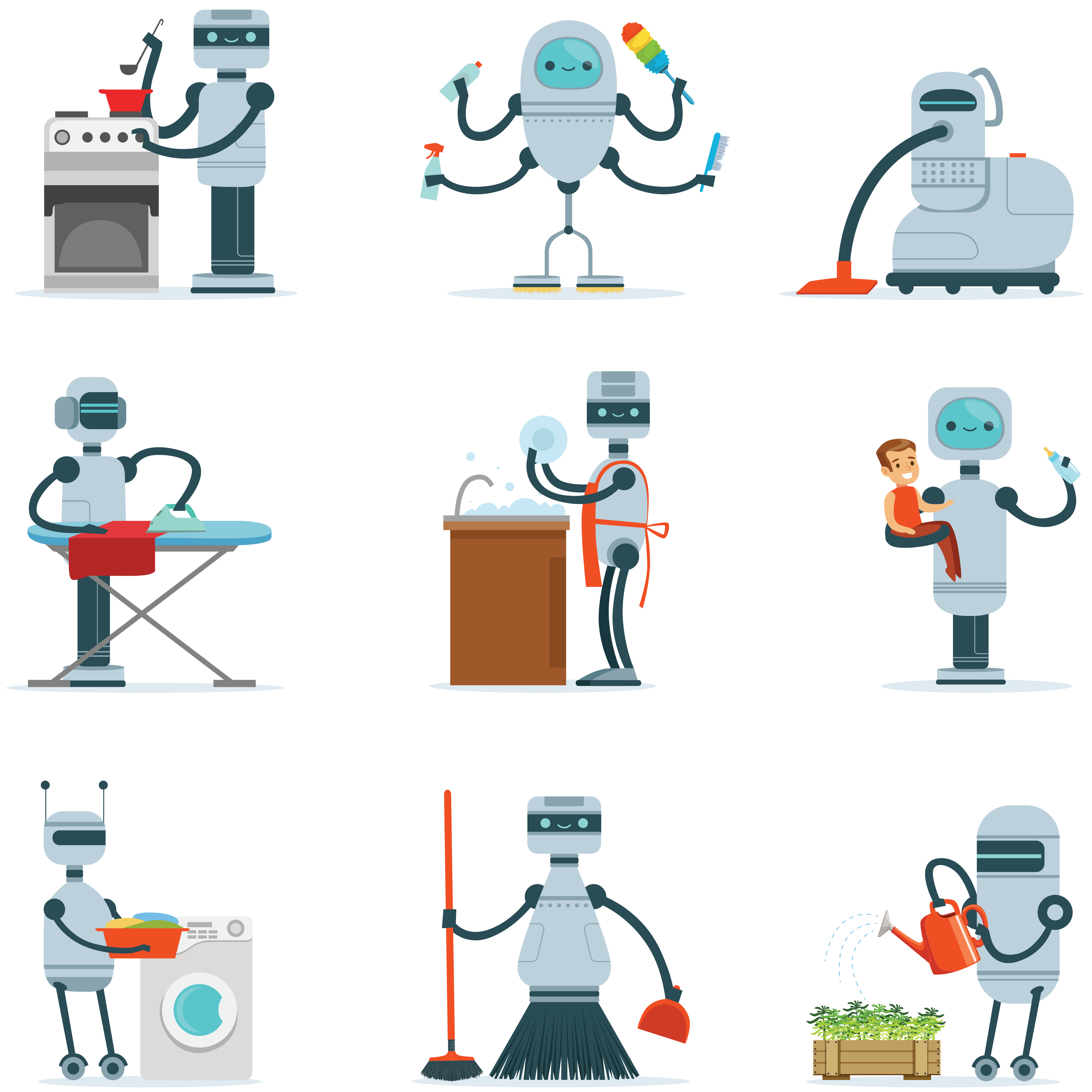
- What is offline RL? Why do we need it for robots?

- Paradigm 1: Offline RL via Pessimism
  - Problem with Q-learning
  - Pessimism to the rescue

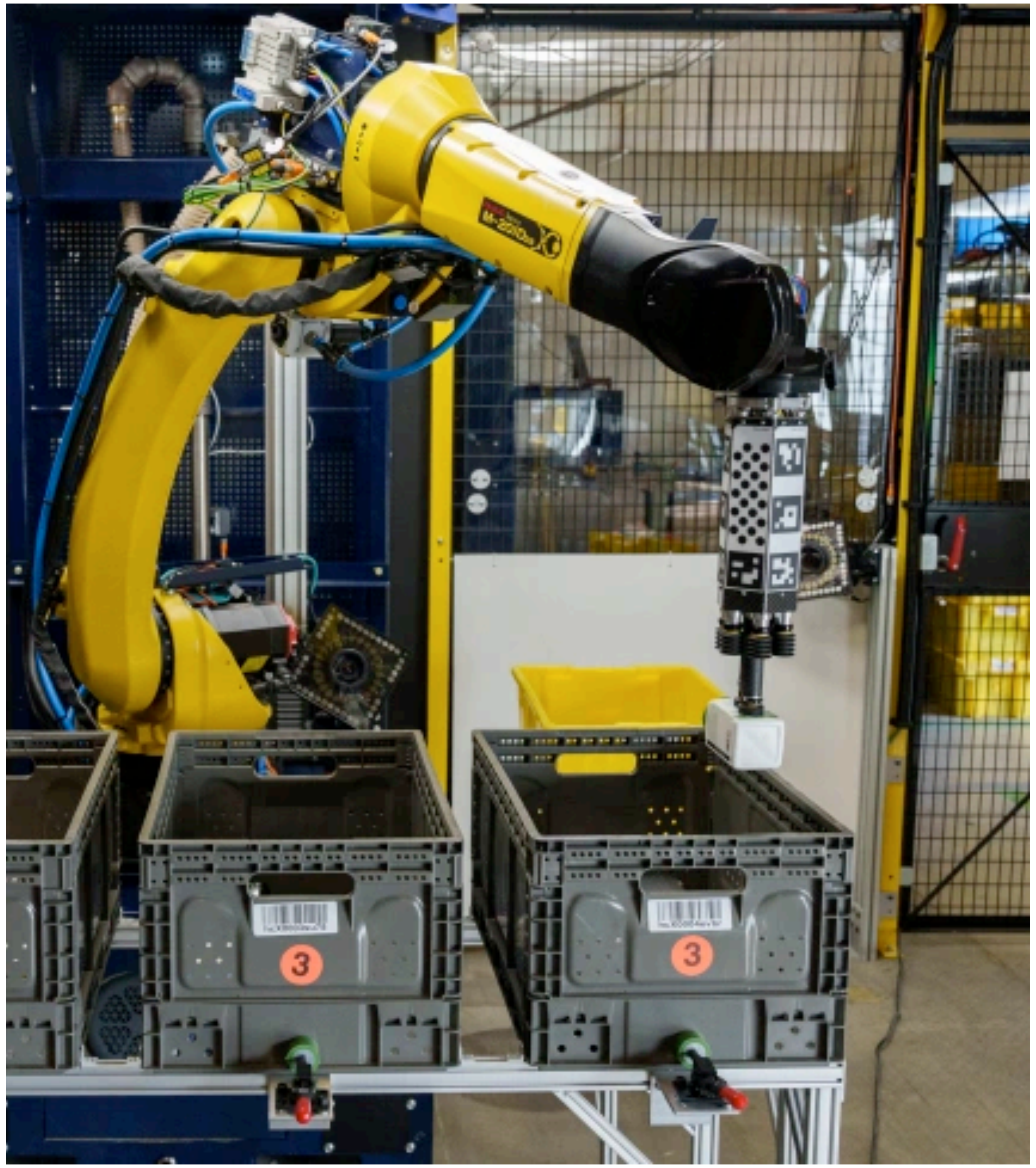
- Paradigm 2: RL via Supervised Learning
  - Return-conditioned Supervised Learning
  - Problem in Stochastic MDPs

Why do we need offline RL for robots?

Robots today still only work in CLOSED world

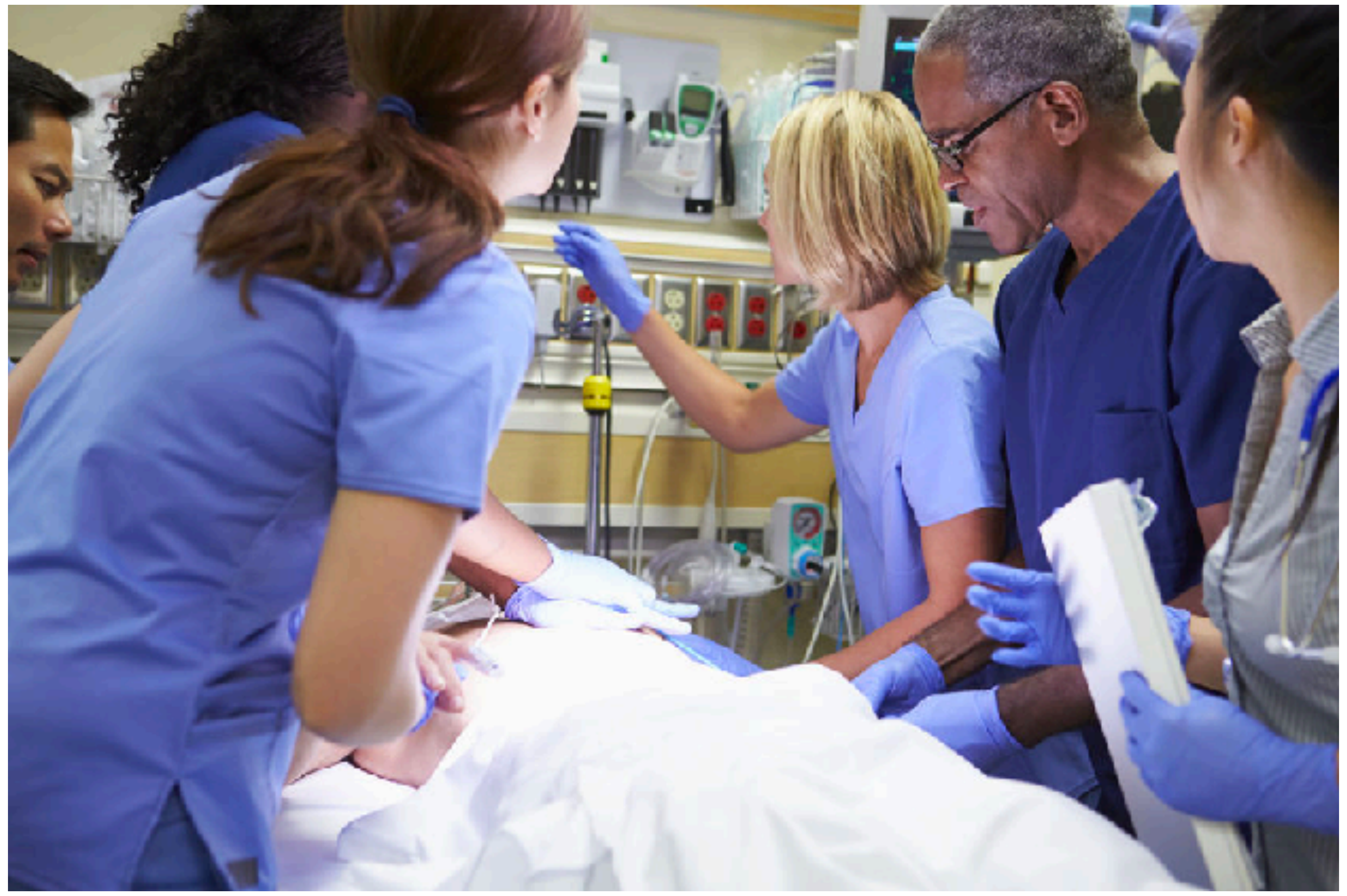


The Dream



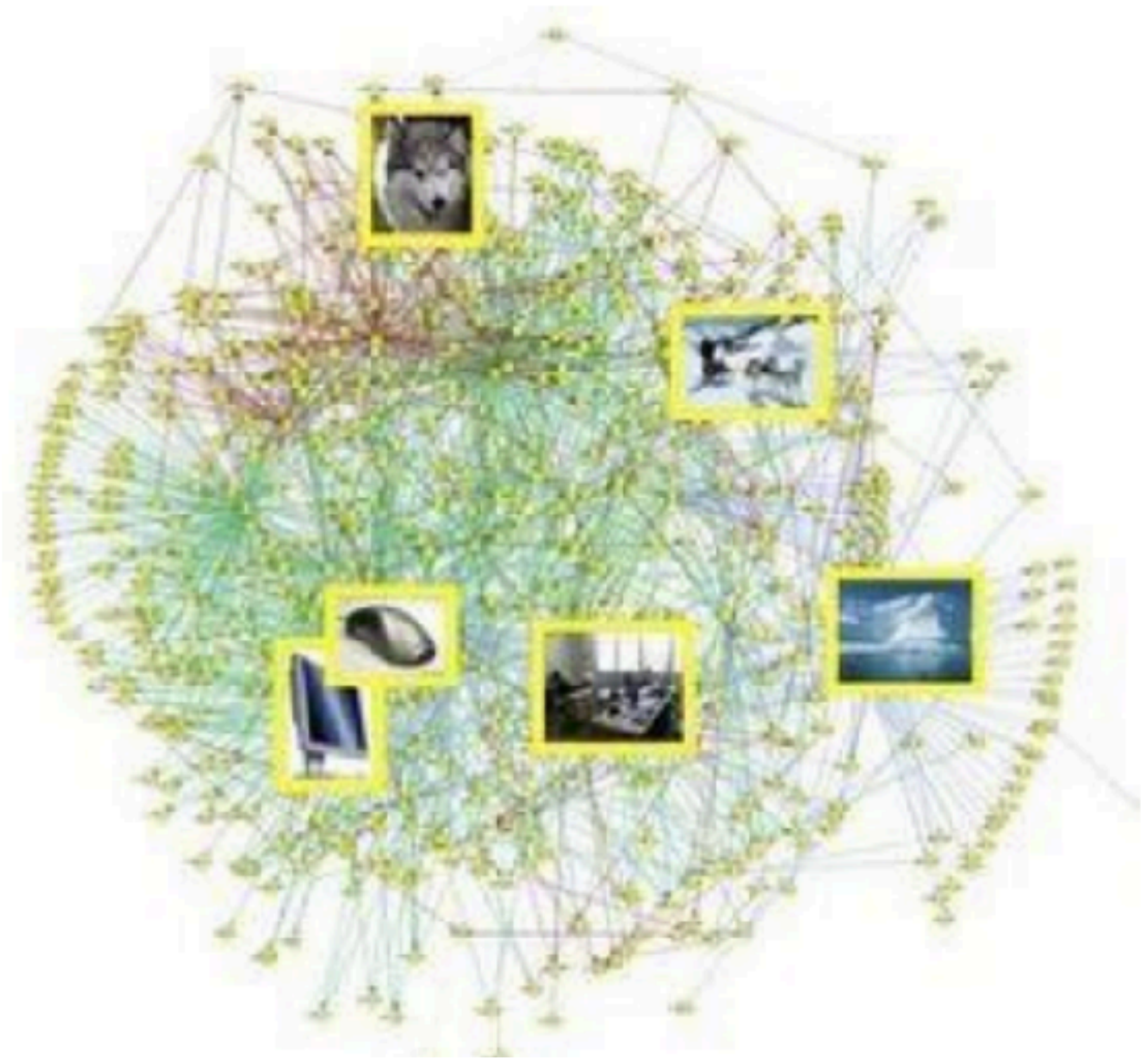
Reality

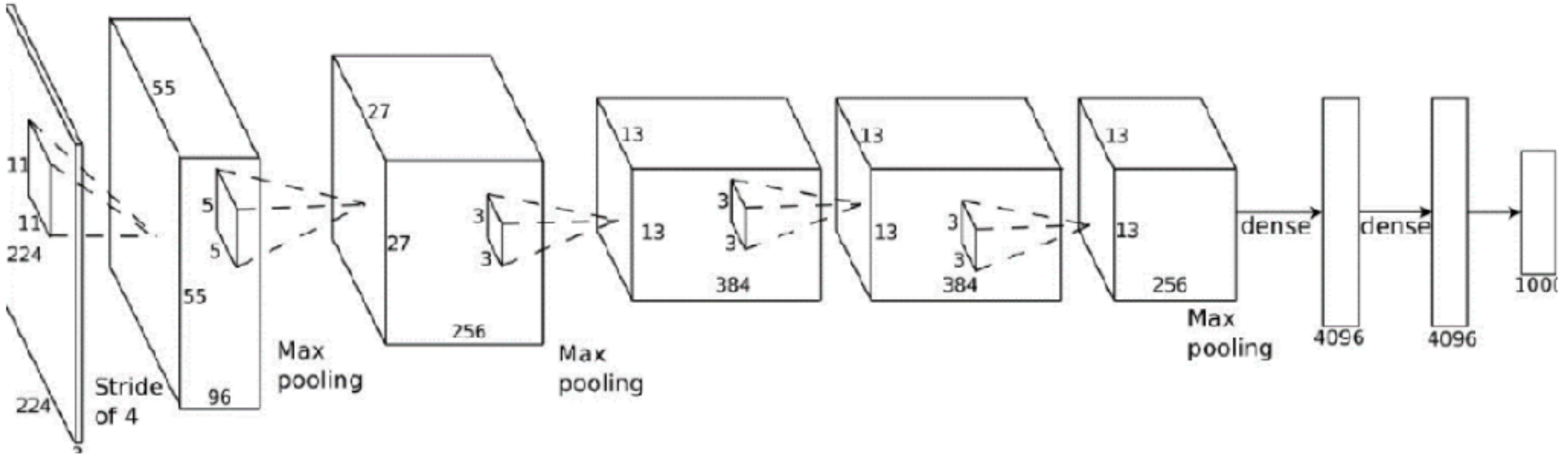
Generalize to variations of the OPEN world?



Why can't we do RL with robots in the real world?

Machine learning's answer!





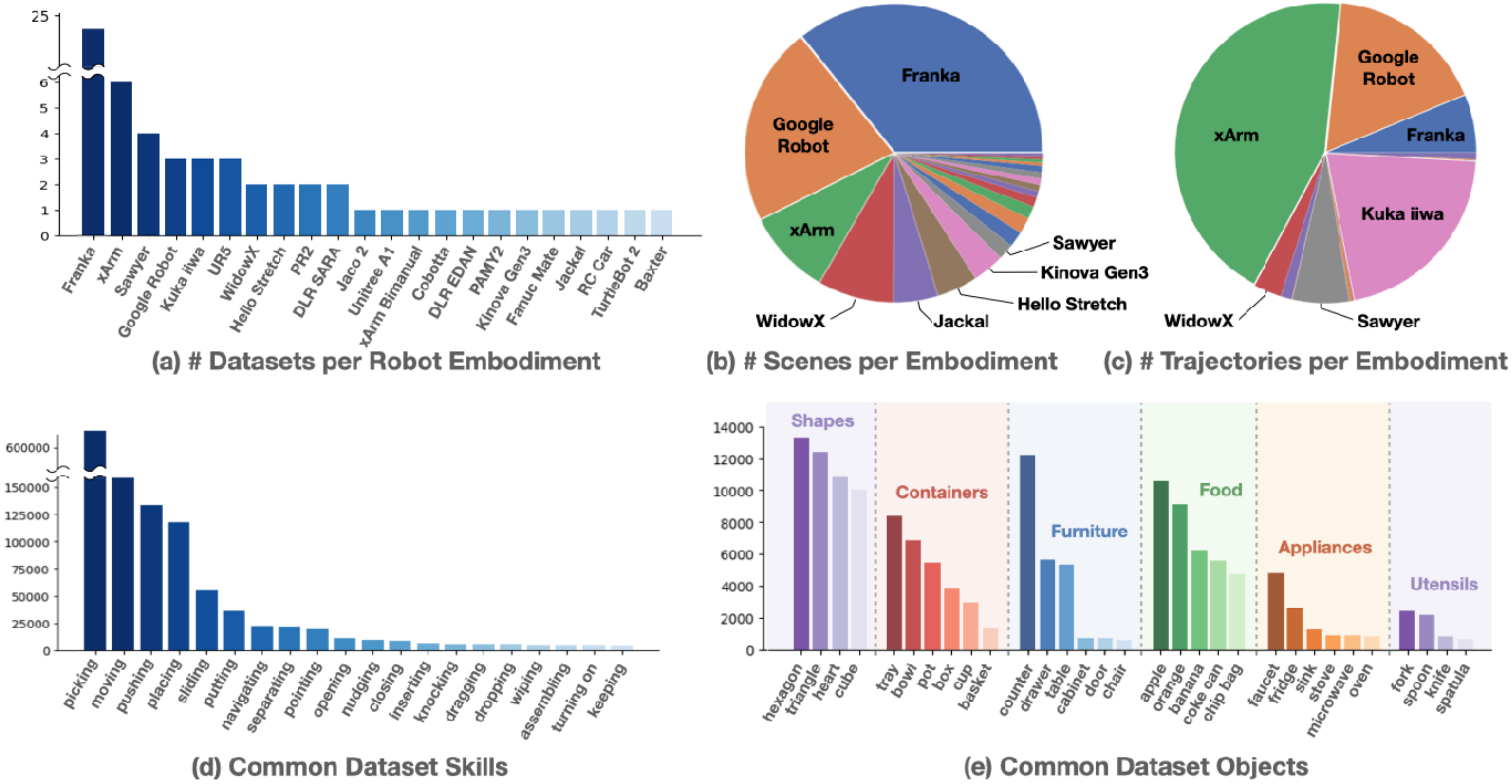
Big Data

Big Models

Credit: **Sergey Levine** "Offline RL lecture"

Efforts underway to scale up robotics data!

1M trajectories, 22 robots, 21 different institutions



(a) # Datasets per Robot Embodiment

(b) # Scenes per Embodiment

(c) # Trajectories per Embodiment

(d) Common Dataset Skills

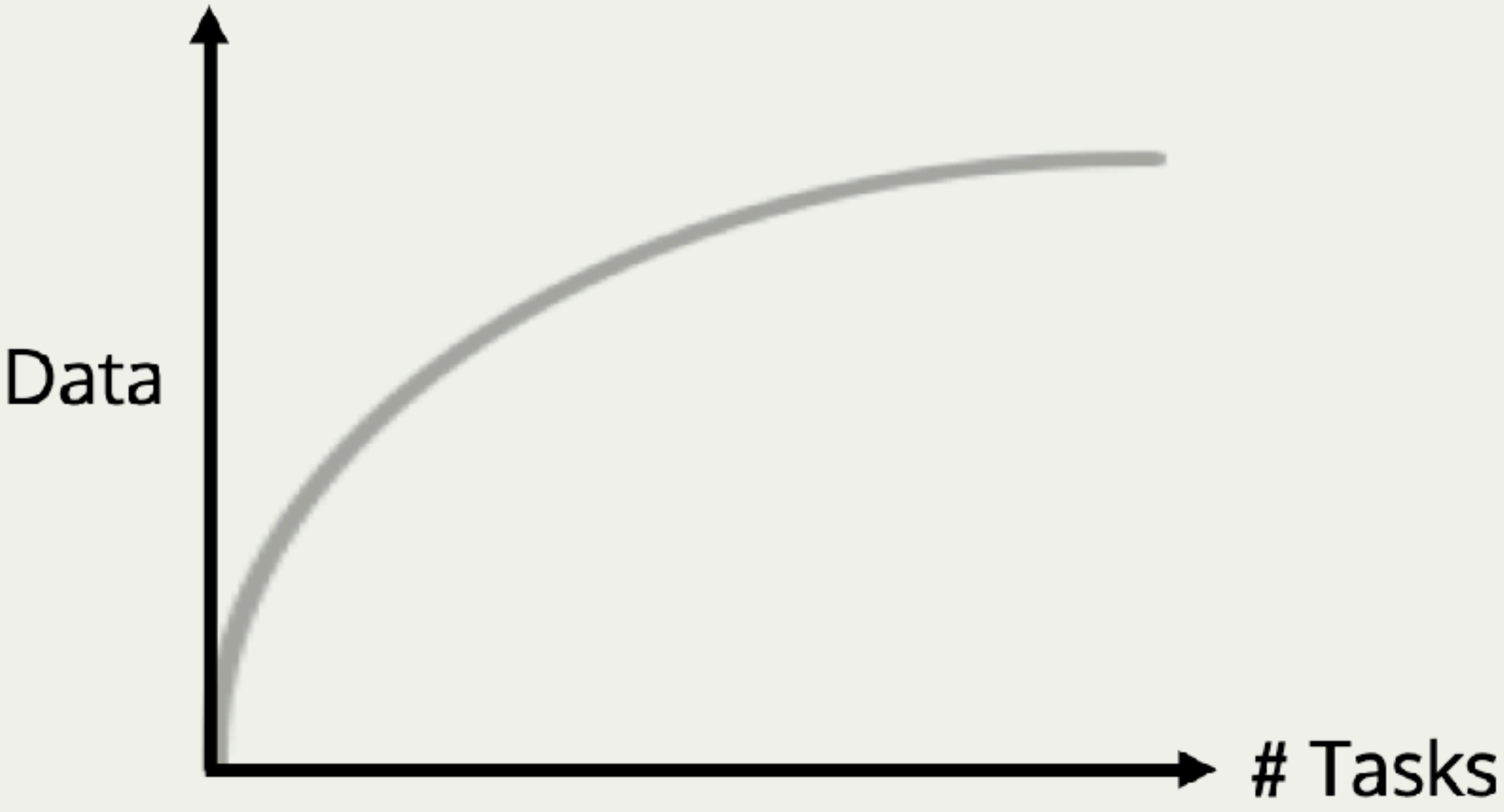
(e) Common Dataset Objects

Open-X Embodiment Dataset

Hope: Data grows logarithmically with tasks

On the quest for shared priors

w/ machine learning



Interact with the **physical** world to learn bottom-up commonsense

↑

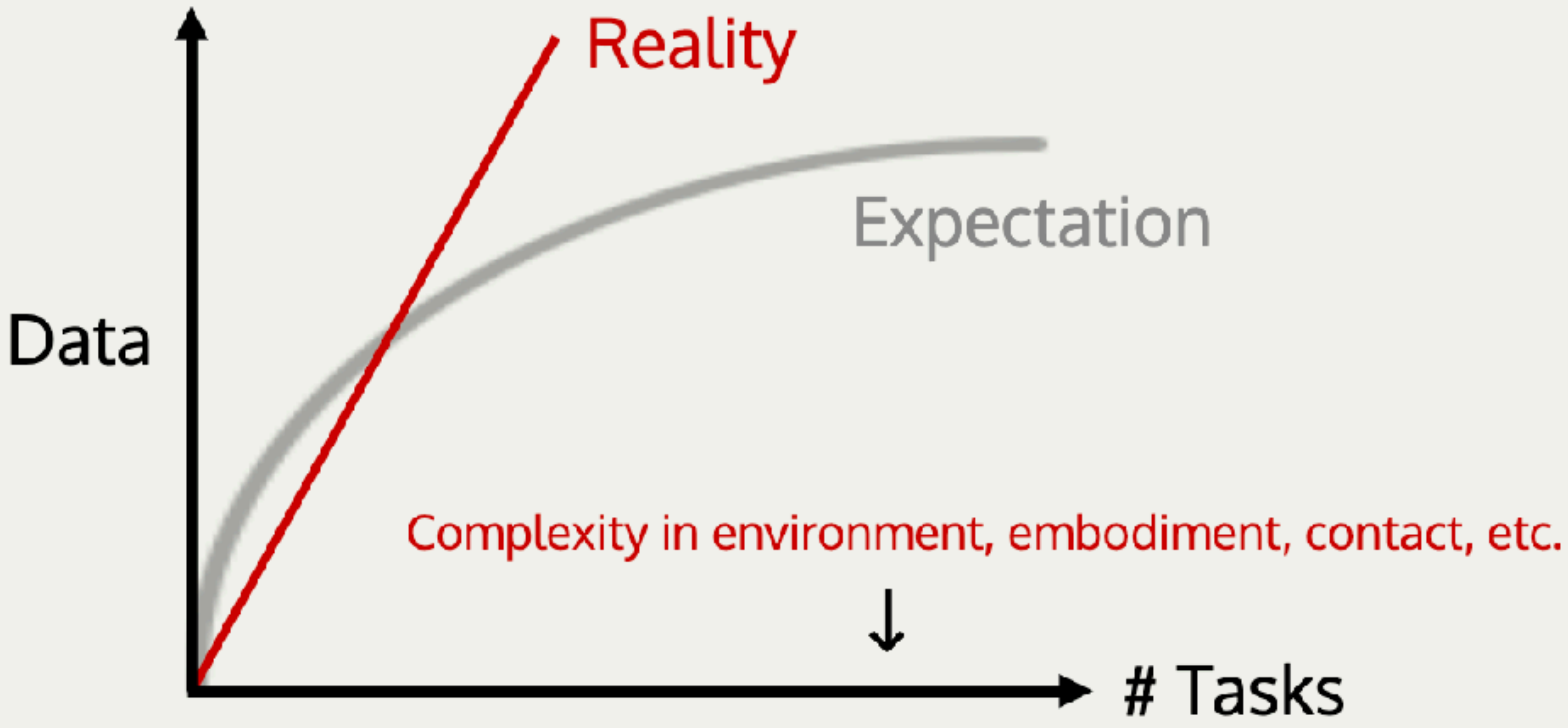
i.e. "how the world works"

Credit: **Andy Zeng**

Reality: Data grows linearly with tasks

On the quest for shared priors

w/ machine learning



Interact with the **physical** world to learn bottom-up commonsense

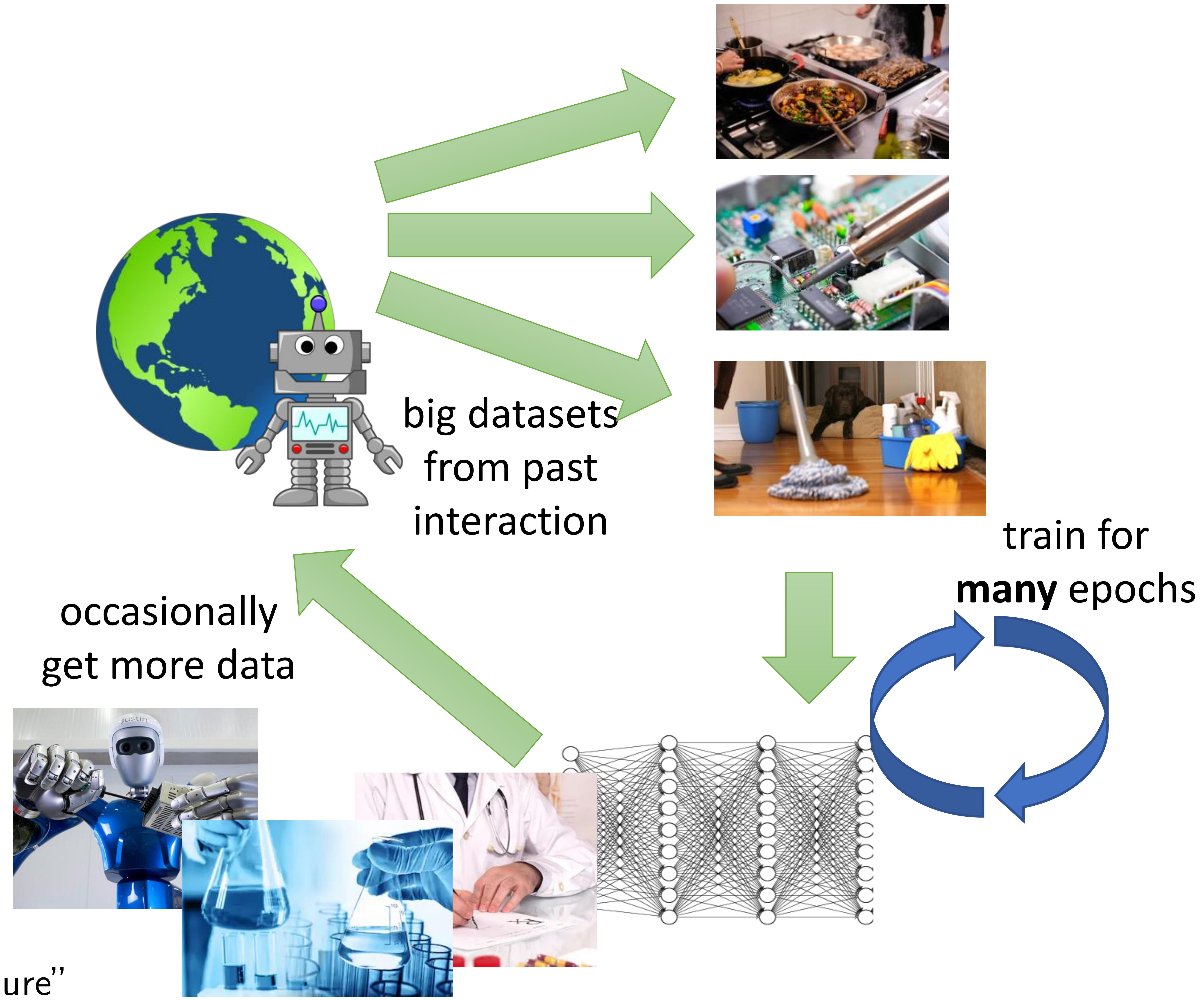
i.e. "how the world works"

Credit: **Andy Zeng**

But for today, let's pretend we can collect a ton of data
that "covers" tasks we care about

How can we learn optimal from large data collected by *any* policy?

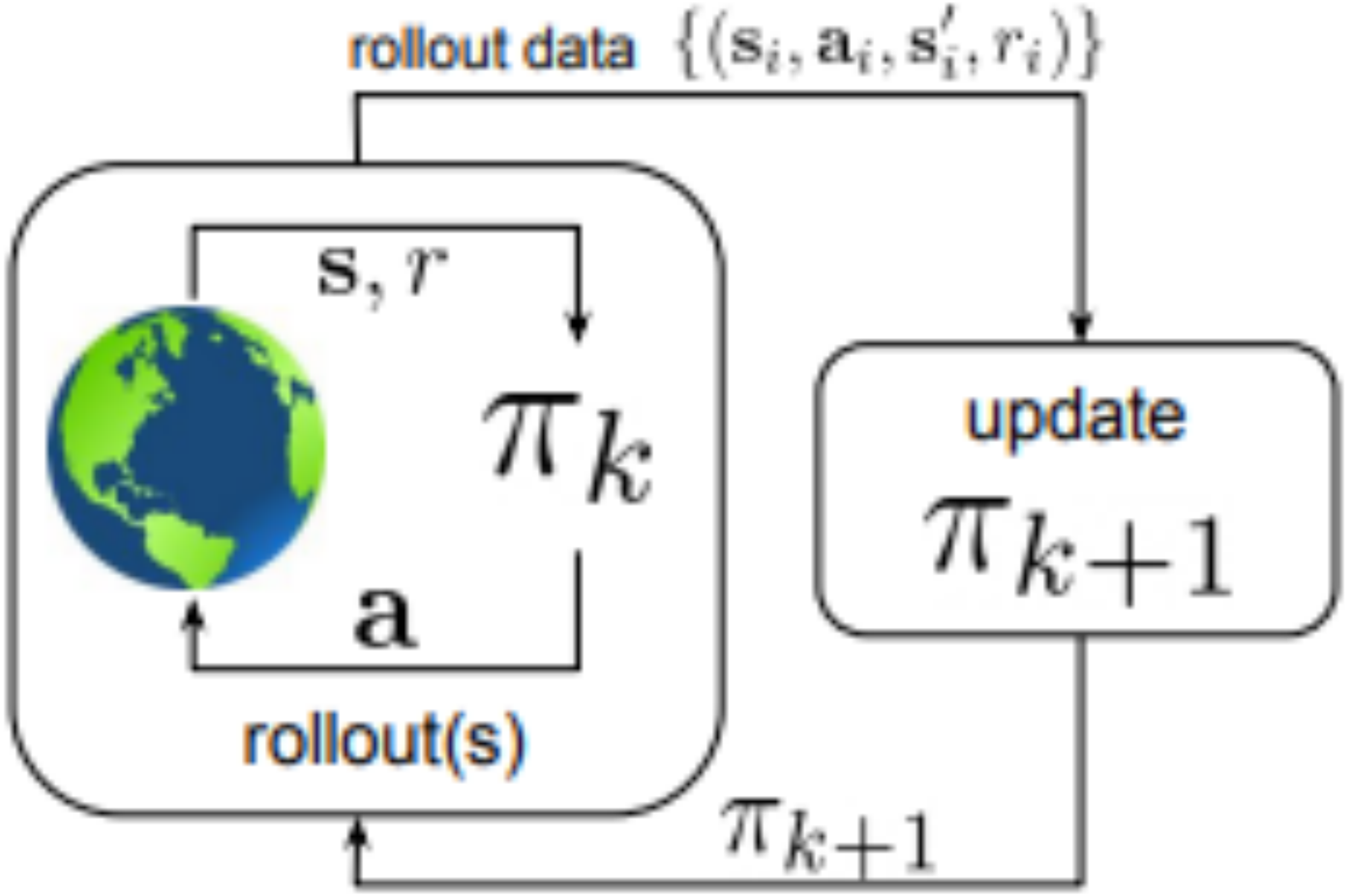
Goal: Offline Reinforcement Learning



Credit: **Sergey Levine** "Offline RL lecture"

Different paradigms of RL

on-policy RL



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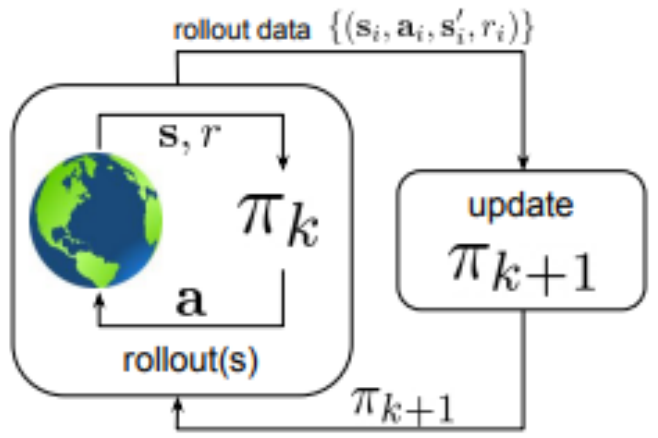
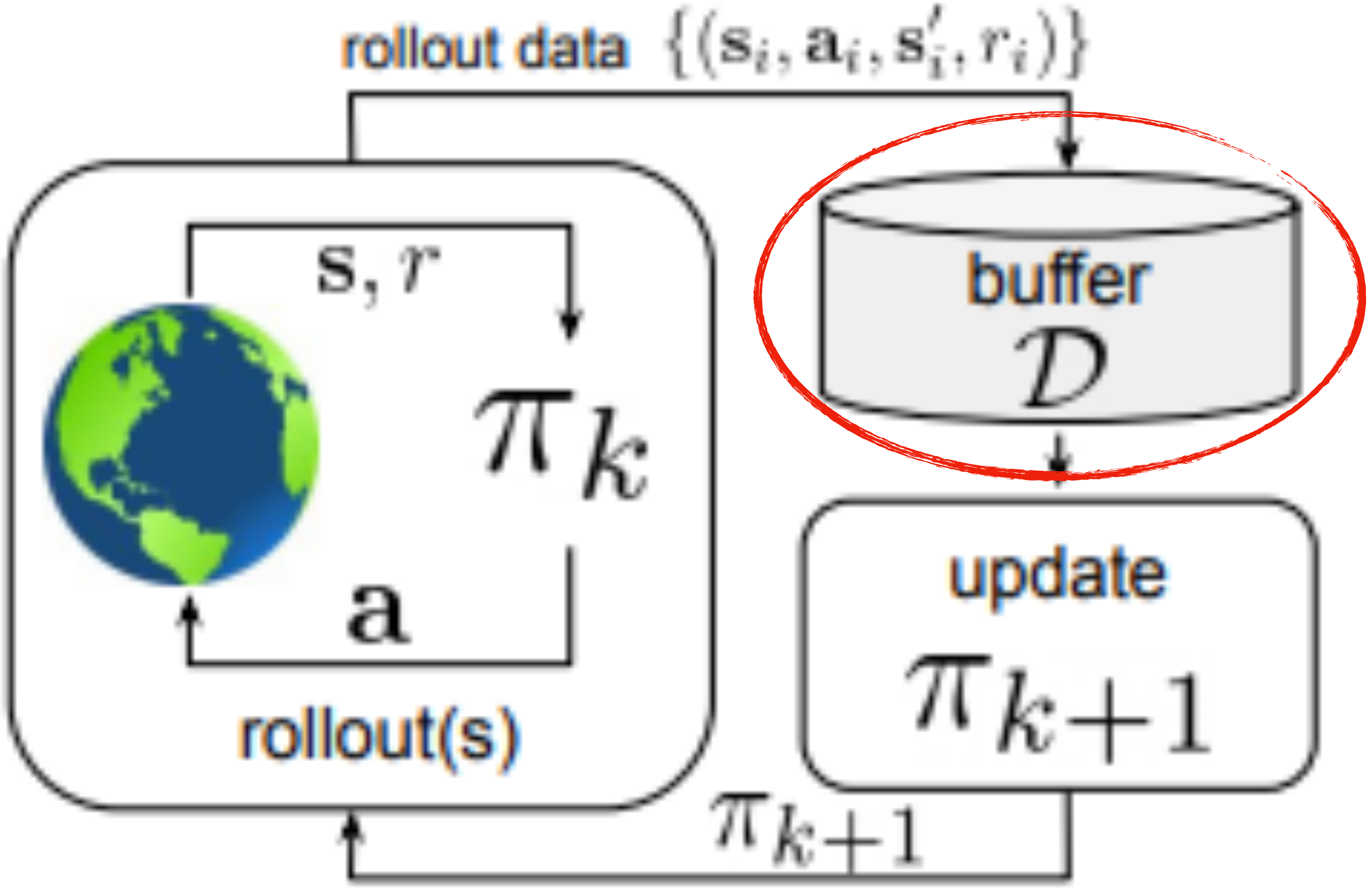
Different paradigms of RL

on-policy RL



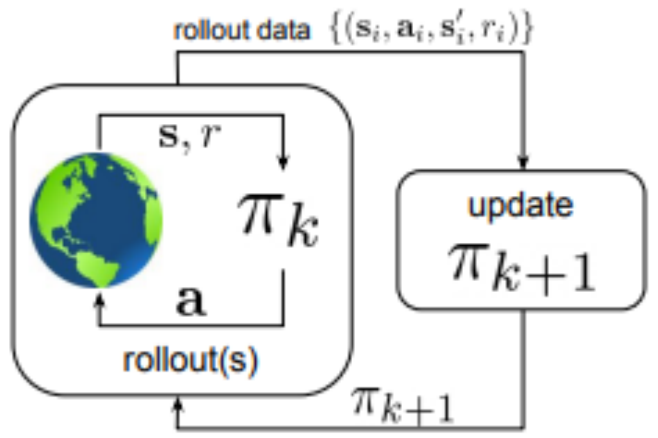
off-policy RL



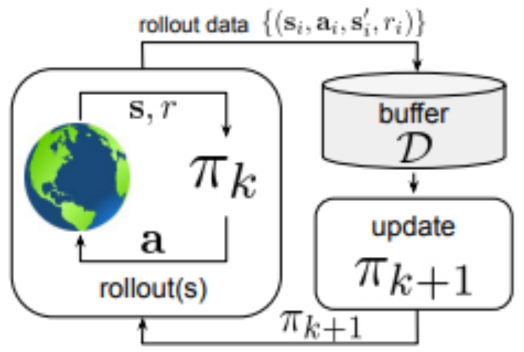
Credit: **Sergey Levine** "Offline RL lecture"

Different paradigms of RL

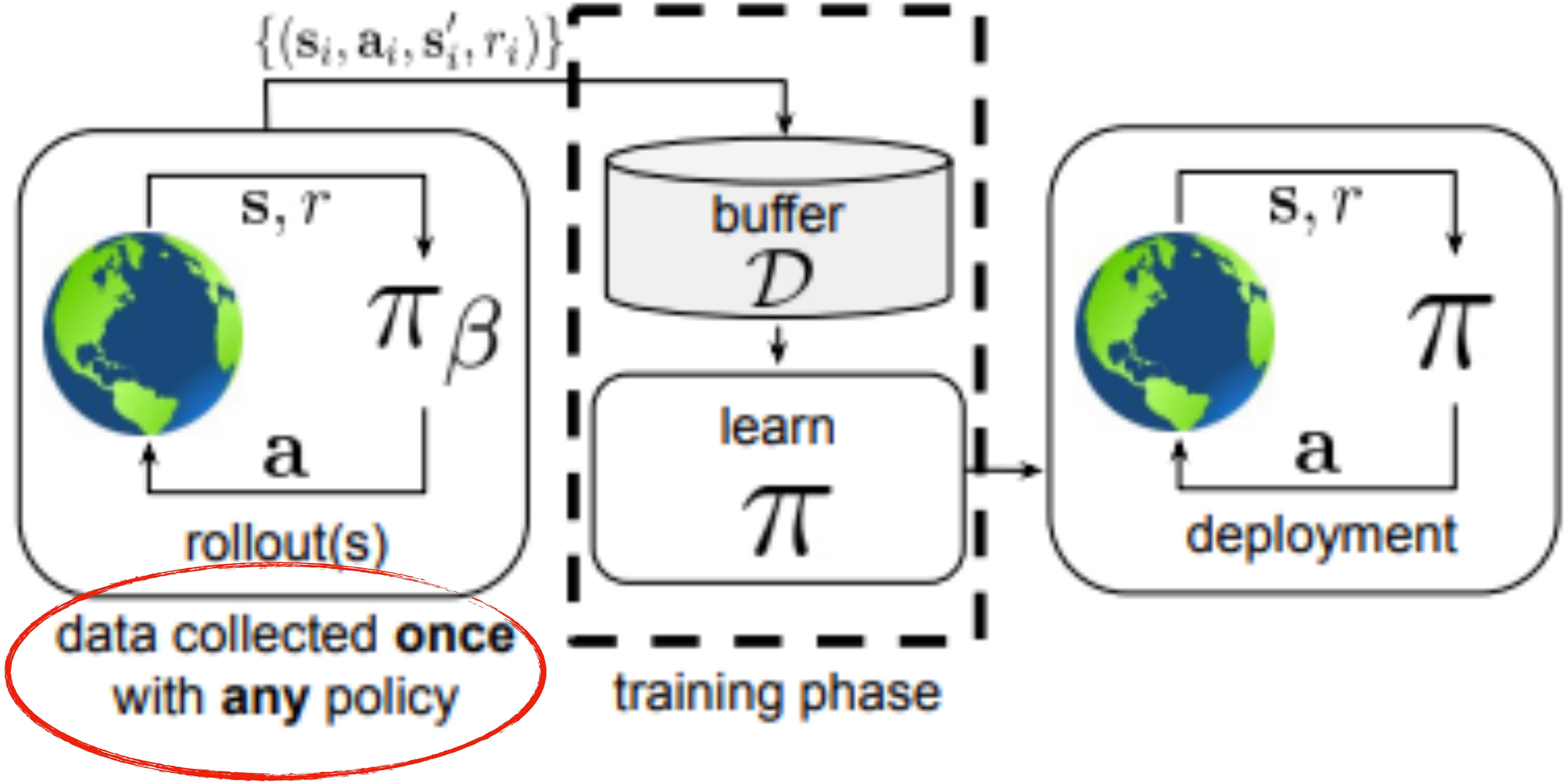
on-policy RL



off-policy RL



offline reinforcement learning



Credit: **Sergey Levine** "Offline RL lecture"

Different paradigms of RL

Offline RL enables robots to learn:
from pre-collected datasets
without real-time interaction,
enabling safer training
and leveraging diverse experiences.

Credit: **Sergey Levine** "Offline RL lecture"

Today's class

- ☑ What is offline RL? Why do we need it for robots?

  (Enables safer training, leverages diverse experience)

- ☐ Paradigm 1: Offline RL via Pessimism
  - ☐ Problem with Q-learning
  - ☐ Pessimism to the rescue

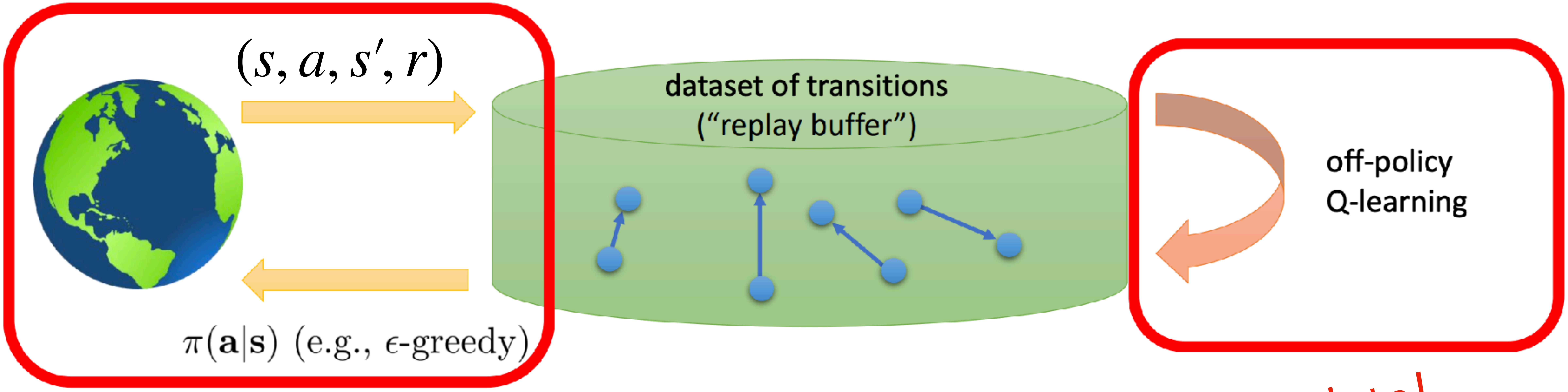
- ☐ Paradigm 2: RL via Supervised Learning
  - ☐ Return-conditioned Supervised Learning
  - ☐ Problem in Stochastic MDPs

Let's begin with a simple "offline" RL algorithm

We have already covered
a fundamental algorithm
in class that can learn
from offline data.

What is it?

Q-learning



Can learn from any data!

For every $\left(s_t, a_t, r_t, s_{t+1}\right)$

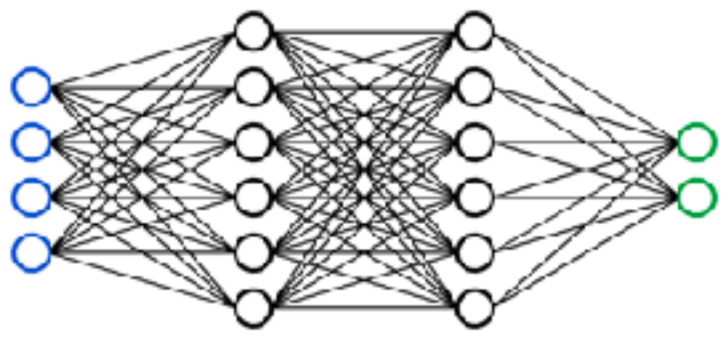
$$Q^*(s_t, a_t) = Q^*(s_t, a_t) + \alpha(r(s_t, a_t) + \gamma \max_{a'} Q^*(s_{t+1}, a') - Q^*(s_t, a_t))$$

Fitted Q-Iteration

Training is a regression problem

$$\ell(\theta) = \sum_{i=1}^{N} (Q_\theta(s_i, a_i) - \mathit{target})^2$$

Fitted Q-iteration



Given $\{s_i, a_i, r_i, s_i'\}_{i=1}^{N}$

Init $Q_\theta(s, a) \leftarrow 0$

while *not converged* **do**

$D \leftarrow \varnothing$

for $i \in 1, \ldots, N$

input $\leftarrow \{s_i, a_i\}$

target $\leftarrow r_i + \boxed{\gamma \max_{a'} Q_\theta(s_i', a')}$

Use old copy of Q to set target

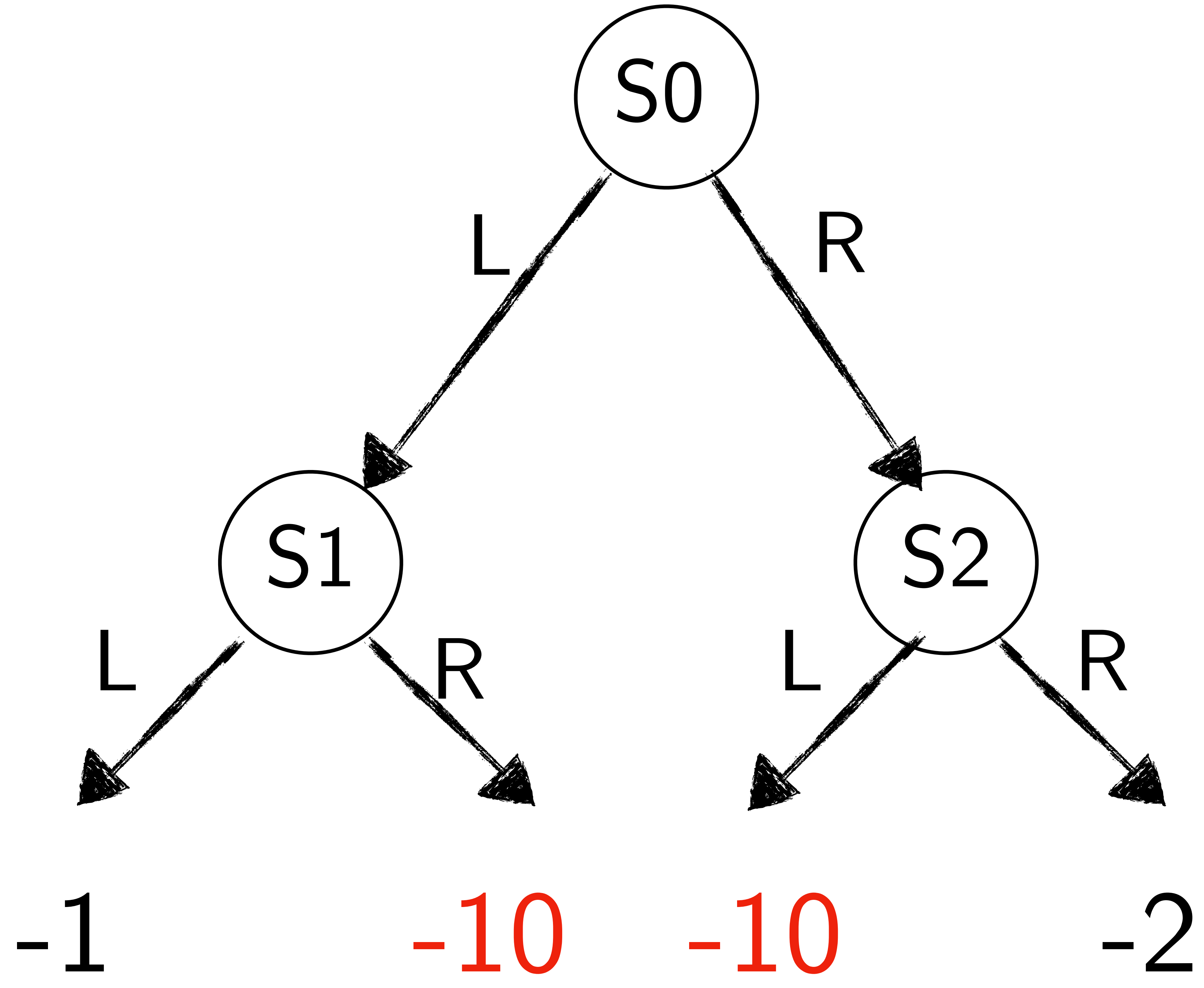
$D \leftarrow D \cup \{\text{input, target}\}$

$\boxed{Q_\theta \leftarrow \textbf{Train}(D)}$

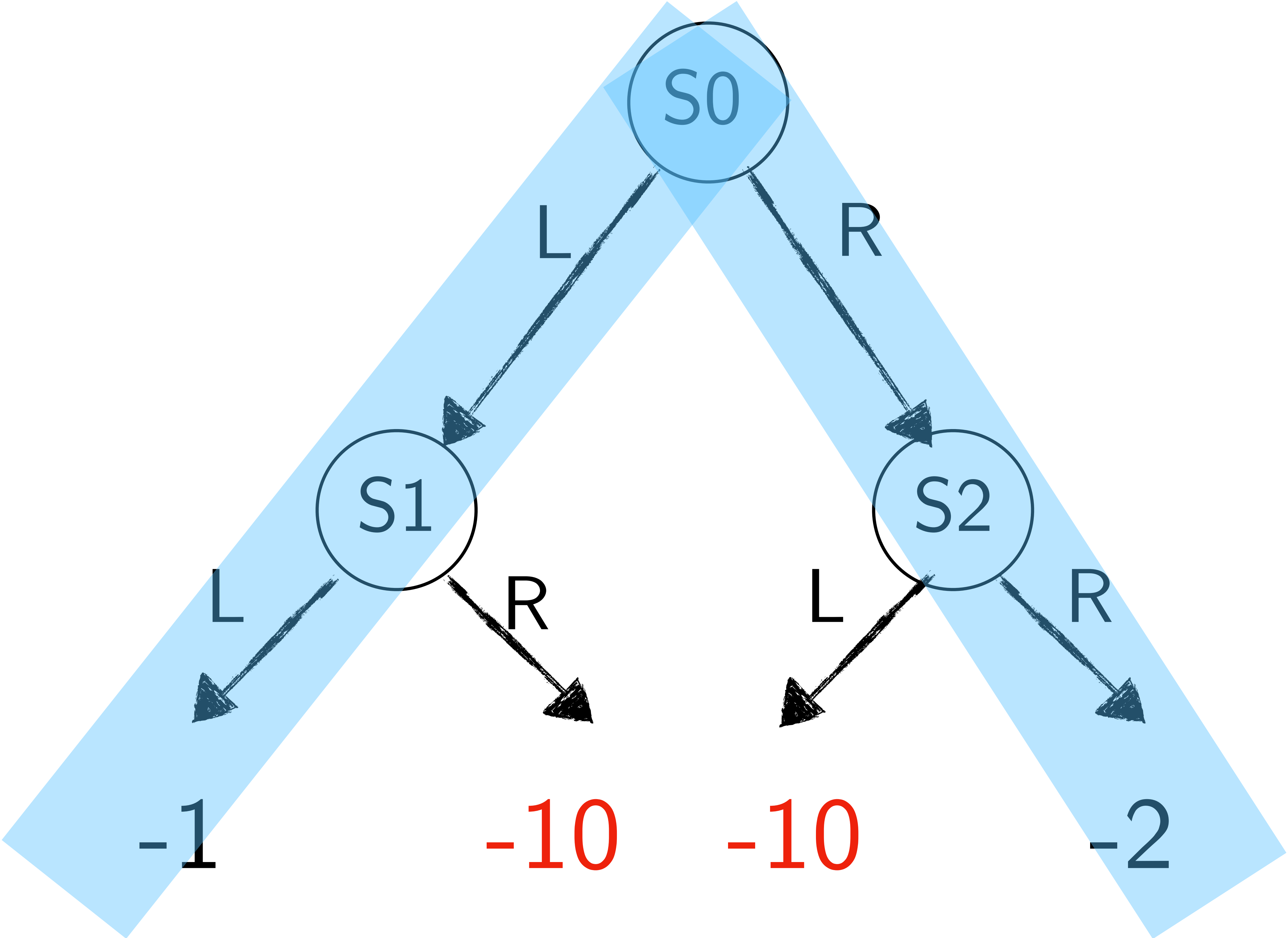
return Q_θ

Activity!

Consider the following MDP



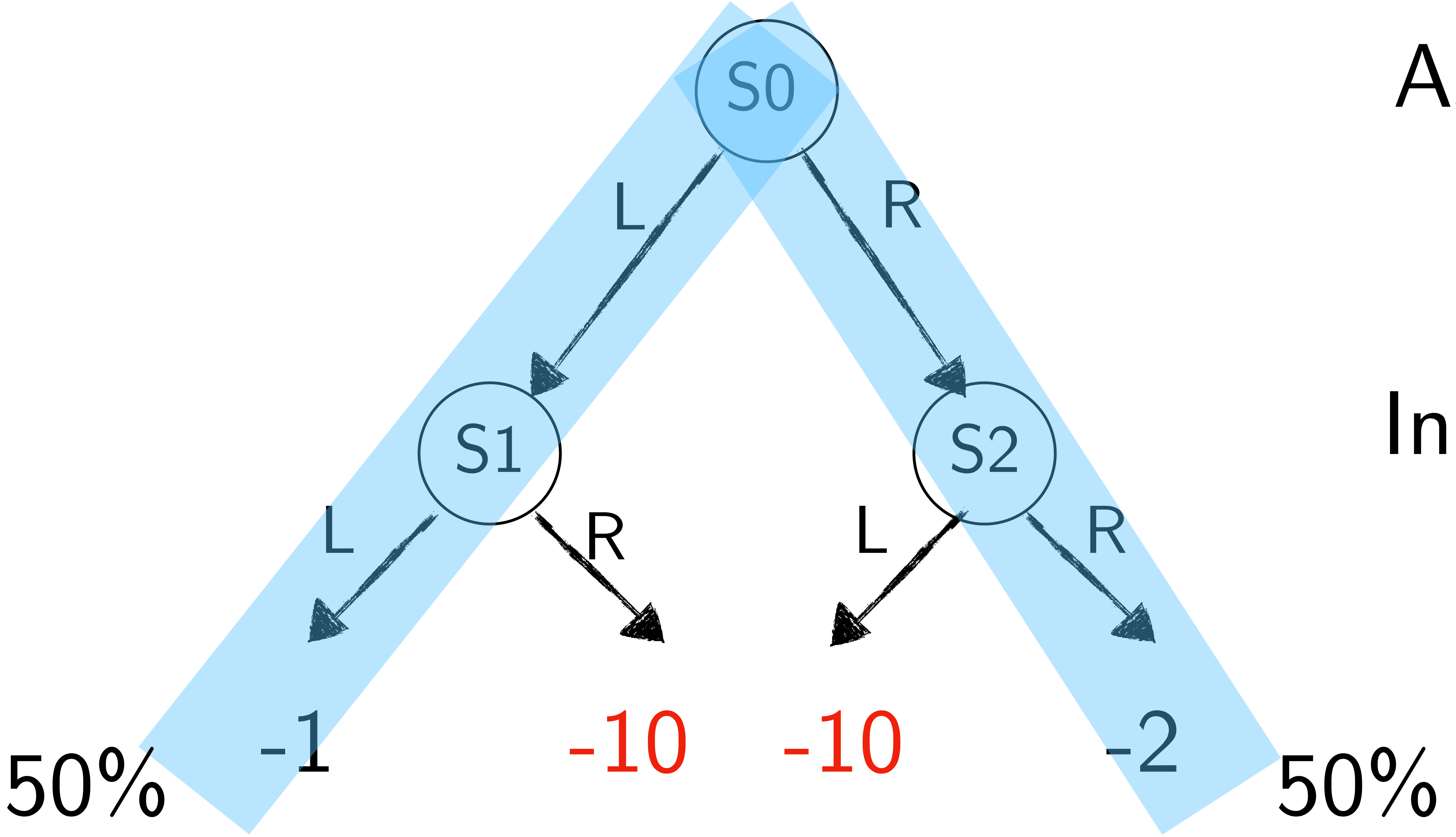
Let's say I collected some data from the MDP



50%

50%

What policy would Q-learning pick?



Assume we are in tabular case

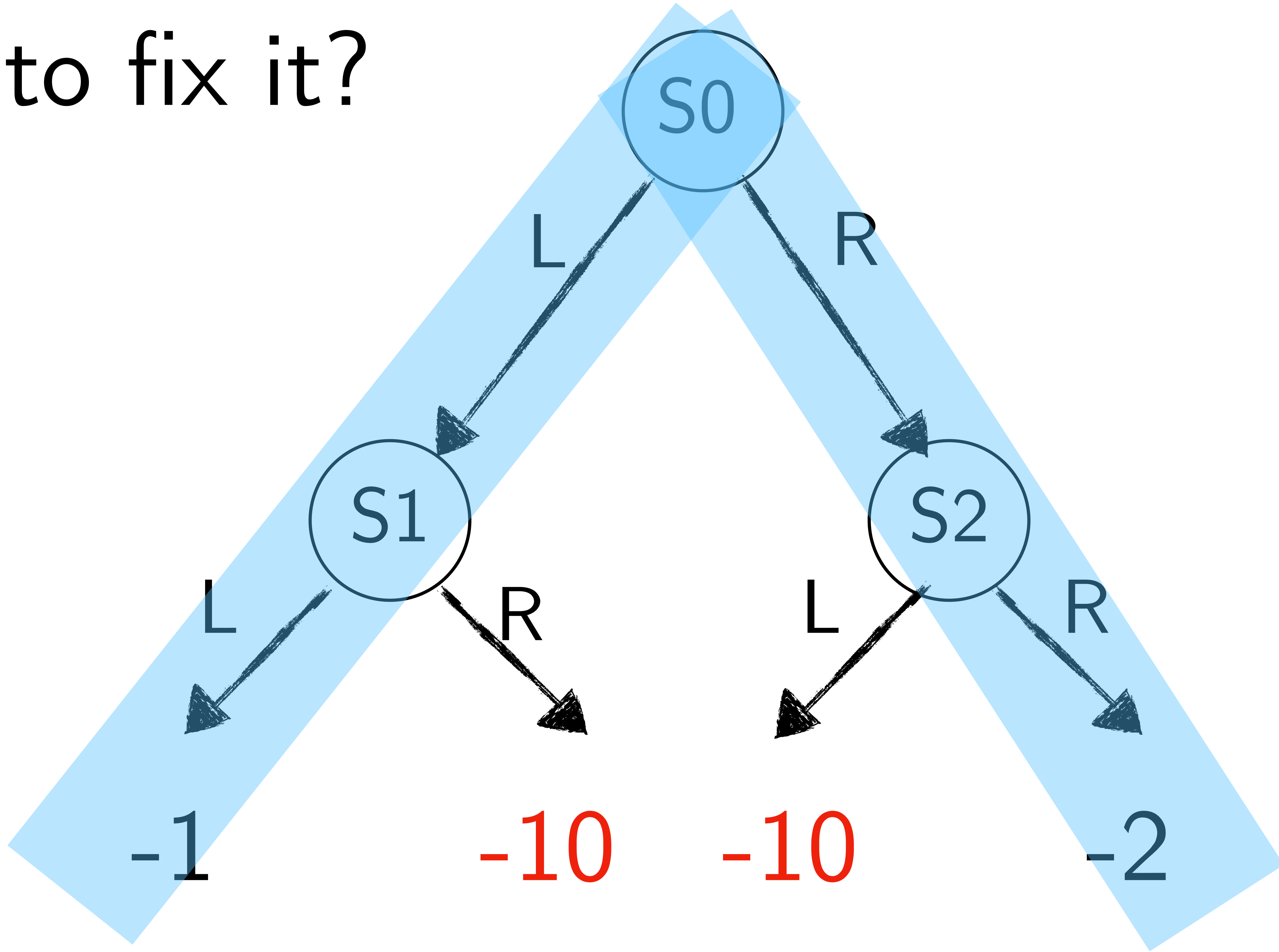
Initialize Q values with 0's

For every (s_t, a_t, r_t, s_{t+1})

$$Q^*(s_t, a_t) = Q^*(s_t, a_t) + \alpha(r(s_t, a_t) + \gamma \max_{a'} Q^*(s_{t+1}, a') - Q^*(s_t, a_t))$$

Think-Pair-Share!

Think (30 sec): What policy would Q-learning pick in the tabular setting? Why? Ideas to fix it?



Pair: Find a partner

Share (45 sec): Partners exchange ideas

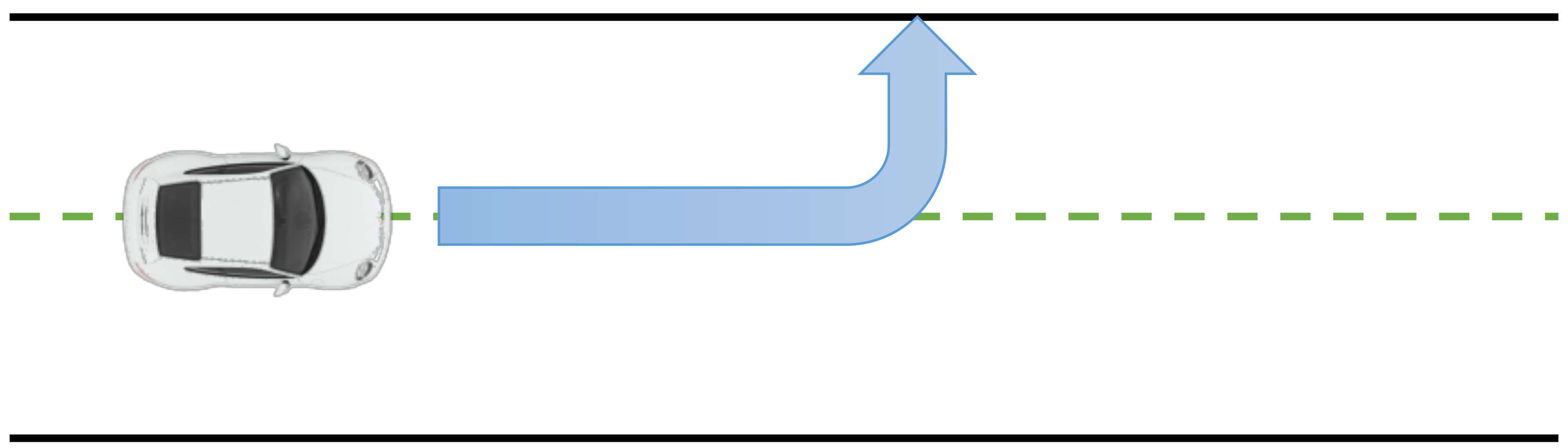
Credit: **Sergey Levine** "Offline RL lecture"

The Problem with Q-learning

Fundamental problem: counterfactual queries

Training data

What the policy wants to do



Is this good? Bad?

How do we know if we didn't see it in the data?

Q-learning can be incorrectly optimistic about actions it has not see in the data

Today's class

- [x] What is offline RL? Why do we need it for robots?

(Enables safer training, leverages diverse experience)

- [ ] Paradigm 1: Offline RL via Pessimism
  - [x] Problem with Q-learning (Incorrectly optimistic about unseen actions)
  - [ ] Pessimism to the rescue

- [ ] Paradigm 2: RL via Supervised Learning
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Pessimism

Pessimism as a policy constraint

Don't deviate too much from the data collecting policy

Pessimism as a policy constraint

Don't deviate too much from the data collecting policy

$$Q(\mathbf{s}, \mathbf{a}) \leftarrow r(\mathbf{s}, \mathbf{a}) + E_{\mathbf{a}' \sim \pi_{\text{new}}}[Q(\mathbf{s}', \mathbf{a}')]$$

$$\pi_{\text{new}}(\mathbf{a}|\mathbf{s}) = \arg\max_{\pi} E_{\mathbf{a} \sim \pi(\mathbf{a}|\mathbf{s})}[Q(\mathbf{s}, \mathbf{a})]$$

Typical Q-learning

Credit: **Sergey Levine** "Offline RL lecture"

Pessimism as a policy constraint

Don't deviate too much from the data collecting policy

$$Q(\mathbf{s},\mathbf{a}) \leftarrow r(\mathbf{s},\mathbf{a}) + E_{\mathbf{a}'\sim\pi_{\text{new}}}[Q(\mathbf{s}',\mathbf{a}')]$$

$$\pi_{\text{new}}(\mathbf{a}|\mathbf{s}) = \arg\max_{\pi} E_{\mathbf{a}\sim\pi(\mathbf{a}|\mathbf{s})}[Q(\mathbf{s},\mathbf{a})] \text{ s.t. } \boxed{D_{\text{KL}}(\pi\|\pi_\beta) \leq \epsilon}$$

Typical Q-learning

Add a constraint on policy

Credit: **Sergey Levine** "Offline RL lecture"

TD3+BC: Most simple and effective offline RL!

A Minimalist Approach to Offline Reinforcement Learning

Scott Fujimoto[1,2] **Shixiang Shane Gu**[2]
[1]Mila, McGill University
[2]Google Research, Brain Team
scott.fujimoto@mail.mcgill.ca

$$\cancel{\pi = \operatorname*{argmax}_{\pi} \mathbb{E}_{(s,a)\sim\mathcal{D}}[Q(s, \pi(s))].}$$

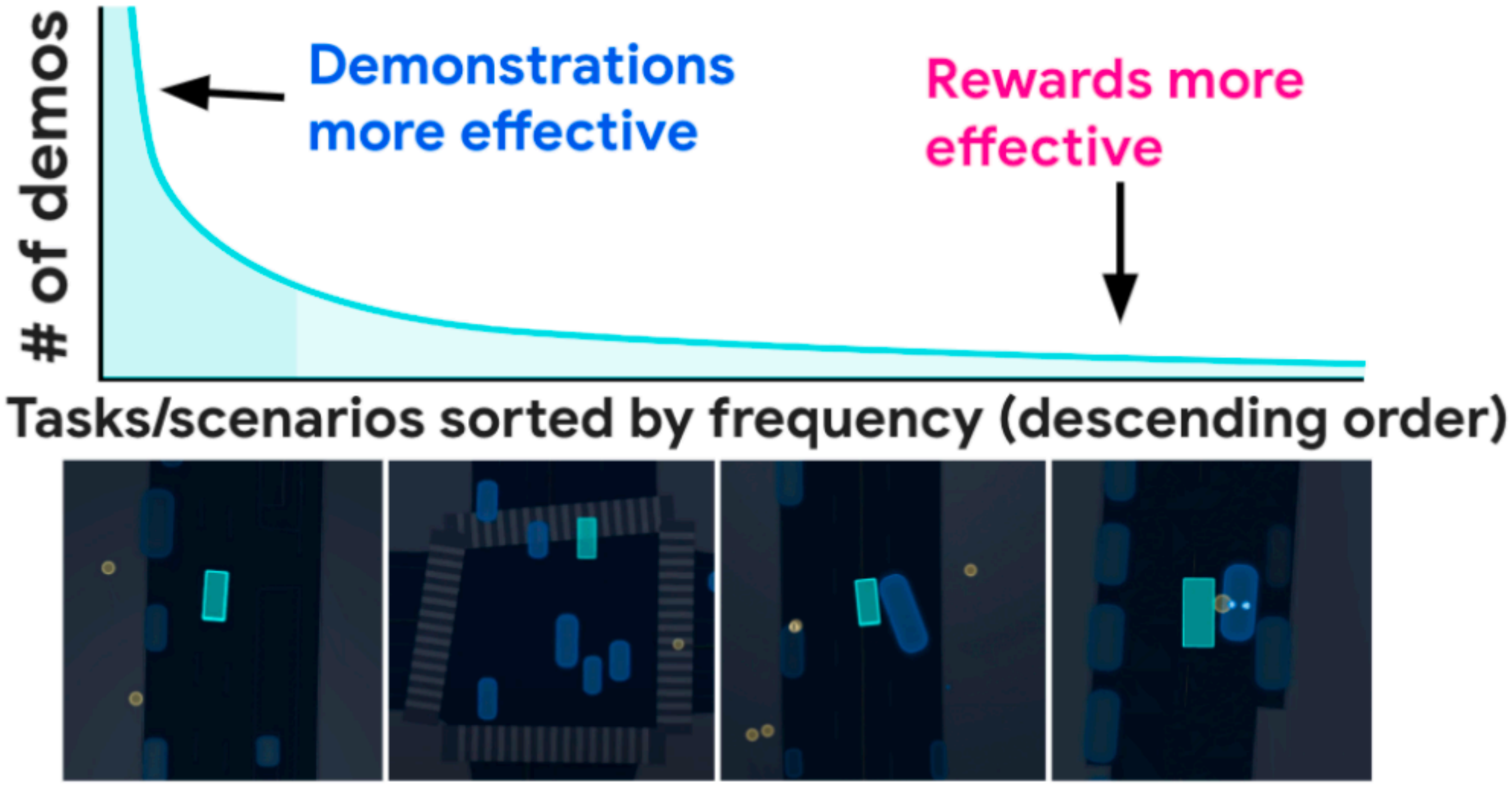
$$\pi = \operatorname*{argmax}_{\pi} \mathbb{E}_{(s,a)\sim\mathcal{D}} \left[\lambda Q(s, \pi(s)) - (\pi(s) - a)^2\right],$$

		BC	BRAC-p	AWAC	CQL	Fisher-BRC	TD3+BC
Random	HalfCheetah	2.0 ±0.1	23.5	2.2	21.7 ±0.9	32.2 ±2.2	10.2 ±1.3
	Hopper	9.5 ±0.1	11.1	9.6	10.7 ±0.1	11.4 ±0.2	11.0 ±0.1
	Walker2d	1.2 ±0.2	0.8	5.1	2.7 ±1.2	0.6 ±0.6	1.4 ±1.6
Medium	HalfCheetah	36.6 ±0.6	44.0	37.4	37.2 ±0.3	41.3 ±0.5	42.8 ±0.3
	Hopper	30.0 ±0.5	31.2	72.0	44.2 ±10.8	99.4 ±0.4	99.5 ±1.0
	Walker2d	11.4 ±6.3	72.7	30.1	57.5 ±8.3	79.5 ±1.0	79.7 ±1.8
Medium Replay	HalfCheetah	34.7 ±1.8	45.6	-	41.9 ±1.1	43.3 ±0.9	43.3 ±0.5
	Hopper	19.7 ±5.9	0.7	-	28.6 ±0.9	35.6 ±2.5	31.4 ±3.0
	Walker2d	8.3 ±1.5	-0.3	-	15.8 ±2.6	42.6 ±7.0	25.2 ±5.1
Medium Expert	HalfCheetah	67.6 ±13.2	43.8	36.8	27.1 ±3.9	96.1 ±9.5	97.9 ±4.4
	Hopper	89.6 ±27.6	1.1	80.9	111.4 ±1.2	90.6 ±43.3	112.2 ±0.2
	Walker2d	12.0 ±5.8	-0.3	42.7	68.1 ±13.1	103.6 ±4.6	101.1 ±9.3
Expert	HalfCheetah	105.2 ±1.7	3.8	78.5	82.4 ±7.4	106.8 ±3.0	105.7 ±1.9
	Hopper	111.5 ±1.3	6.6	85.2	111.2 ±2.1	112.3 ±0.2	112.2 ±0.2
	Walker2d	56.0 ±24.9	-0.2	57.0	103.8 ±7.6	79.9 ±32.4	105.7 ±2.7
	Total	595.3 ±91.5	284.1	-	764.3 ±61.5	974.6 ±108.3	979.3 ±33.4

Works on real self-driving problems!

Imitation Is Not Enough: Robustifying Imitation with Reinforcement Learning for Challenging Driving Scenarios

Yiren Lu[1], Justin Fu[1], George Tucker[2], Xinlei Pan[1], Eli Bronstein[1], Rebecca Roelofs[2], Benjamin Sapp[1], Brandyn White[1], Aleksandra Faust[2], Shimon Whiteson[1], Dragomir Anguelov[1], Sergey Levine[2,3]



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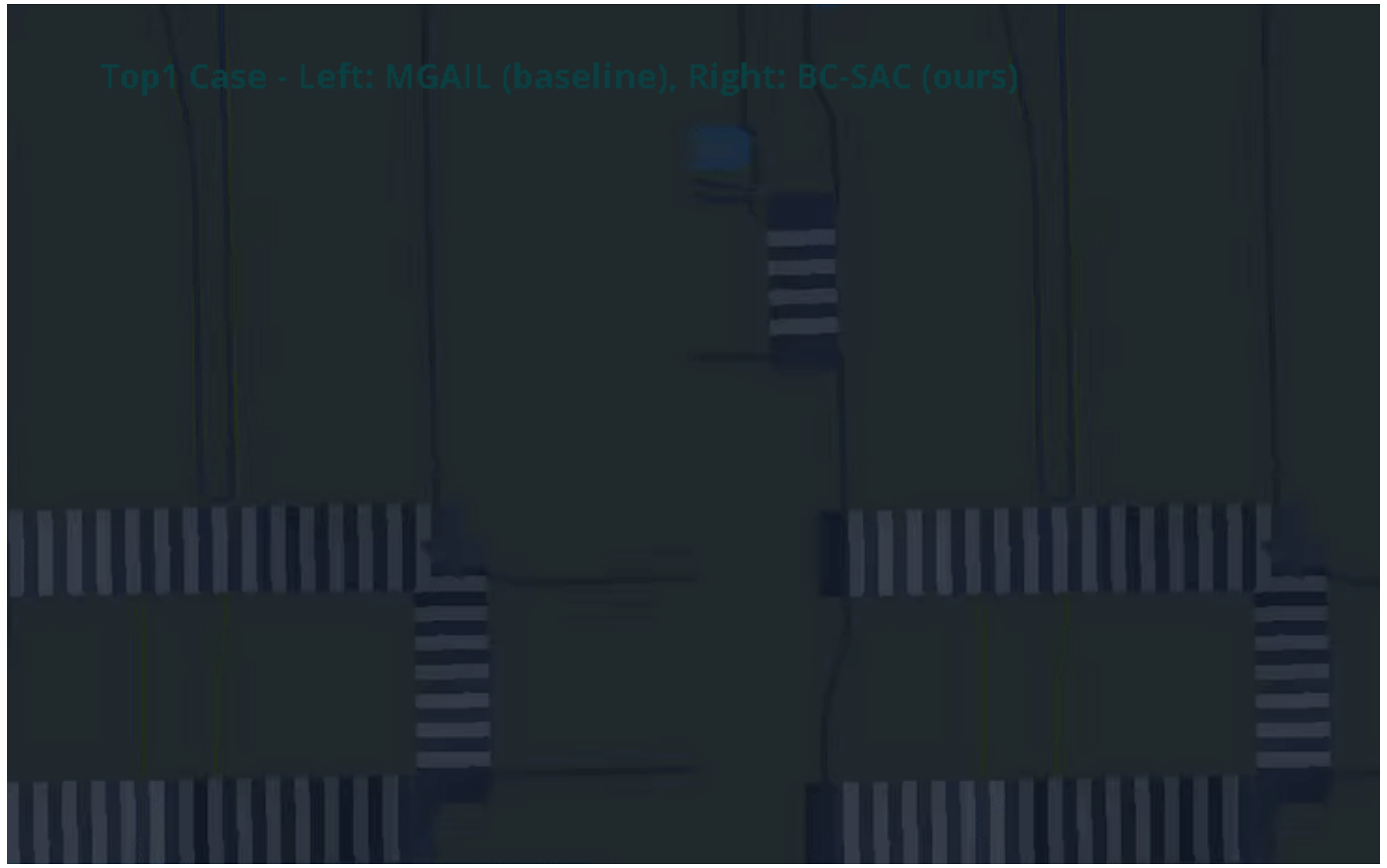

https://waymo.com/research/imitation-is-not-enough-robustifying-imitation-with-reinforcement-learning/

Many more sophisticated offline RL methods

Conservative Q-Learning for Offline Reinforcement Learning

Aviral Kumar[1], Aurick Zhou[1], George Tucker[2], Sergey Levine[1,2]
[1]UC Berkeley, [2]Google Research, Brain Team
aviralk@berkeley.edu

Instead of constraining policy, compute pessimistic Q values

Adversarially Trained Actor Critic for Offline Reinforcement Learning

Ching-An Cheng[*1] Tengyang Xie[*2] Nan Jiang[2] Alekh Agarwal[3]

Optimize the best worst case performance

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(Enables safer training, leverages diverse experience)

- [ ] Paradigm 1: Offline RL via Pessimism
  - [x] Problem with Q-learning (Incorrectly optimistic about unseen actions)
  - [x] Pessimism to the rescue (Constrain policy to not deviate from data)

- [ ] Paradigm 2: RL via Supervised Learning
  - [ ] Return-conditioned Supervised Learning
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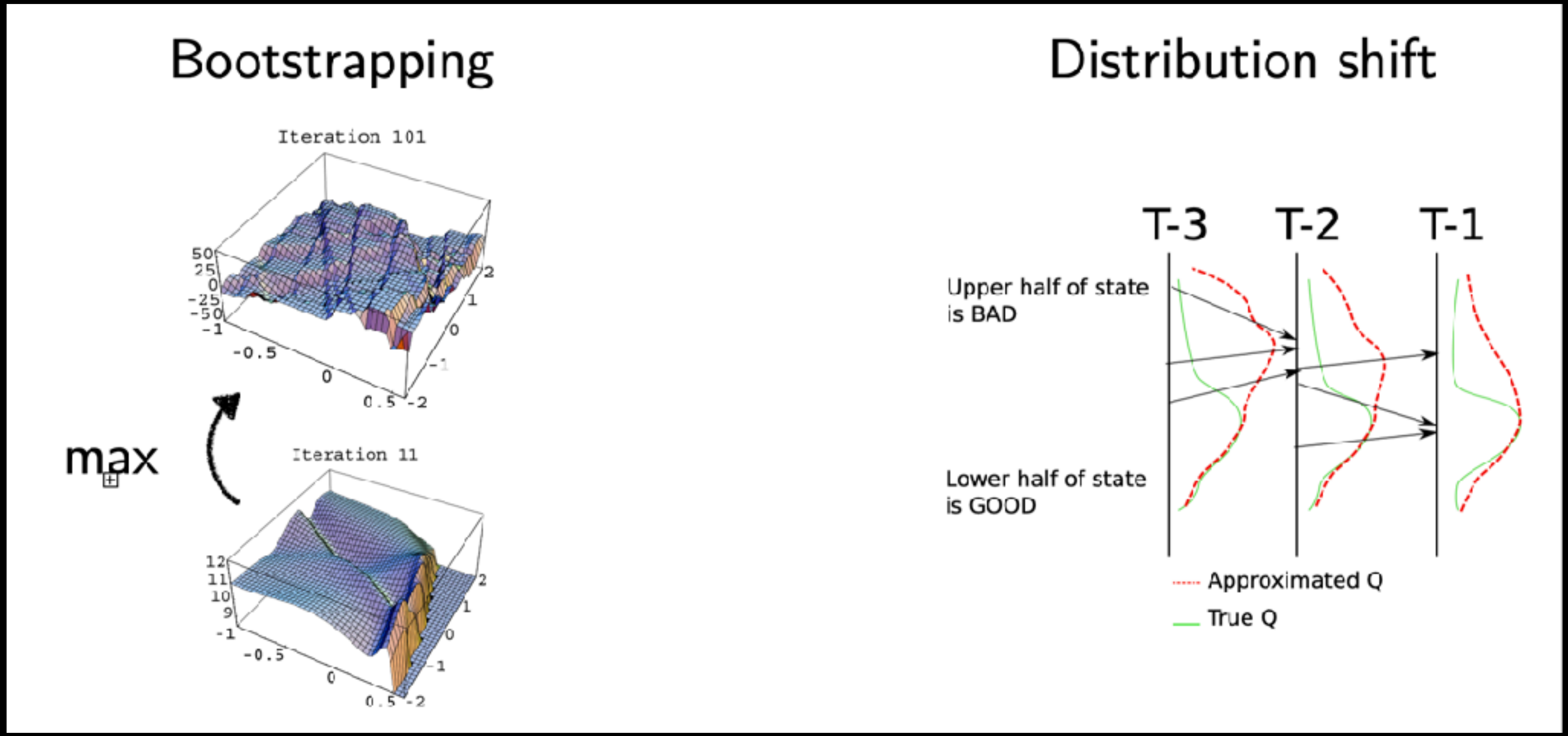
Reinforcement Learning is Hard ...

Many horror stories of RL!

Nightmares of
Policy Optimization



Need many tricks to make Q-learning work in practice!

Rainbow: Combining Improvements in Deep Reinforcement Learning

Matteo Hessel DeepMind
Joseph Modayil DeepMind
Hado van Hasselt DeepMind
Tom Schaul DeepMind
Georg Ostrovski DeepMind
Will Dabney DeepMind
Dan Horgan DeepMind
Bilal Piot DeepMind
Mohammad Azar DeepMind
David Silver DeepMind

Double Q Learning

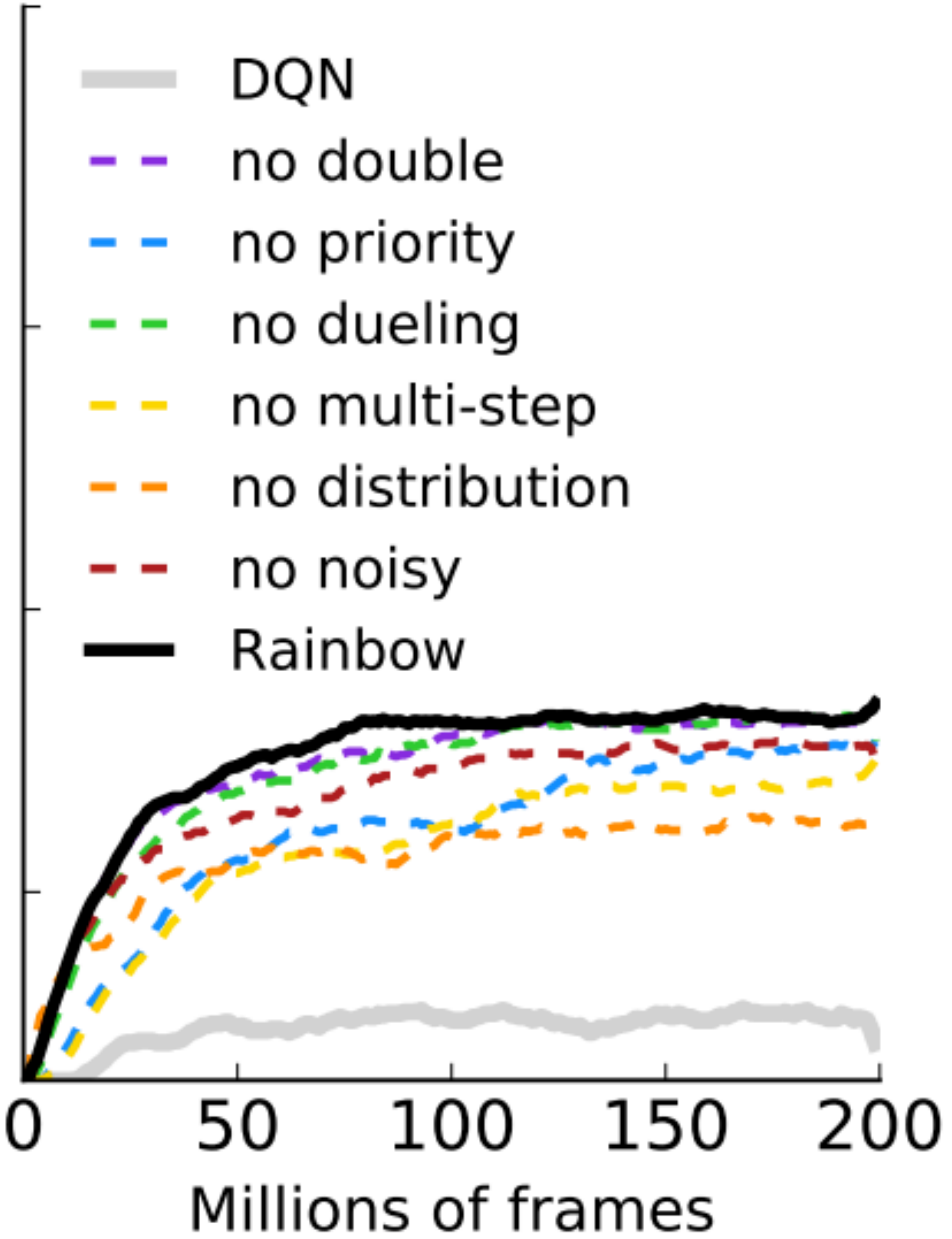
Prioritized Replay

Dueling Networks

Multi-step Learning

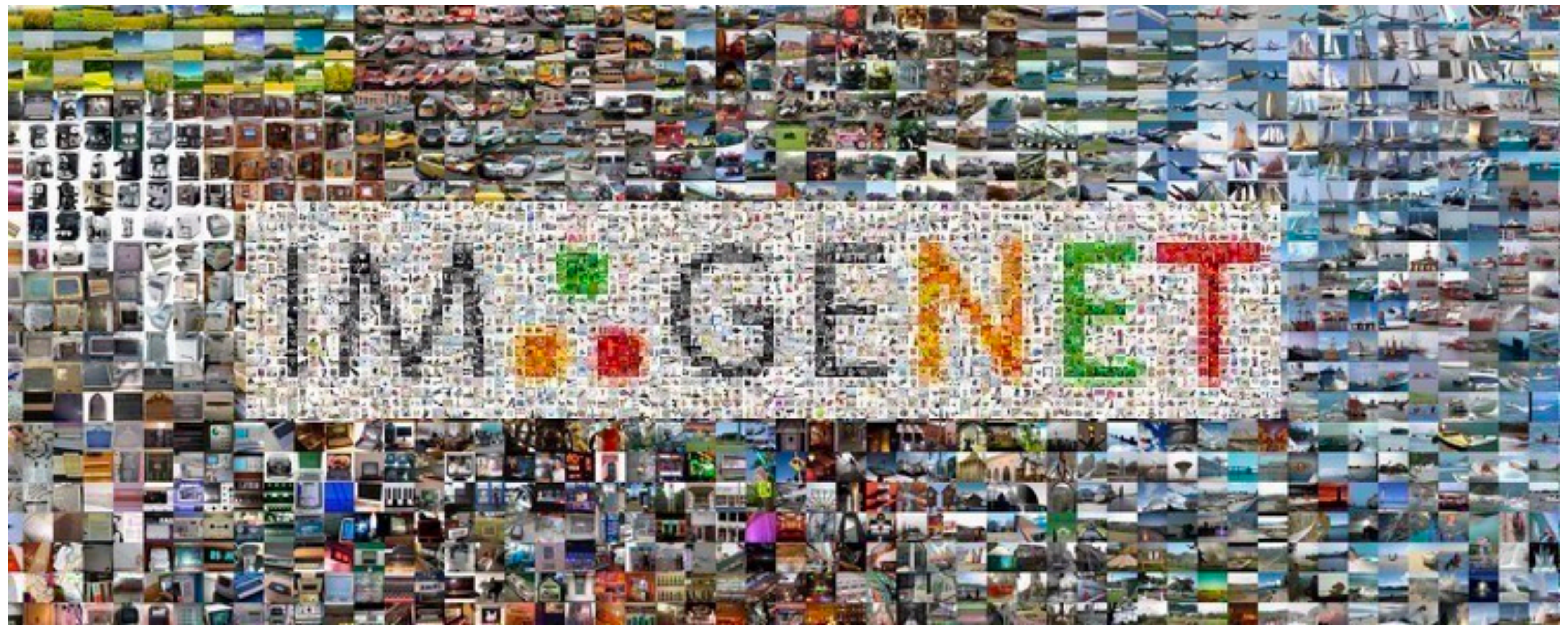
Distributional RL

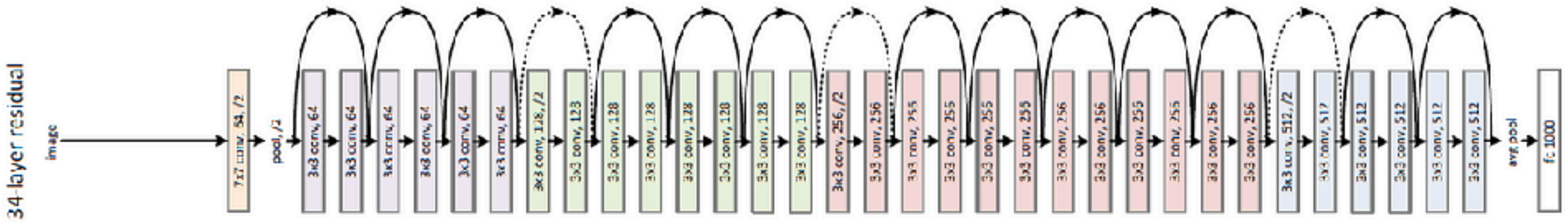
Noisy Nets

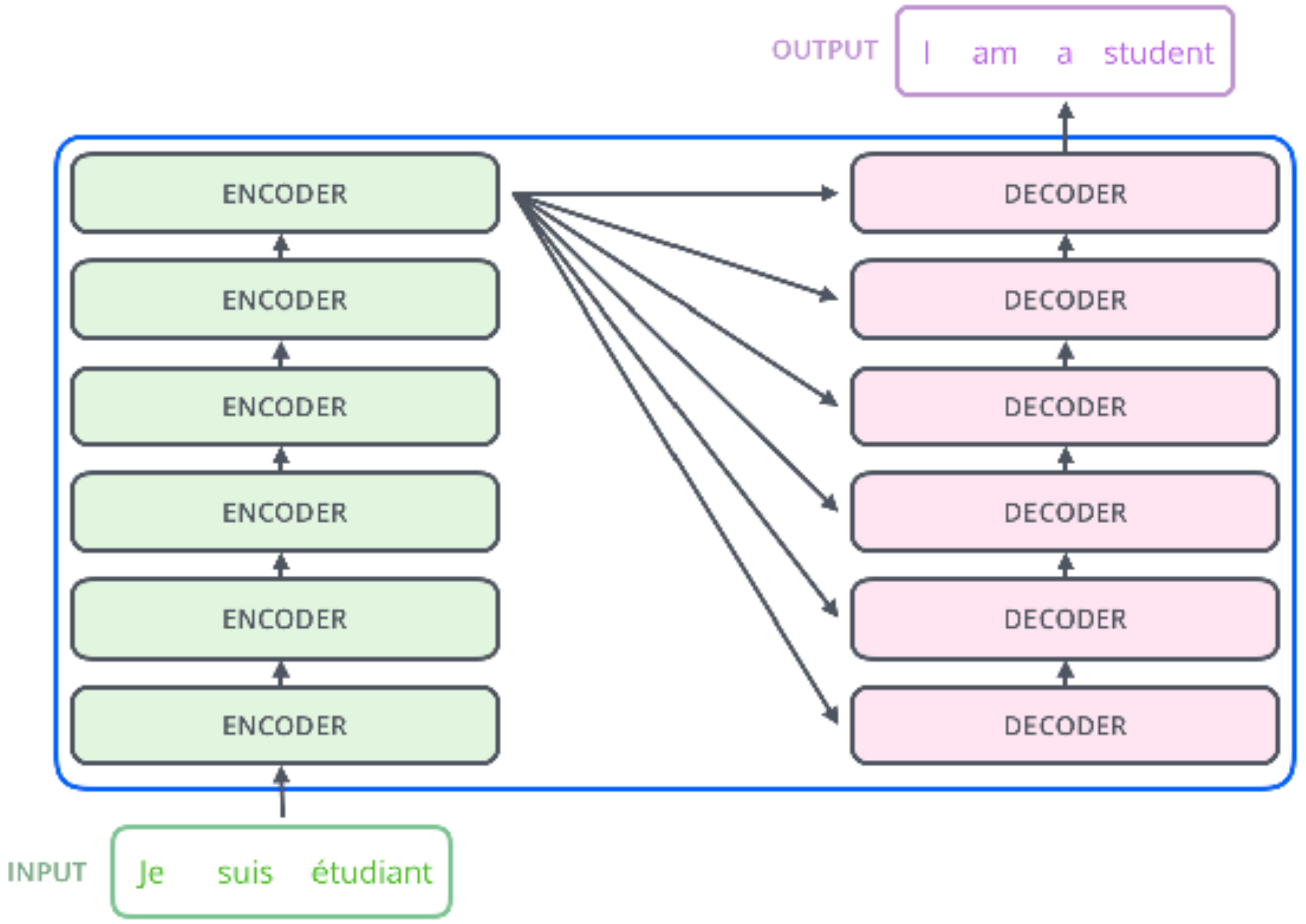


Can we just go back to good old supervised learning?

Supervised Learning success stories

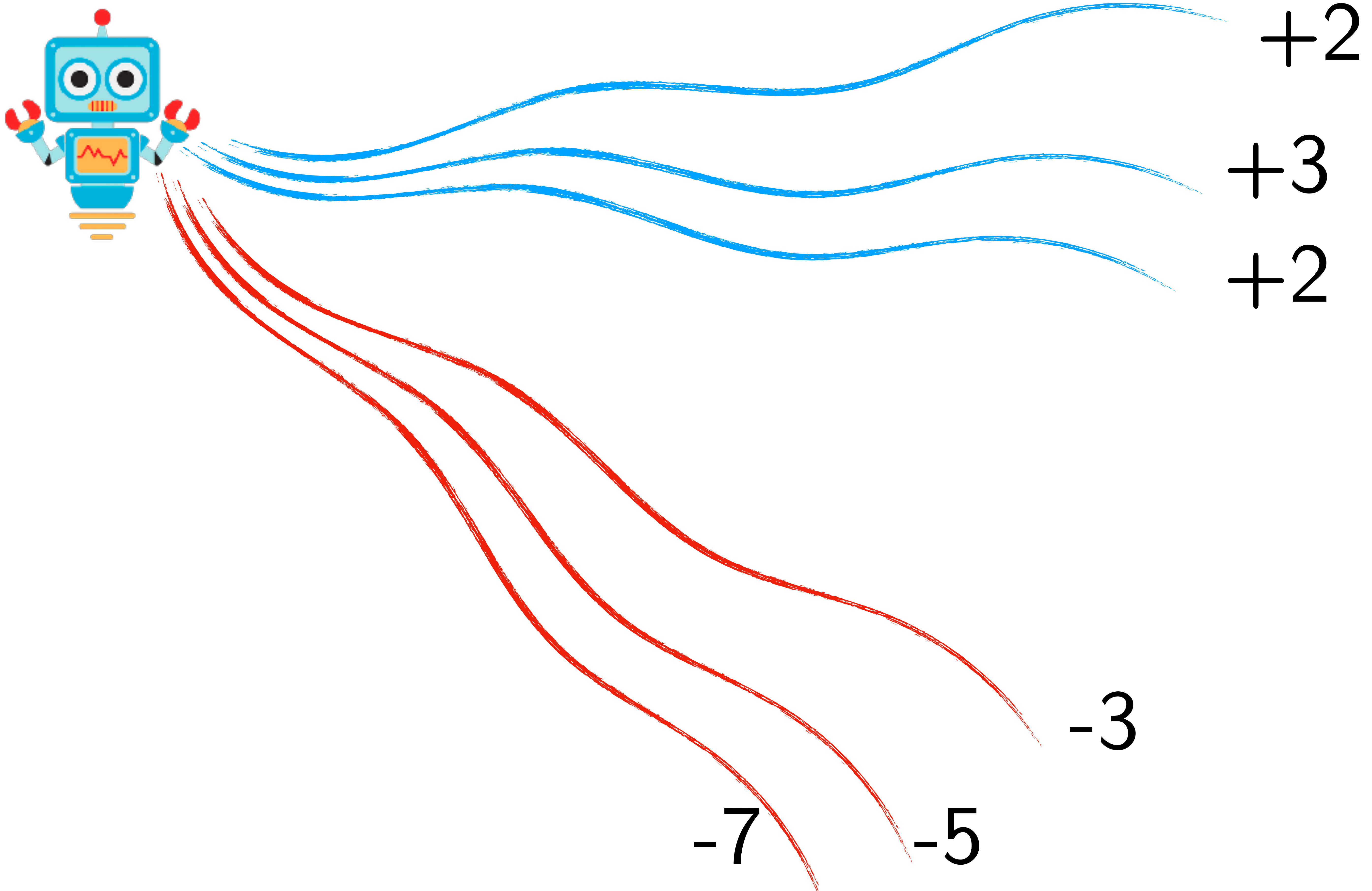




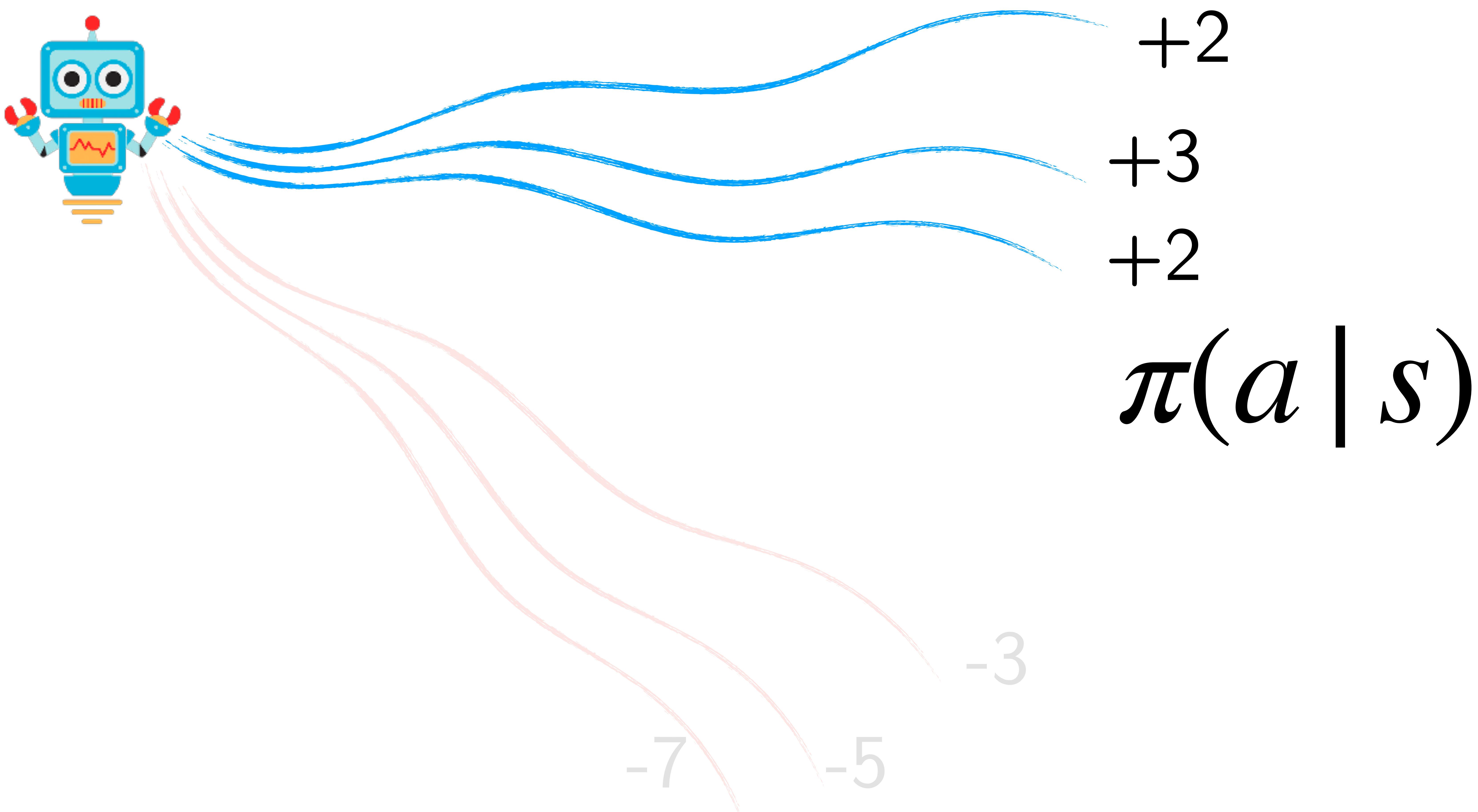


Common Crawl

What if I did supervised learning (BC) here?



What if I did supervised learning (BC) only on the top % rollouts?



An embarrassingly simply algorithm: BC%

1. Collect offline dataset using whatever behavior policy

2. Get the top % trajectories based on returns

3. Do BC on just that!

Does this even work ?!?

A legit Offline RL Algo

Dataset	Environment	10%BC	25%BC	40%BC	100%BC	CQL
Medium	HalfCheetah	42.9	43.0	43.1	43.1	**44.4**
Medium	Hopper	65.9	65.2	65.3	63.9	58.0
Medium	Walker	78.8	**80.9**	78.8	77.3	79.2
Medium	Reacher	51.0	48.9	58.2	**58.4**	26.0
Medium-Replay	HalfCheetah	40.8	40.9	41.1	4.3	**46.2**
Medium-Replay	Hopper	70.6	58.6	31.0	27.6	48.6
Medium-Replay	Walker	**70.4**	67.8	67.2	36.9	26.7
Medium-Replay	Reacher	**33.1**	16.2	10.7	5.4	19.0
Average		**56.7**	52.7	49.4	39.5	43.5

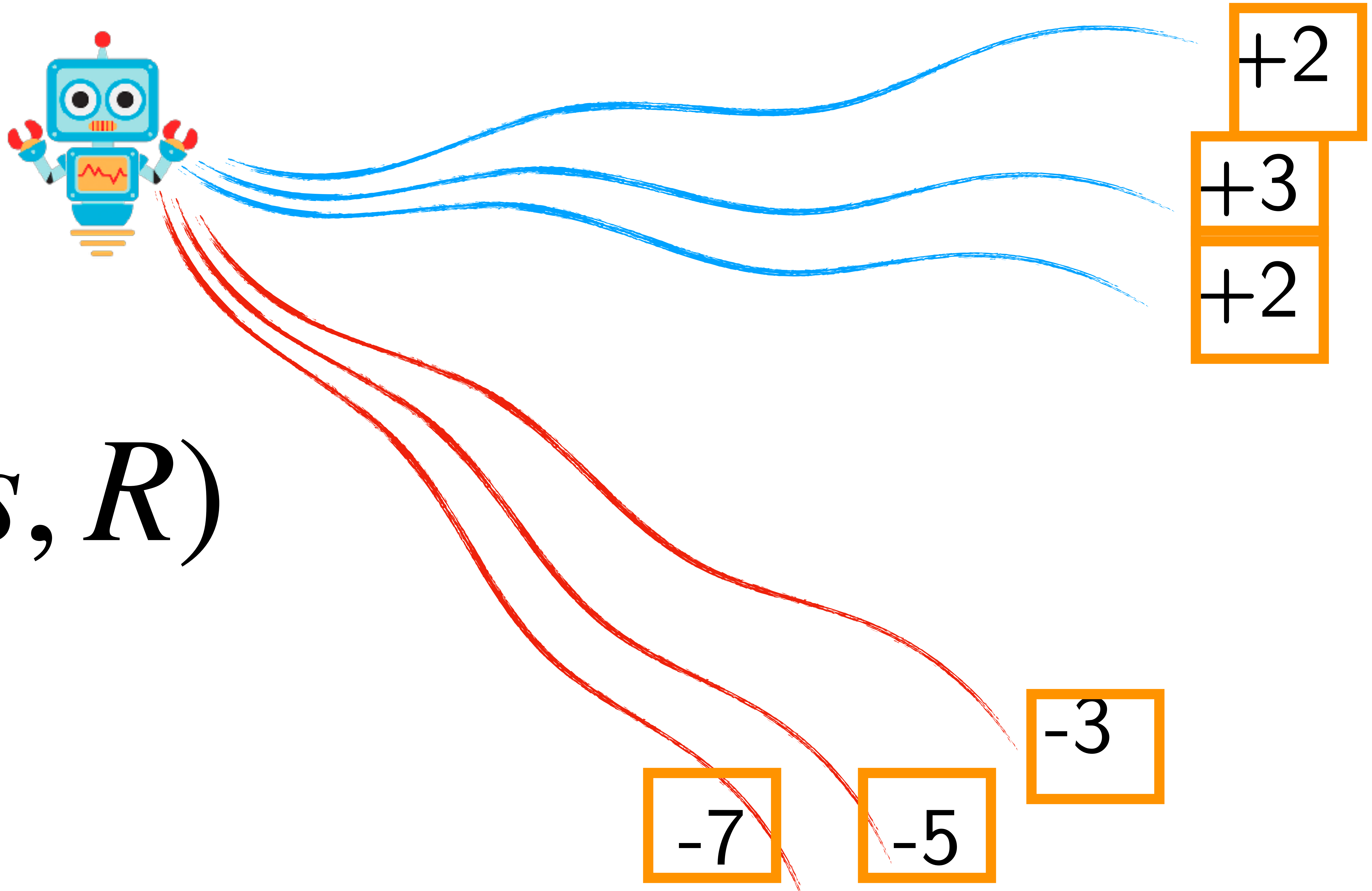
An embarrassingly simply algorithm: BC%

1. Collect offline dataset using whatever behavior policy
2. Get the top % trajectories based on returns
3. Do BC on just that!

Challenge with BC%:
What happens as I vary % from small to high values?

Can we have a more principled approach?

Idea: Train a policy *conditioned* on the returns

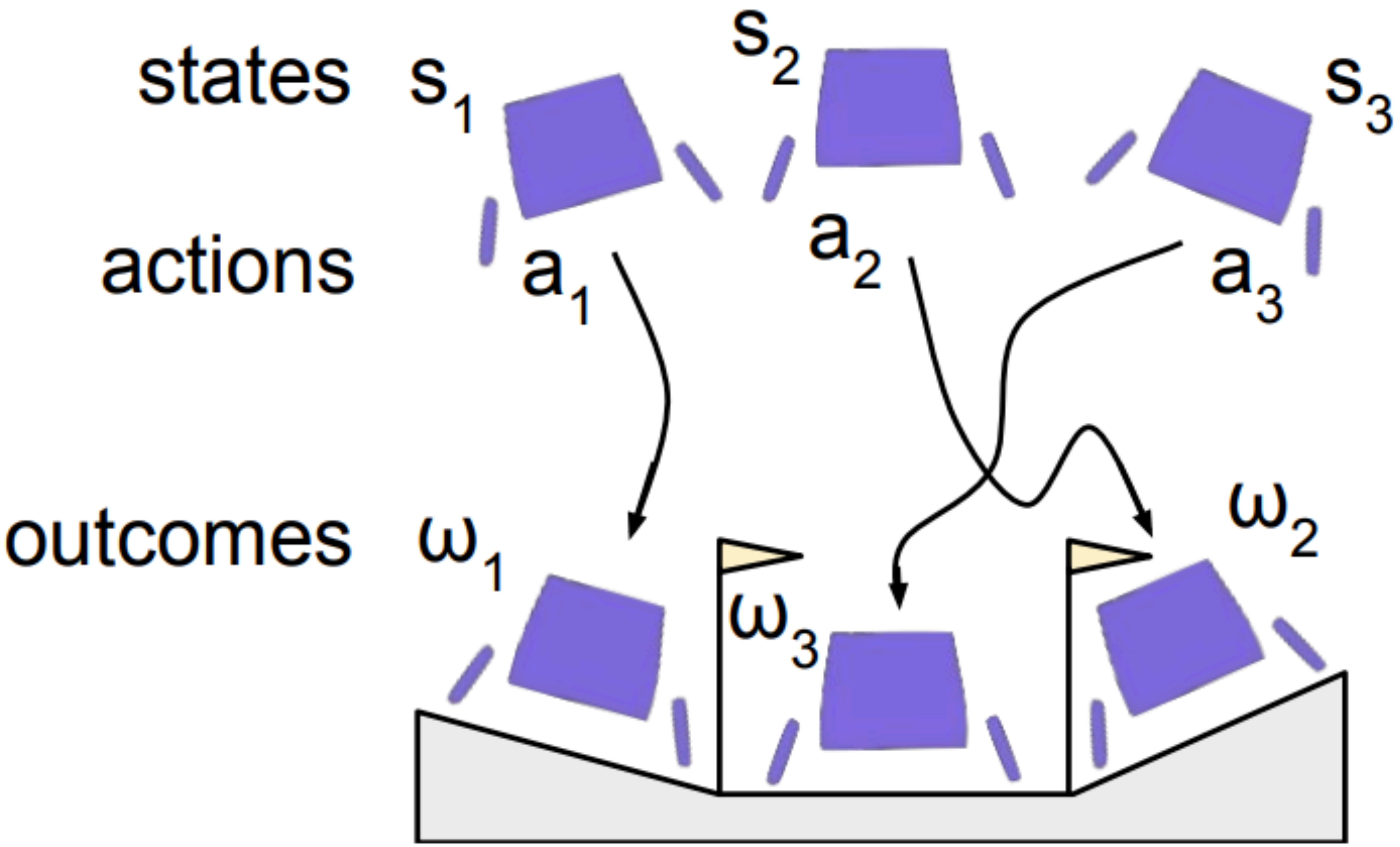


$$\pi(a \mid s, R)$$

RvS: What is Essential for Offline RL via Supervised Learning?

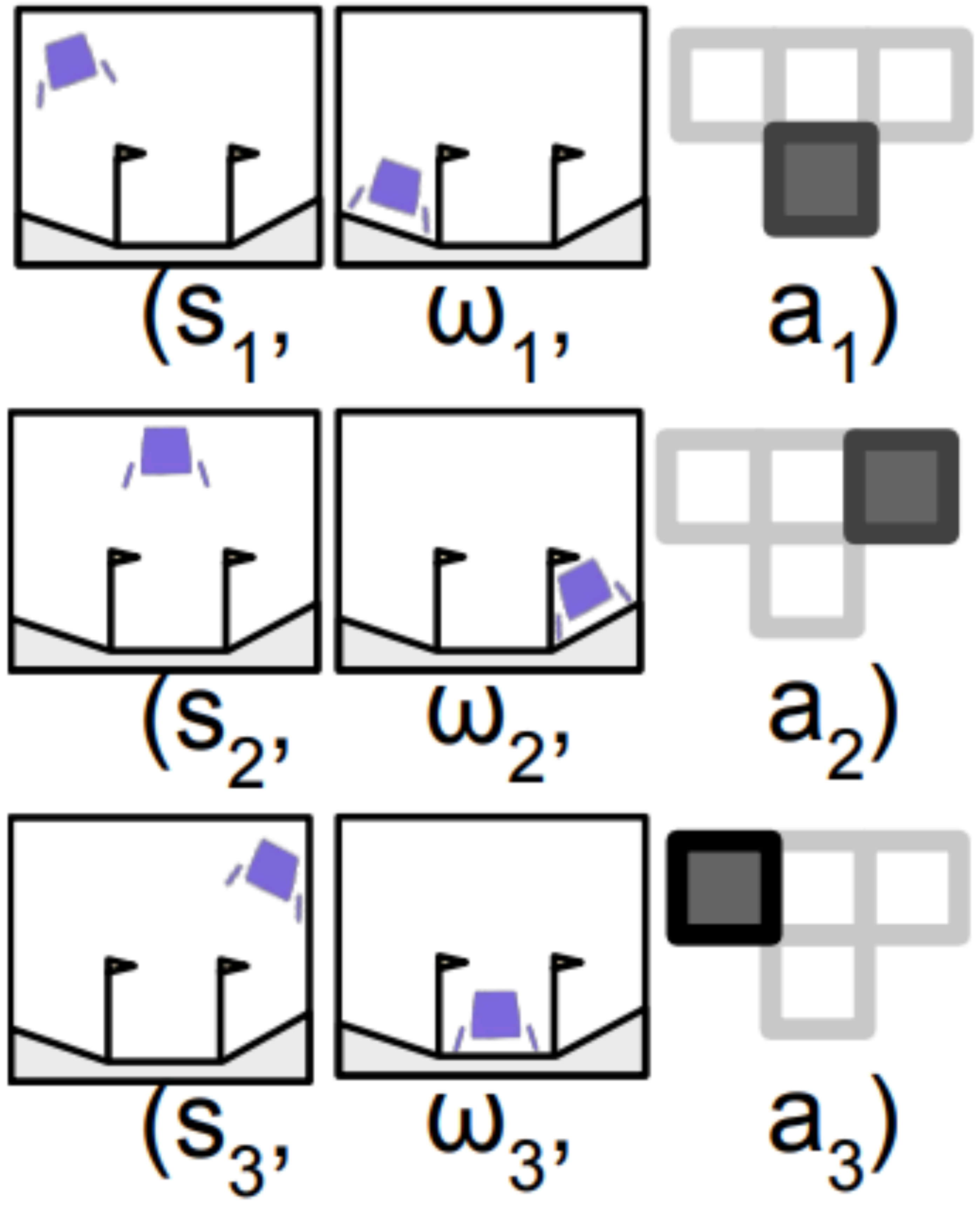
Scott Emmons[1], **Benjamin Eysenbach**[2], **Ilya Kostrikov**[1], **Sergey Levine**[1]
[1]UC Berkeley, [2]Carnegie Mellon University
emmons@berkeley.edu

The Idea



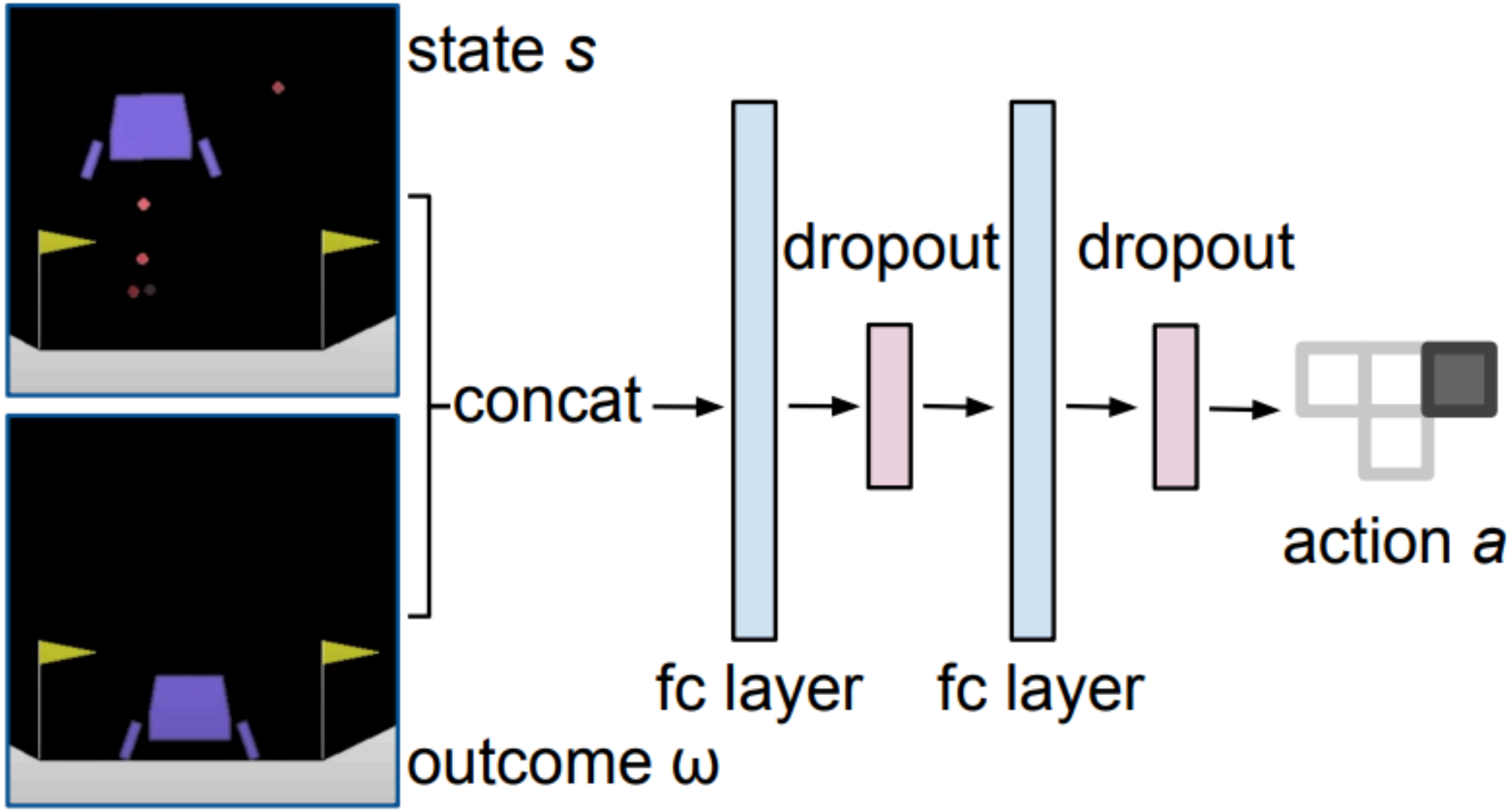
(a) replay buffer

The Idea



(b) training dataset

The Idea



(c) network architecture

The Algorithm

For all trajectories: / For all timesteps in that trajectory: / For all achieved outcomes:

$$\max_\theta \underbrace{\sum_{\tau \in \mathcal{D}}}_{\text{For all trajectories}} \underbrace{\sum_{1 \le t \le |\tau|}}_{\text{For all timesteps in that trajectory}} \underbrace{\mathbb{E}_{\omega \sim f(\omega \mid \tau_{t:H})}}_{\text{For all achieved outcomes}} [\log \pi_\theta(a_t \mid s_t, \omega)].$$

Algorithm 1 RvS-Learning

1: **Input**: Dataset of trajectories, $\mathcal{D} = \{\tau\}$
2: Initialize policy $\pi_\theta(a \mid s, \omega)$.
3: **while** not converged **do**
4: Randomly sample trajectories: $\tau \sim \mathcal{D}$.
5: Sample time index for each trajetory, $t \sim [1, H]$, and sample a corresponding outcome: $\omega \sim f(\omega \mid \tau_{t:H})$.
6: Compute loss: $\mathcal{L}(\theta) \leftarrow \sum_{(s_t, a_t, \omega)} \log \pi_\theta(a_t \mid s_t, \omega)$
7: Update policy parameters: $\theta \leftarrow \theta + \eta \nabla_\theta \mathcal{L}(\theta)$
8: **end while**
9: **return** Conditional policy $\pi_\theta(a \mid s, \omega)$

What are some choices for “outcomes”?

Option 1: What is the future state the agent ended up at?

RvS-G (Goal conditioned)

Option 2: What is the total return that the agent got?

RvS-R (Return conditioned)

A very *popular* idea

Lili Chen, Kevin Lu, Aravind Rajeswaran, Kimin Lee, Aditya Grover, Michael Laskin, Pieter Abbeel, Aravind Srinivas, and Igor Mordatch. **Decision transformer: Reinforcement learning via sequence modeling**

Felipe Codevilla, Matthias Muller, Antonio Lopez, Vladlen Koltun, and Alexey Dosovitskiy. **End-to-end driving via conditional imitation learning**

Yiming Ding, Carlos Florensa, Pieter Abbeel, and Mariano Phielipp. **Goal-conditioned imitation learning.**

Michael Janner, Qiyang Li, and Sergey Levine. **Offline reinforcement learning as one big sequence modeling problem**

Aviral Kumar, Xue Bin Peng, and Sergey Levine. **Reward-conditioned policies**

Xue Bin Peng, Aviral Kumar, Grace Zhang, and Sergey Levine. **Advantage-weighted regression: Simple and scalable off-policy reinforcement learning**

Rupesh Kumar Srivastava, Pranav Shyam, Filipe Mutz, Wojciech Jaskowski, and Jurgen Schmidhuber. ¨ **Training agents using upside-down reinforcement learning**

Many popular algorithm, e.g. Decision Transformer

Today's class

- [x] What is offline RL? Why do we need it for robots?

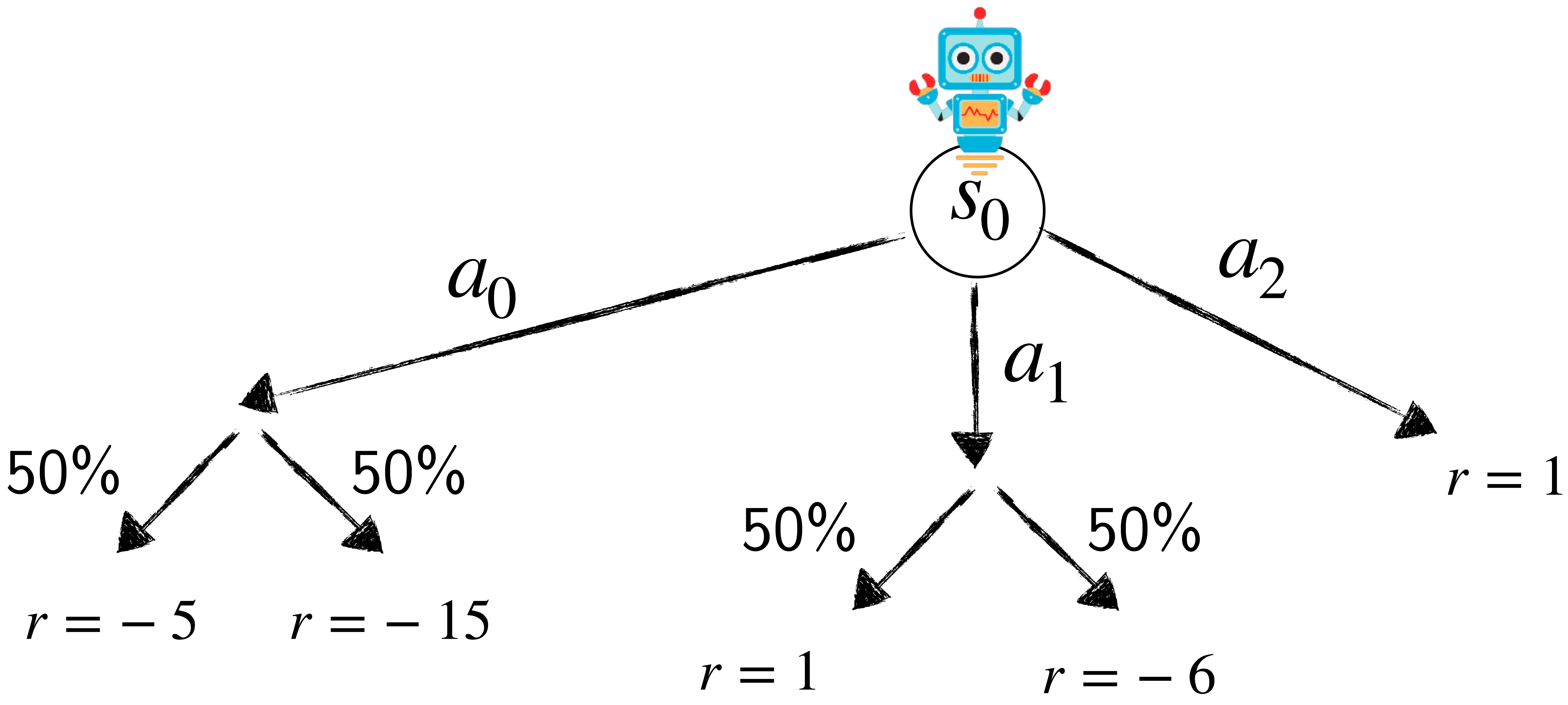
  (Enables safer training, leverages diverse experience)

- [ ] Paradigm 1: Offline RL via Pessimism
  - [x] Problem with Q-learning (Incorrectly optimistic about unseen actions)
  - [x] Pessimism to the rescue (Constrain policy to not deviate from data)

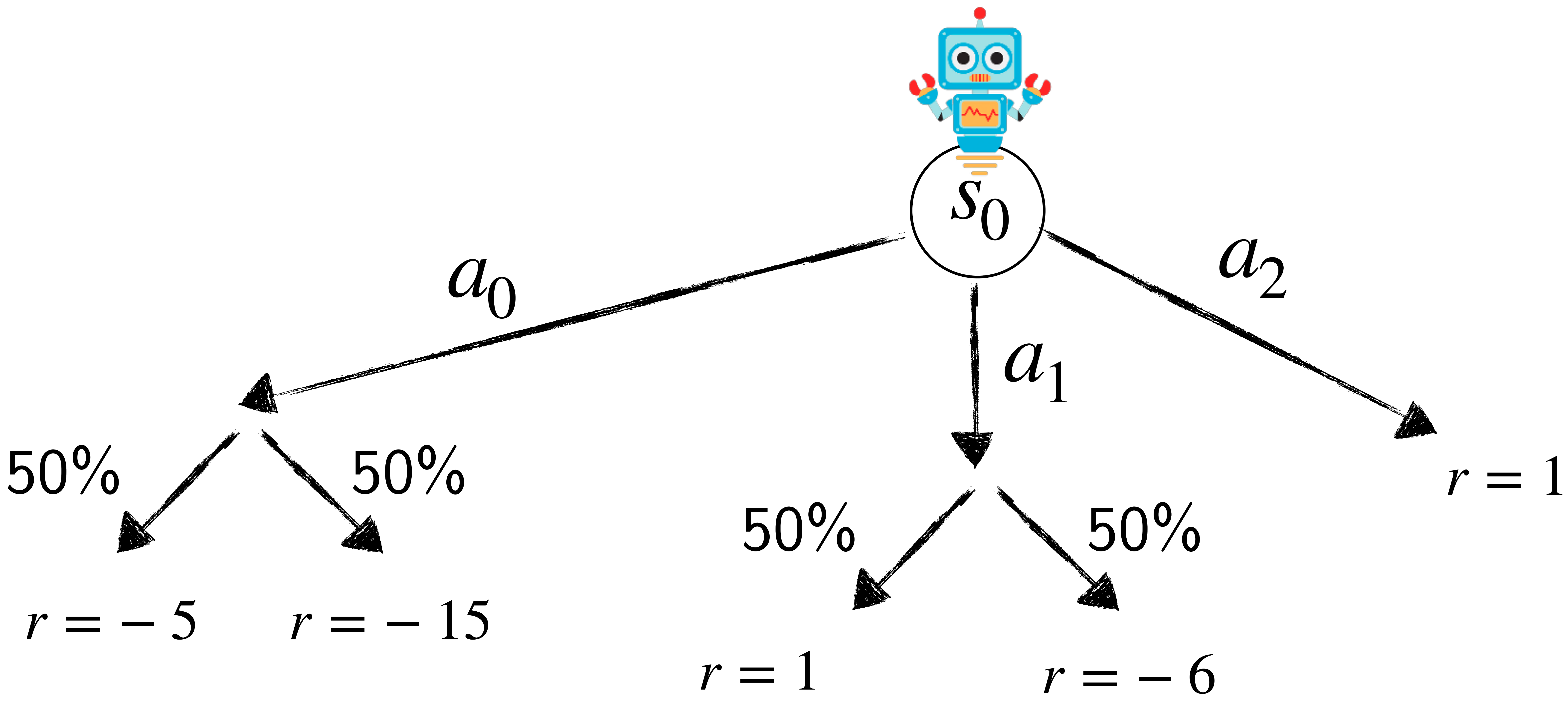
- [ ] Paradigm 2: RL via Supervised Learning
  - [x] Return-conditioned Supervised Learning
  - [ ] Problem in Stochastic MDPs

Activity!

Consider the following MDP



Consider the following MDP



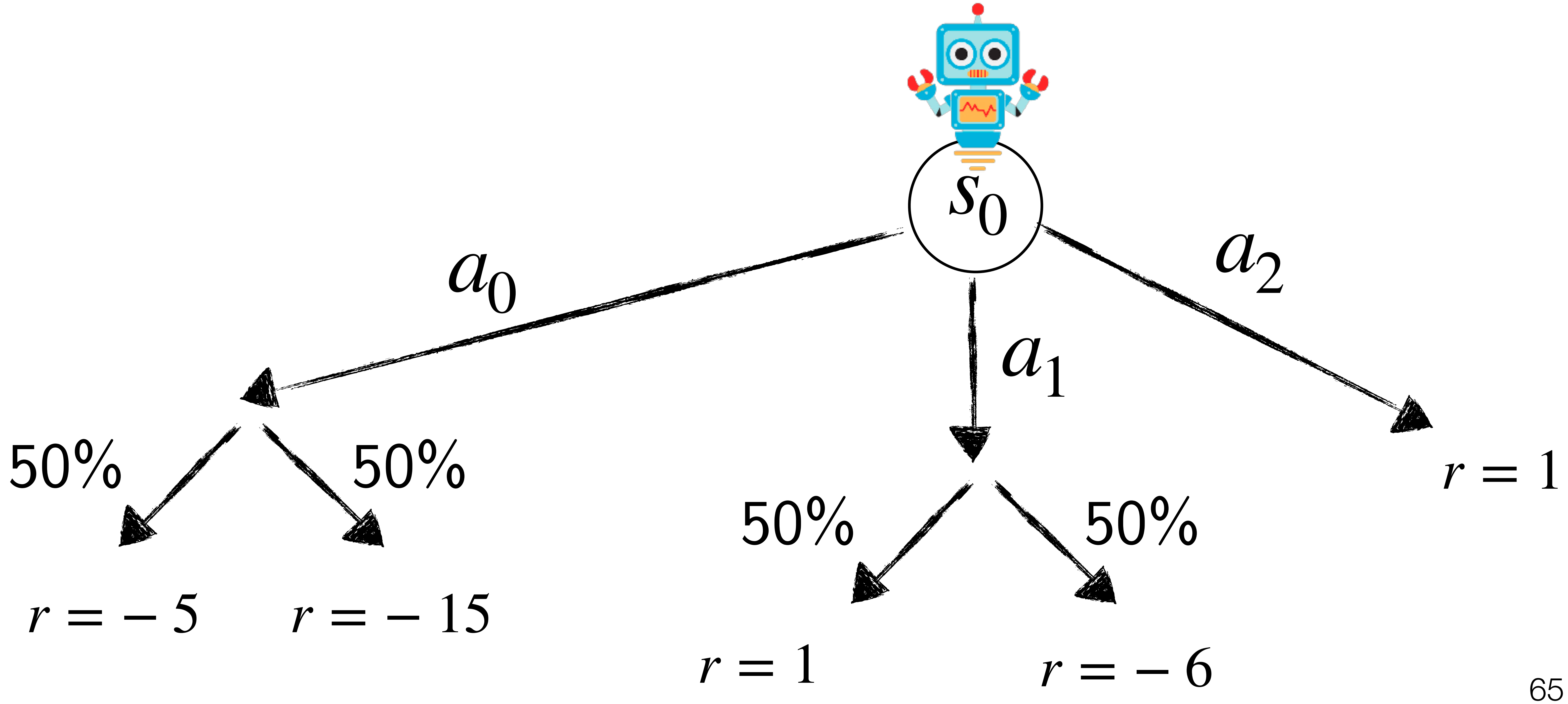
What is the optimal action? What will Decision Transformer play?

Think-Pair-Share!

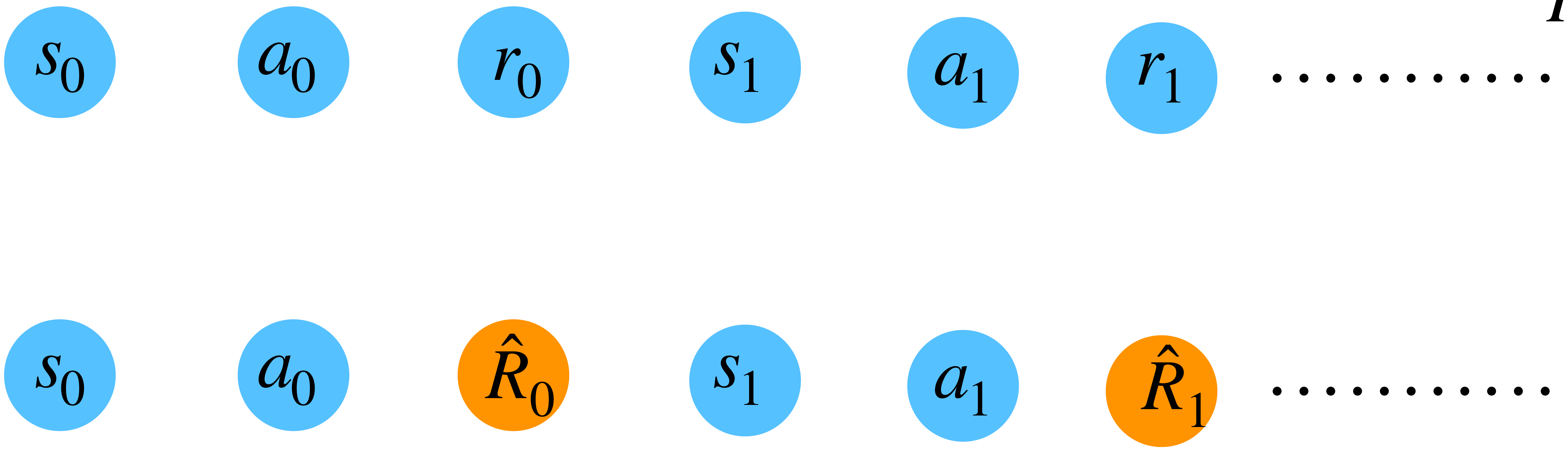
Think (30 sec): What is the optimal action? What would decision transformers play?

Pair: Find a partner

Share (45 sec): Partners exchange ideas

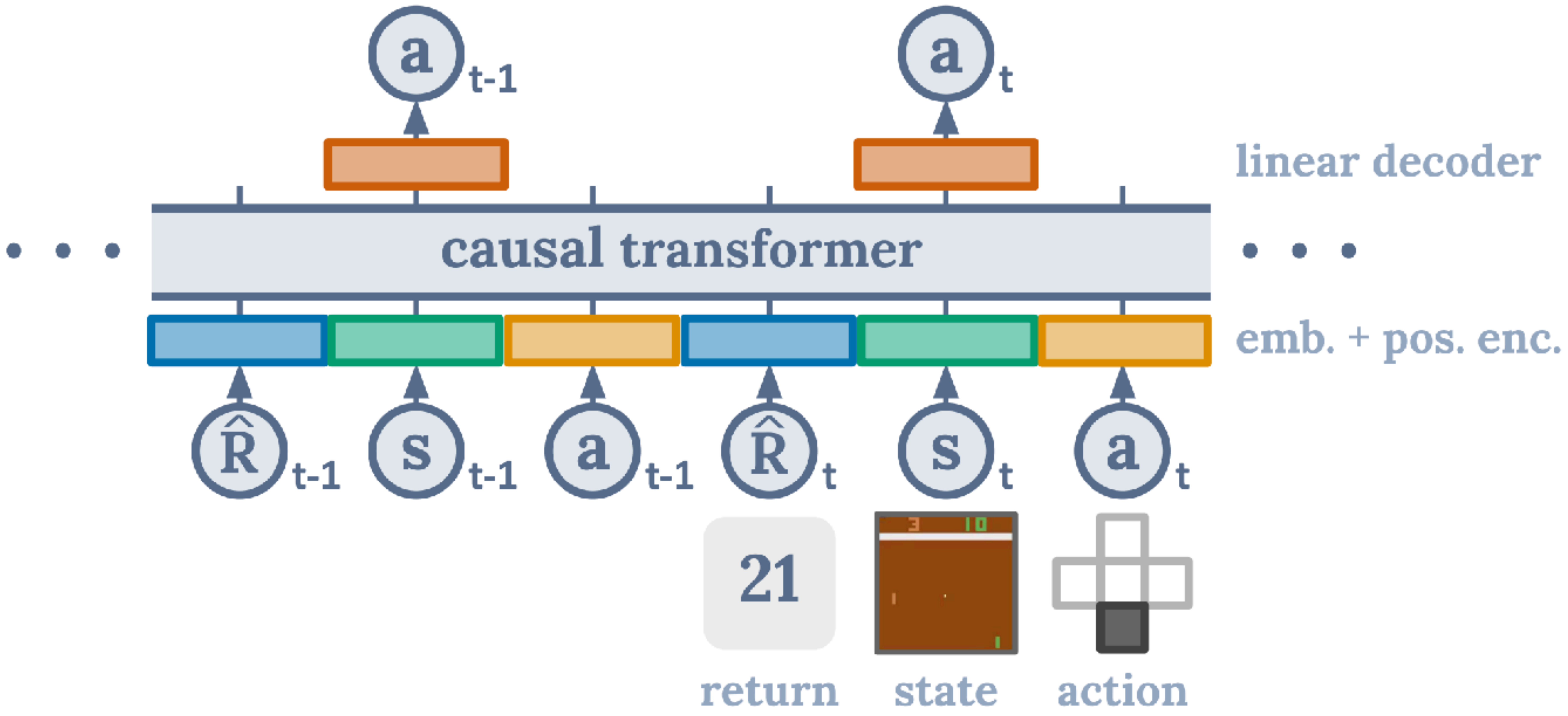


$$\hat{R} = \sum_{t=0}^{T-1} r_t$$



$$\hat{R}_0 = \sum_{t=0}^{T-1} r_t \qquad \hat{R}_1 = \sum_{t=1}^{T-1} r_t$$

$\cdots \quad \hat{R}_{t-1}$



Introducing Decision Transformers on Hugging Face 🤗

Published March 28, 2022

Update on GitHub

edbeeching
Edward Beeching
ThomasSimonini
Thomas Simonini

Test Time

Start at initial state s_0

Specify the desired target return R_0

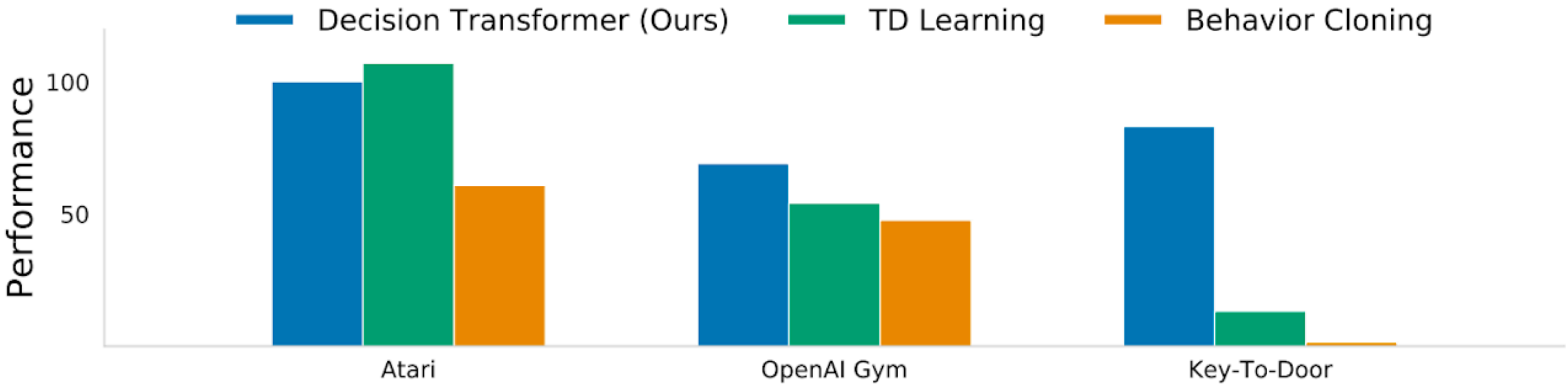
$a_0 = \text{Transformer}(R_0, s_0)$

Execute action, observe reward and next state (r_0, s_1)

Decrement the target return $R_1 = R_0 - r_0$

$a_1 = \text{Transformer}(R_0, s_0, a_0, R_1, s_1)$

Seems to work!



Seems to work!

Game	DT (Ours)	CQL	QR-DQN	REM	BC
Breakout	$\mathbf{267.5 \pm 97.5}$	211.1	17.1	8.9	138.9 ± 61.7
Qbert	15.4 ± 11.4	**104.2**	0.0	0.0	17.3 ± 14.7
Pong	106.1 ± 8.1	**111.9**	18.0	0.5	85.2 ± 20.0
Seaquest	$\mathbf{2.5 \pm 0.4}$	1.7	0.4	0.7	2.1 ± 0.3

Atari

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